INDUSTRIAL MOTOR CONTROL

Fifth Edition

Stephen L. Herman

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Industrial Motor Control, Fifth Edition
By Stephen L. Herman

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PREFACE

In recent years, the amount of knowledge an electrician must possess to be able to install and troubleshoot modern industrial control systems has increased dramatically. A continuous influx of improved control components allows engineers and electricians to design and install even more sophisticated and complex control systems. *Industrial Motor Control* presents the solid-state devices common in an industrial environment early in the text. This is intended to help the student understand the operation of many control components, including solid state relays, rectifiers, SCR drives for direct current motors, variable frequency drives for alternating current motors, and the inputs and outputs of programmable controllers. Although most electricians do not troubleshoot circuits on a component level, a basic knowledge of how these electronic devices operate is necessary for understanding how various control components perform their function.

The influx of programmable logic controllers into industry has bridged the gap between the responsibilities of the electrician and the instrumentation technician. Many industries are now insisting that electricians and instrumentation technicians be cross-trained so they can work more closely together. *Industrial Motor Control* helps to fulfill this requirement. Many of the common control devices found throughout industry are also discussed from a basic instrumentation standpoint by providing information on analog sensing of pressure, flow, temperature, and liquid level.

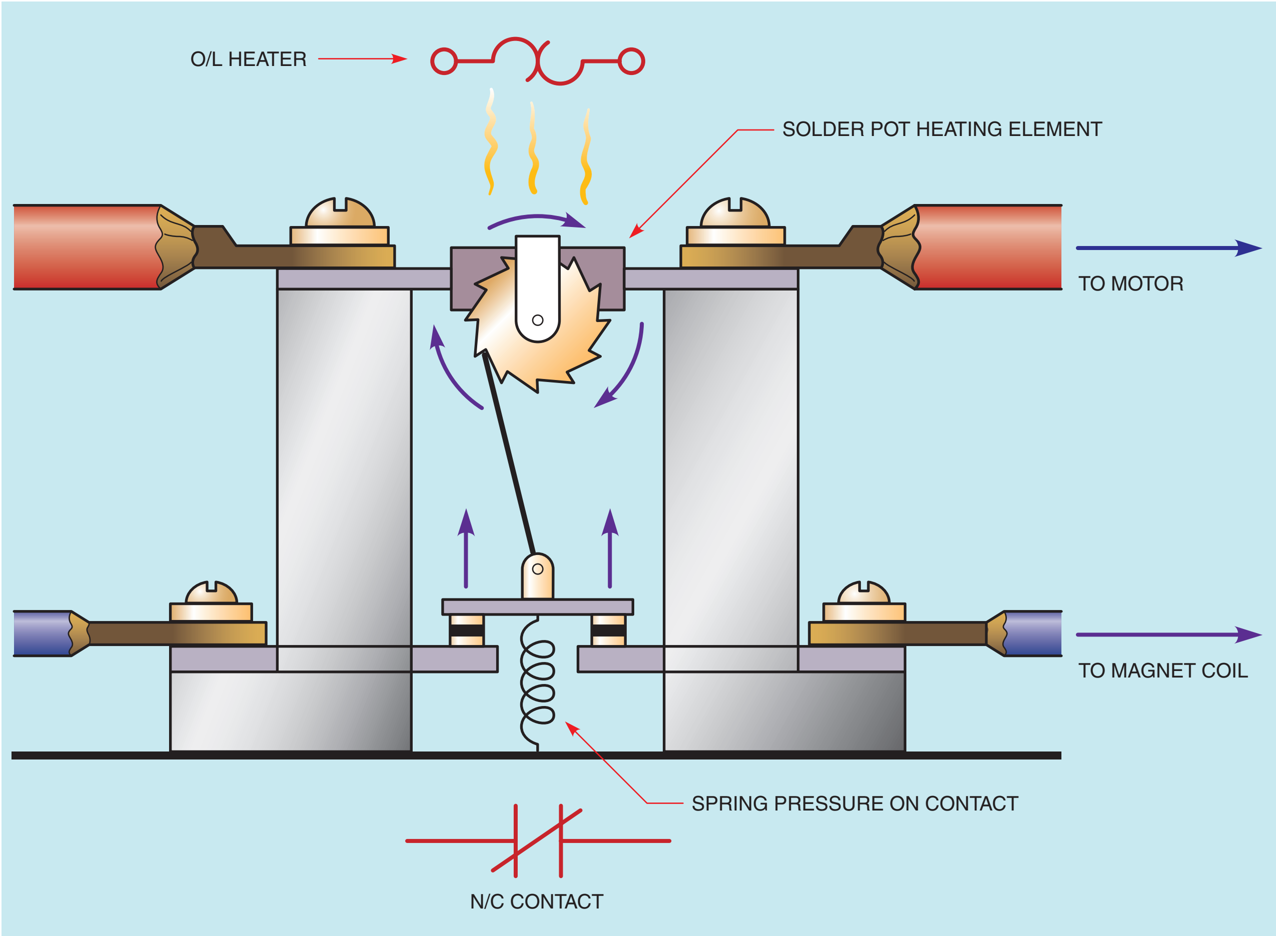
The fifth edition of *Industrial Motor Control* has updated many of the schematic diagrams of previous editions. The unit on motor installation has been updated to reflect changes in the 2005 *National Electrical Code*®, and a new unit has been added that instructs students on how to read large schematic diagrams.

Industrial Motor Control presents many examples of control logic and gives the student step-by-step instructions on how these circuits operate. There are examples of how ladder diagrams can be converted into wiring diagrams. This is the basis for understanding how to connect control circuits in the field. The concept of how motor control schematics are numbered is thoroughly discussed. Students are also given a set of conditions that a circuit must meet, and then that circuit is developed in a step-by-step procedure. Learning to design control circuits is a very effective means of learning how circuit logic works. It is impossible to effectively troubleshoot a control circuit if you do not understand the logic of what the circuit is intended to do.

Features of the Fifth Edition

This edition is based on the results of extensive research into content, organization, and effective learning styles. The textbook is built around short units of instruction that allow the student to completely understand and digest one topic before going on to the next. Each unit contains extensive illustrations, which have been designed for maximum learning. The illustrations in this edition have been improved to make them easier to read and many have been redrawn in a more pictorial style, so the student can quickly identify components and understand how they relate to one another. Color images make it easier for the reader to understand the information in the illustration (see the following sample illustration).

Industrial Motor Control, fifth edition, is a complete learning package which includes this comprehensive



Sample Illustration

textbook, a hands-on Lab Manual, an Interactive Companion on CD, an Instructor's Guide, and an instructor's e.resource. The Lab Manual offers practical hands-on circuits to be wired by the student. Each of the labs uses standard components that most electrical laboratories either have on hand or can be obtained without difficulty. Using this approach, students learn by doing.

The Interactive Companion CD, which can be found in a sleeve on the inside back cover of this textbook, includes applications and explanations of the concepts developed in the textbook. This exciting CD includes outstanding graphics, animations, and video segments and provides students with reinforcement of important concepts. The text of the licensing agreement for this software, along with instructions for installing and operating it, can be found on the pages following the index.

The *Instructor's Guide* includes the learning objectives from the textbook for the instructor's convenience, as well as a bank of test questions, and the answers to all of the test questions and textbook Unit Review Questions.

The new *Instructor's e.resource* is an invaluable addition to the Industrial Motor Control package. It includes PowerPoint slides for each unit (a total of nearly 500), nearly 1,000 Computerized Test Bank questions, and an image library containing hundreds of full-color images in electronic format.

Content Highlights

- The most commonly used solid-state devices are thoroughly described, in terms of both operation and typical application.
- Information on analog devices that sense pressure, flow, and temperature has been added to help bridge the gap between the industrial electrician and the instrumentation technician.

- DC and AC motor theory is included so students will understand the effects of control circuits on motor characteristics.
- The text covers the operating characteristics of stepping motors when connected to either DC or AC voltage.
- Detailed instructions are given for connecting motors in the field, including the size of conductors, overload relays, and fuses or circuit breakers. All calculations are taken from the National Electrical Code®.
- The principles of digital logic are described in sufficient detail for students to understand programmable controllers and prepare basic programs.
- A step-by-step testing procedure for electronic components is provided in the Appendix.
- Starting methods for hermetically sealed single-phase motors includes the hot-wire relay, solid state starting relay, current relay, and potential relay.
- The fifth edition provides increased coverage on overload relays and methods of protecting large horsepower motors.
- Increased coverage of variable frequency drives has been added to the fourth edition.
- Extensive coverage of solid-state control devices in addition to electromagnetic devices.
- Basic electronics is not a prerequisite for studying this text. Sufficient solid-state theory is presented to enable the student to understand and apply the concepts discussed.

About the Author

Stephen L. Herman has been both a teacher of industrial electricity and an industrial electrician for many years. He obtained formal training at Catawba Valley Technical College in Hickory, North Carolina, and at numerous seminars and manufacturers' schools. He also attended Stephen F. Austin University in Nacogdoches, Texas, and earned an Associates Degree in Electrical Technology from Lee College in Baytown, Texas. He was employed as an electrical installation and maintenance instructor at Randolph Technical College in Asheboro, North Carolina for nine years. Mr. Herman then returned to industry for a period of time before becoming the lead instructor for the Electrical Technology Program at Lee College in Baytown, Texas. He retired from Lee College with 20 years of service and presently lives with his wife in Pittsburg, Texas. Mr. Herman is a recipient of the Excellence in Teaching Award presented by the Halliburton Education Foundation.

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Section 1

SOLID-STATE DEVICES

UNIT 1

GENERAL PRINCIPLES OF ELECTRIC MOTOR CONTROL

OBJECTIVES

After studying this unit, the student will be able to:

- State the purpose and general principles of electric motor control.
- State the difference between manual and remote control.
- List the conditions of starting and stopping, speed control, and protection of electric motors.
- Explain the difference between compensating and definite time delay action.

There are certain conditions that must be considered when selecting, designing, installing, or maintaining motor control equipment. The general principles are discussed to help understanding and to motivate students by simplifying the subject of electric motor control.

Motor control was a simple problem when motors were used to drive a common line shaft to which several machines were connected. It was simply necessary to start and stop the motor a few times a day. However, with individual drive, the motor is now almost an integral part of the machine and it is necessary to design the motor controller to fit the needs of the machine to which it is connected. Modern installations and the problems of controlling motors in these situations may be observed in Figures 1–1 and 1–2.

Motor control is a broad term that means anything from a simple toggle switch to a complex system with components such as relays, timers, and switches. The common function of all controls, however, is to control the operation of an electric motor. As a result, when motor control equipment is selected and installed, many factors must be considered to ensure that the control will function properly for the motor and the machine for which it is selected.

Motor Control Installation Considerations

When choosing a specific device for a particular application, it is important to remember that the motor, machine, and motor controller are interrelated and need to be considered as a package. In general, five basic factors influence the selection and installation of a controller.

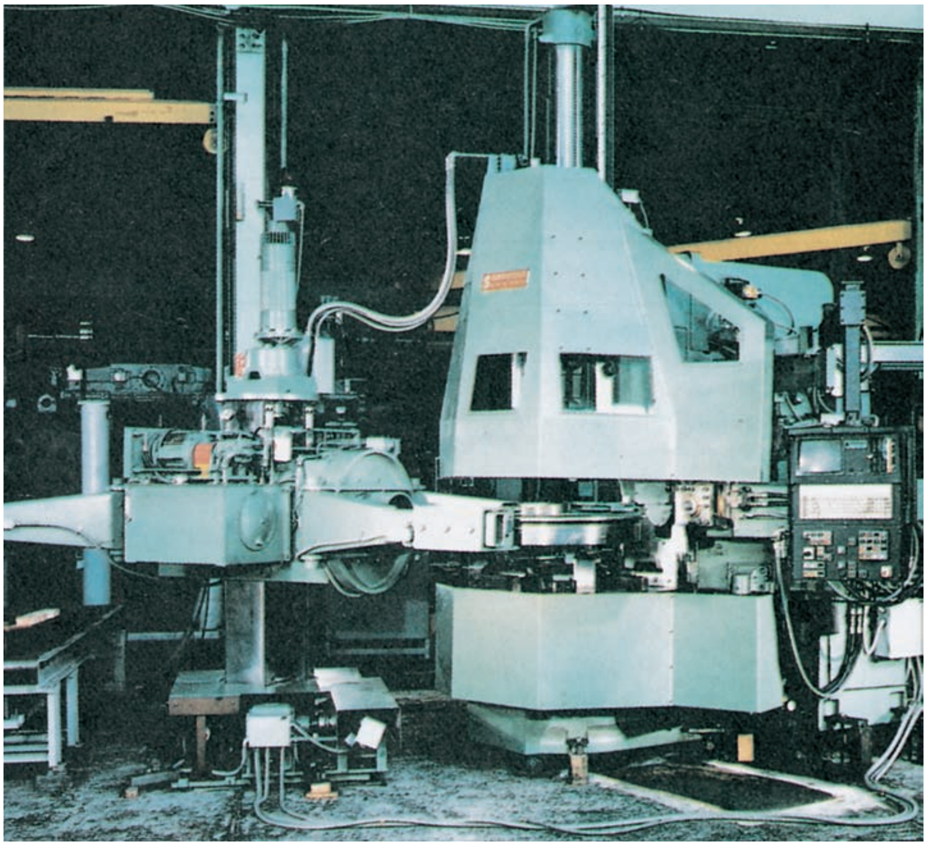


Figure 1–1 Programmable controller operates several motors in the manufacturing process. (Courtesy Simmons Machine Tool Co.)

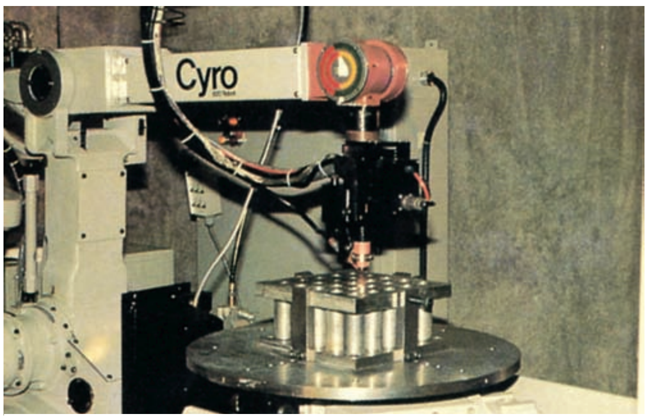


Figure 1–2 Robot arm controlled by a programmable controller.

1. ELECTRICAL SERVICE
   Establish whether the service is direct (dc) or alternating current (ac). If ac, determine the frequency (hertz) and number of phases in addition to the voltage.

2. MOTOR
   The motor should be attached to the electrical service, and correctly sized for the machine load in horsepower rating (hp). Other considerations include motor speed and torque. To select proper protection for the motor, its full load current rating (FLC), service factor (SF), time rating (duty), and other pertinent data—as shown on the motor nameplate—must be used.

3. OPERATING CHARACTERISTICS OF CONTROLLER
   The fundamental tasks of a motor controller are to start and stop the motor, and to protect the motor, machine, product, and operator. The controller may

also be called upon to provide supplementary functions such as reversing, jogging or inching, plugging, operating at several speeds or at reduced levels of current and motor torque.

4. ENVIRONMENT
Controller enclosures provide safety protection for operating personnel by preventing accidental contact with live parts. In certain applications, the controller itself must be protected from a variety of environmental conditions that might include:
   - Water, rain, snow or sleet
   - Dirt or noncombustible dust
   - Cutting oils, coolants or lubricants

   Both personnel and property require protection in environments made hazardous by the presence of explosive gases or combustible dusts.

5. ELECTRICAL CODES AND STANDARDS
Motor control equipment is designed to meet the provisions of the *National Electrical Code*® (*NEC*®). (*National Electrical Code*® and *NEC*® are registered trademarks of the National Fire Protection Association Inc., Quincy, MA 02269.) Also, local code requirements must be considered and met when installing motors and control devices. Presently, code sections applying to motors, motor circuits, and controllers and industrial control devices are found in Article 430 on motors and motor controllers, Article 440 on air conditioning and refrigeration equipment, and Article 500 on hazardous locations of the *NEC*®.
   The 1970 Occupational Safety and Health Act (OSHA) as amended, requires that each employer furnish employment in an environment free from recognized hazards likely to cause serious harm.
   Standards established by the National Electrical Manufacturers Association (NEMA) assist users in the proper selection of control equipment. NEMA standards provide practical information concerning the construction, testing, performance, and manufacture of motor control devices such as starters, relays, and contactors.
   One of the organizations that actually test for conformity to national codes and standards is Underwriters' Laboratories (UL). Equipment that is tested and approved by UL is listed in an annual publication, which is kept current by means of bimonthly supplements to reflect the latest additions and deletions. A UL listing does not mean that a product is approved by the NEC®. It must be acceptable to the local authority having jurisdiction.

Purpose of Controller

Some of the complicated and precise automatic applications of electrical control are illustrated in Figures 1–3 and 1–6. Factors to be considered when selecting and installing motor control components for use with particular machines or systems are described in the following paragraphs.

Starting

The motor may be started by connecting it directly across the source of voltage. Slow and gradual starting may be required, not only to protect the machine, but also to ensure that the line current inrush on starting is not too great for the power company's system. Some driven machines may be damaged if they are started with a sudden turning effort. The frequency of starting

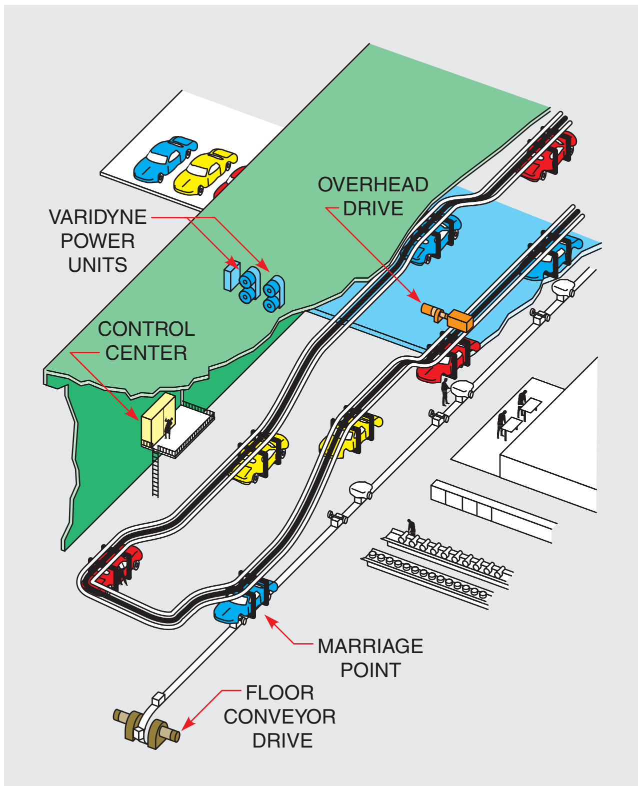


Figure 1–3 Automotive assembly line.

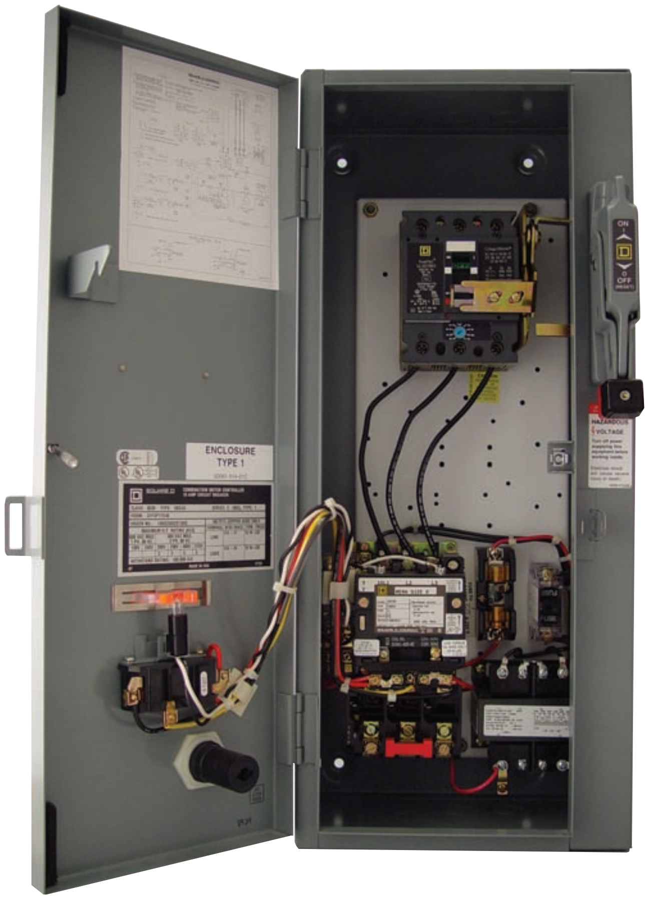


Figure 1–4 Combination motor starter with circuit breakers, disconnect switch, and control transformer. (Shown inside module used for insertion into a motor control center.) (Courtesy Square D Company.)

a motor is another factor affecting the controller. A combination motor starter with circuit breaker and control transformer is shown in Figure 1–4.

Stopping

Most controllers allow motors to coast to a standstill. Some impose braking action when the machine must stop quickly. Quick stopping is a vital function of the controller for emergency stops. Controllers assist the stopping action by retarding centrifugal motion of machines and lowering operations of crane hoists.

Reversing

Controllers are required to change the direction of rotation of machines automatically or at the command of an operator at a control station. The reversing action of a controller is a continual process in many industrial applications.

Running

Maintaining desired operational speeds and characteristics is a prime purpose and function of controllers. They protect motors, operators, machines, and materials while running. There are many different types of safety circuits and devices to protect people, equipment, and industrial production and processes against possible injury that may occur while the machines are running.

Speed Control

Some controllers can maintain very precise speeds for industrial processes. Other controllers can change the speeds of motors either in steps or gradually through a continuous range of speeds.

Safety of Operator

Many mechanical safeguards have been replaced or aided by electrical means of protection. Electrical control pilot devices in controllers provide a direct means of protecting machine operators from unsafe conditions.

Protection from Damage

Part of the operation of an automatic machine is to protect the machine itself and the manufactured or processed materials it handles. For example, a certain machine control function may be the prevention of conveyor pileups. A machine control can reverse, stop, slow, or do whatever is necessary to protect the machine or processed materials.

Maintenance of Starting Requirements

Once properly installed and adjusted, motor starters will provide reliable operation of starting time, voltages, current, and torques for the benefit of the driven machine and the power system. The National Electrical Code, supplemented by local codes, governs the selection of the proper sizes of conductors, starting fuses, circuit breakers, and disconnect switches for specific system requirements.

Manual Control

A manual control is one whose operation is accomplished by mechanical means. The effort required to actuate the mechanism is almost always provided by a human operator. The motor may be controlled manually using any one of the following devices.

Toggle Switch

A toggle switch is a manually operated electric switch. Many small motors are started with toggle switches. This means the motor may be started directly without the use of magnetic switches or auxiliary equipment. Motors started with toggle switches are protected by the branch circuit fuse or circuit breaker. These motors generally drive fans, blowers, or other light loads.

Safety Switch

In some cases it is permissible to start a motor directly across the full line voltage if an externally-operated safety switch is used (Figure 1–5). The motor receives starting and running protection from dual-element, time-delay fuses. The use of a safety switch requires manual operation. A safety switch, therefore, has the same limitations common to most manual starters.

Drum Controller

Drum controllers are rotary, manual switching devices often used to reverse motors and to control the speed of ac and dc motors. They are used particularly where frequent start, stop, or reverse operation is required. These controllers may be used without other control components in small motors, generally those with fractional horsepower ratings. Drum controllers are used with magnetic starters in large motors. A drum controller is shown in Figure 1–6.

Figure 1–5 Three-phase disconnect switch. (Courtesy Square D Company.)

Figure 1–6 Drum controller with cover removed so that inside is visible. (Courtesy Square D Company.)

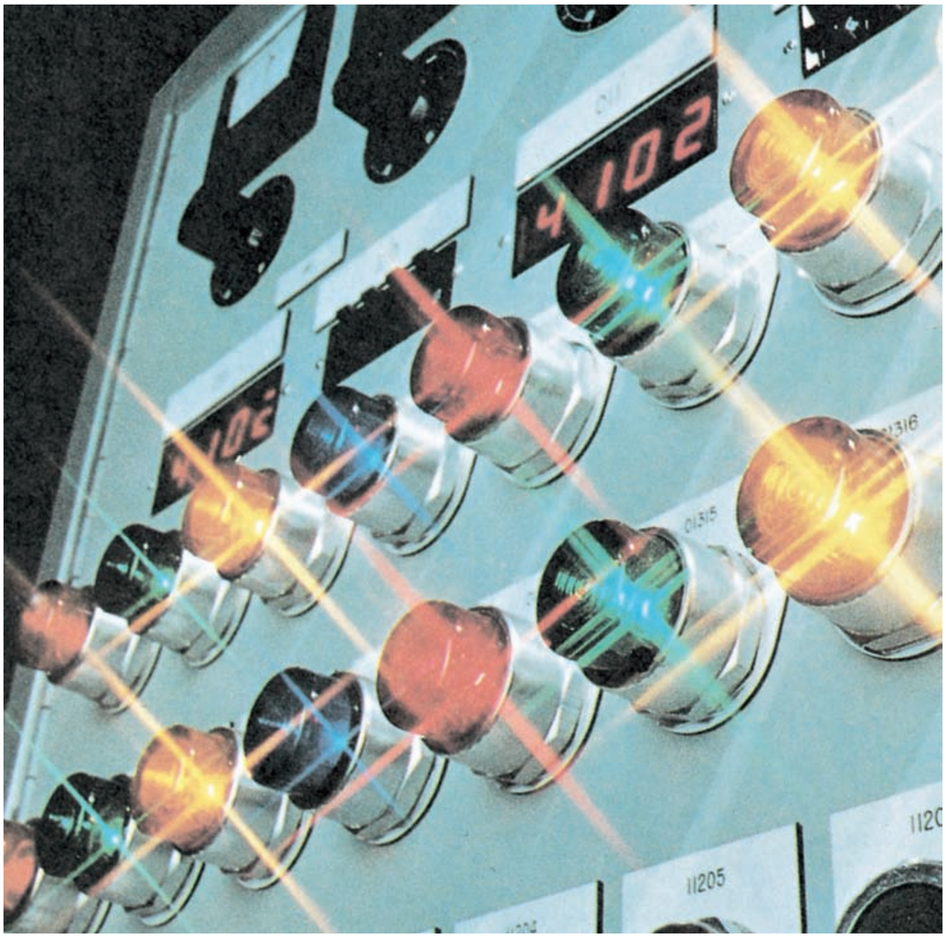


Figure 1–7 Pushbutton control center.

Remote and Automatic Control

The motor may be controlled by remote control using push buttons (Figure 1–7). When push-button remote control is used or when automatic devices do not have the electrical capacity to carry the motor starting and running currents, magnetic switches must be included. Magnetic switch control is accomplished by electromagnetic means. The effort required to actuate the electromagnet is supplied by electrical energy rather than by the human operator. If the motor is to be automatically controlled, the following two-wire pilot devices may be used.

Float Switch

The raising or lowering of a float that is mechanically attached to electrical contacts may start motor-driven pumps to empty or fill tanks. Float switches are also used to open or close piping solenoid valves to control fluids (Figure 1–8).

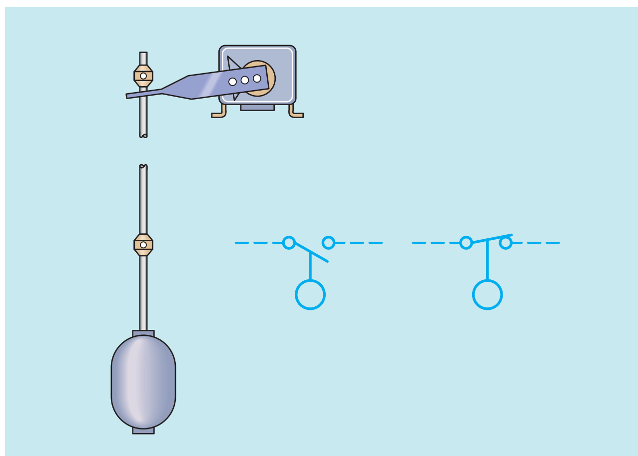


Figure 1–8 Rod operated float switch with electrical wiring symbols.

Pressure Switch

Pressure switches are used to control the pressure of liquids and gases (including air) within a desired range (Figure 1–9). Air compressors, for example, are started directly or indirectly on a call for more air by a pressure switch. Electrical wiring symbols are shown as normally closed and normally open in Figure 1–10.

Time Clock

Time clocks can be used when a definite "on and off" period is required and adjustments are not necessary for long periods of time. A typical requirement is a motor that must start every morning at the same time and shut off every night at the same time, or that switches the floodlights on and off.

Thermostat

In addition to pilot devices sensitive to liquid levels, gas pressures, and time of day, thermostats sensitive to temperature changes are widely used (Figure 1–11). Thermostats indirectly control large motors in air conditioning systems and in many industrial applications to maintain the desired temperature range of air, gases, liquids, or solids. There are many types of thermostats and temperature-actuated switches.

Limit Switch

Limit switches (Figure 1–12) are designed to pass an electrical signal only when a predetermined limit is reached. The limit may be a specific position for a machine part or a piece of work, or a certain rotating speed. These devices take the place of a human operator and are often used under conditions where it would be impossible or impractical for the operator to be present or to efficiently direct the machine.

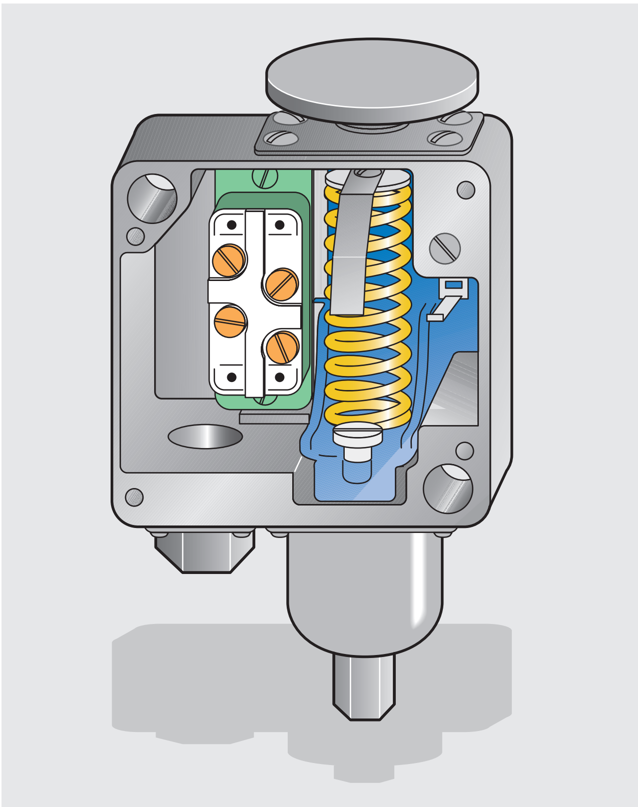


Figure 1–9 Pressure switch with cover removed.

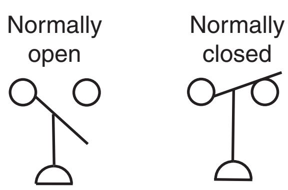


Figure 1–10 NEMA symbols for pressure switch contacts.

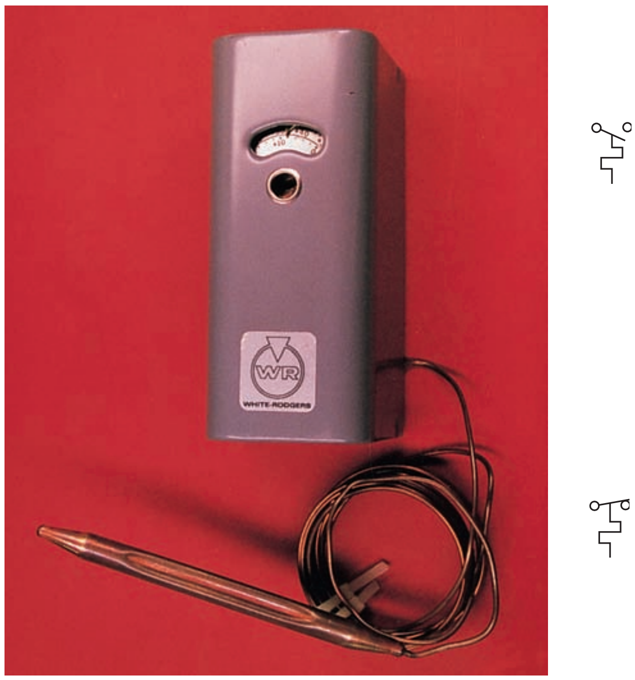


Figure 1–11 Line voltage thermostat. (Courtesy White Rogers.)

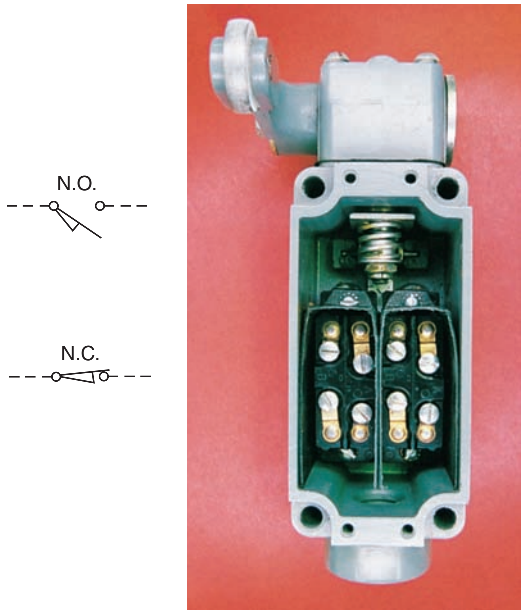


Figure 1–12 Limit switch with cover removed to show internal connections.

Limit switches are used most frequently as overtravel stops for machines, equipment, and products in process. These devices are used in the control circuits of magnetic starters to govern the starting, stopping, or reversal of electric motors.

Electrical or Mechanical Interlock and Sequence Control

Many of the electrical control devices described in this unit can be connected in an interlocking system so that the final operation of one or more motors depends upon the electrical position of each individual control device. For example, a float switch may call for more liquid but will not be satisfied until the prior approval of a pressure switch or time clock is obtained. To design, install, and maintain electrical controls in any electrical or mechanical interlocking system, the electrical technician must understand the total operational system and the function of the individual components. With practice, it is possible to transfer knowledge of circuits and descriptions for an understanding of additional similar controls. It is impossible—in instructional materials—to show all possible combinations of an interlocking control system. However, by understanding the basic functions of control components and their basic circuitry, and by taking the time to trace and draw circuit diagrams, difficult interlocking control systems can become easier to understand.

Starting and Stopping

In starting and stopping a motor and its associated machinery, there are a number of conditions that may affect the motor. A few of them are discussed here.

Frequency of Starting and Stopping

The starting duty cycle of a controller is an important factor in determining how satisfactorily the controller will perform in a particular application. Magnetic switches, such as motor starters, relays, and contactors, actually beat themselves apart from repeated opening and closing thousands of times. An experienced electrician soon learns to look for this type of component failure when troubleshooting any inoperative control panels. NEMA standards require that the starter size be derated if the frequency of start-stop, jogging, or plugging is more than 5 times per minute. Therefore, when the frequency of starting the controller is great, the use of heavy duty controllers and accessories should be considered. For standard duty controllers, more frequent inspection and maintenance schedules should be followed.

Light or Heavy Duty Starting

Some motors may be started with no loads and others must be started with heavy loads. When motors are started, large feeder line disturbances may be created that can affect the electrical distribution system of the entire industrial plant. The disturbances may even affect the power company's system. As a result, the power companies and electrical inspection agencies place certain limitations on "across-the-line" motor starting.

Fast or Slow Start (Hard or Soft)

To obtain the maximum twisting effort (torque) of the rotor of an ac motor, the best starting condition is to apply full voltage to the motor terminals. The driven machinery, however, may be damaged by the sudden surge of motion. To prevent this type of damage to machines, equipment, and processed materials, some controllers are designed to start slowly and then increase the motor speed gradually in definite steps. This type is often used by power companies and inspection agencies to avoid electrical line surges.

Smooth Starting

Although reduced electrical and mechanical surges can be obtained with a step-by-step motor starting method, very smooth and gradual starting will require different controlling methods. These are discussed in detail later in the text.

Manual or Automatic Starting and Stopping

While the manual starting and stopping of machines by an operator is still a common practice, many machines and industrial processes are started and restarted automatically. These automatic devices result in tremendous savings of time and materials. Automatic stopping devices are used in motor control systems for the same reasons. Automatic stopping devices greatly reduce the safety hazards of operating some types of machinery, both for the operator and the materials being processed. An electrically operated, mechanical brake is shown in Figure 1–13. Such a brake may be required to stop a machine's motion in a hurry to protect materials being processed or people in the area.

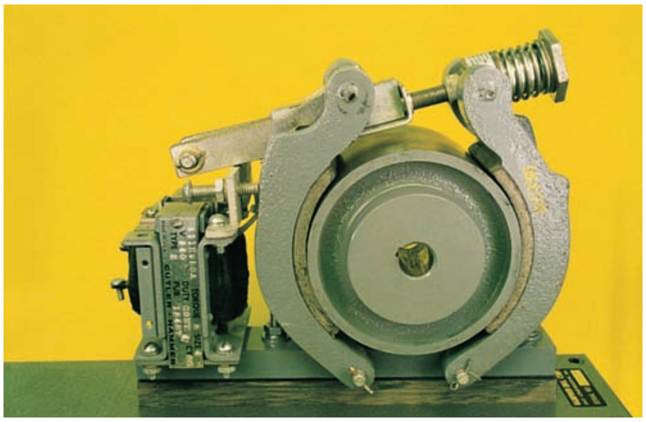


Figure 1–13 Typical electric brake.

Quick Stop or Slow Stop

Many motors are allowed to coast to a standstill. However, manufacturing requirements and safety considerations often make it necessary to bring machines to as rapid a stop as possible. Automatic controls can retard and brake the speed of a motor and also apply a

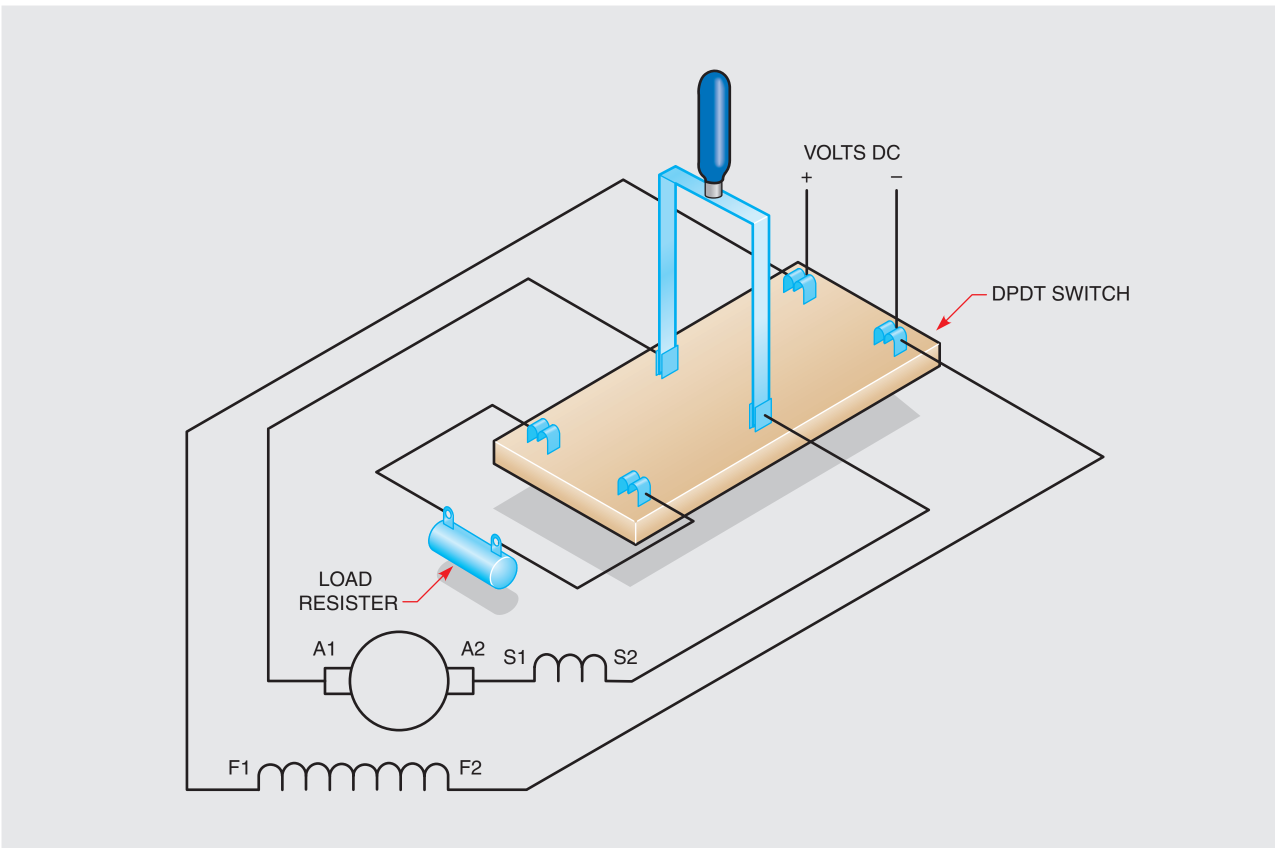


Figure 1–14 Dynamic braking for a dc compound motor.

torque in the opposite direction of rotation to bring about a rapid stop. This is called *plugging*. Plugging can only be used if the driven machine and its load will not be damaged by the reversal of the motor torque. The control of deceleration is one of the important functions of a motor control.

Another method of braking electric motors is known as *dynamic braking*. When this method is used to reduce the speed of dc motors, the armature is connected across a load resistor when power is disconnected from the motor. If the field winding of the motor remains energized, the motor becomes a generator and current is supplied to the load resistor by the armature (Figure 1–14). The current flowing through the armature winding creates a magnetic field around the armature. This magnetic field causes the armature to be attracted to the magnetic field of the pole pieces. This action in a dc generator is known as *counter torque*. Using counter torque to brake a dc motor is known as dynamic braking.

Ac induction motors can be braked by momentarily connecting dc voltage to the stator winding (Figure 1–15). When direct current is applied to the stator winding of an ac motor, the stator poles become electromagnets. Current is induced into the windings of the rotor as the rotor continues to spin through the magnetic field. This induced current produces a magnetic field around the rotor. The magnetic field of the rotor is

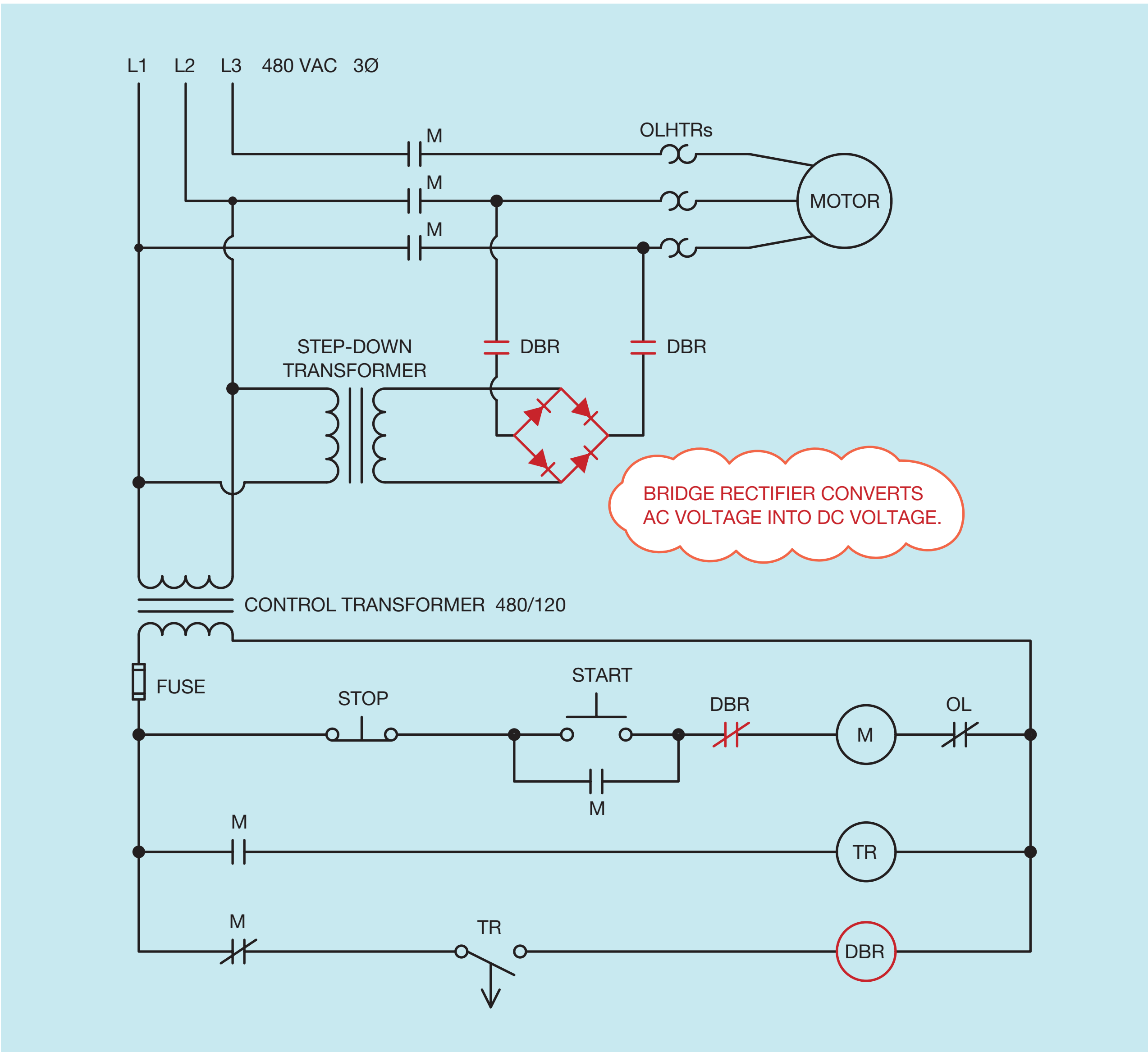


Figure 1–15 Dynamic braking for an ac motor.

attracted to the magnetic field produced in the stator. The attraction of these two magnetic fields produces a braking action in the motor.

An advantage of using dynamic braking is that motors can be stopped rapidly without wearing brake linings or drums. It cannot be used to hold a suspended load, however. Mechanical brakes must be employed when a load must be held, such as with a crane or hoist.

Accurate Stops

An elevator must stop at precisely the right location so that it is aligned with the floor level. Such accurate stops are possible with the use of automatic devices interlocked with control systems.

Frequency of Reversals Required

Frequent reversals of the direction of rotation of the motor impose large demands on the controller and the electrical distribution system. Special motors and special starting and running protective devices may be required to meet the conditions of frequent reversals. A heavy duty drum switch-controller is often used for this purpose.

Speed Control of Motors

The speed control is concerned not only with starting the motor but also with maintaining or controlling the motor speed while it is running. There are a number of conditions to be considered for speed control.

Constant Speed

Constant speed motors are used on water pumps (Figures 1–10 and 1–16). Maintenance of constant speed is essential for motor generator sets under all load

Figure 1–16 (Courtesy Tennessee Valley Authority.)

conditions. Constant speed motors with ratings as low as 80 rpm and horsepower ratings up to 5000 hp are used in direct drive units. The simplest method of changing speeds is by gearing. Using gears, almost any "predetermined" speed may be developed by coupling the input gear to the shaft of a squirrel-cage induction motor. A speed-reducing cycloidal gear motor is shown in Figure 1–17.

Varying Speed

A varying speed is usually preferred for cranes and hoists (Figure 1–18). In this type of application, the motor speed slows as the load increases and speeds up as the load decreases.

Adjustable Speed

With adjustable speed controls, an operator can gradually adjust the speed of a motor over a wide range while the motor is running. The speed may be preset, but once it is adjusted it remains essentially constant at any load within the rating of the motor.

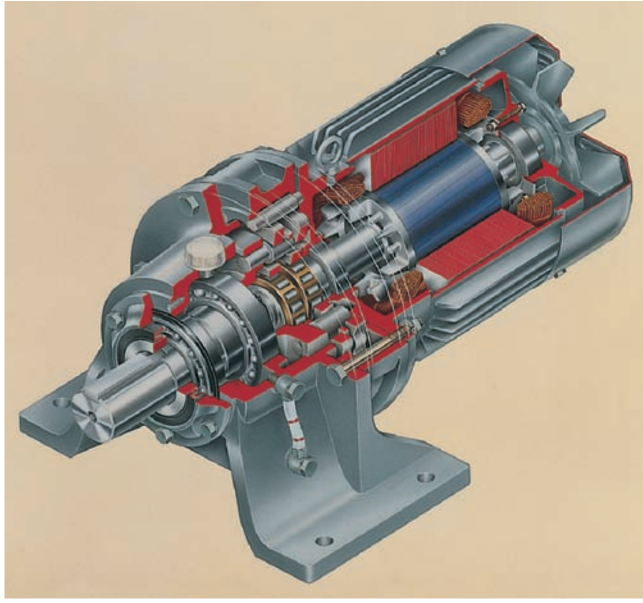


Figure 1–17 Cutaway view of a speed reducing cycloidal gear motor. Cycloidal gear boxes use a concentric cam with rollers instead of conventional gears. (Courtesy Sumitomo Machinery Corporation of America.)

Figure 1–18 Large traveling overhead crane. (Courtesy Harrington Hoists and Cranes.)

Multispeed

For multispeed motors, such as the type used on turret lathes in a machine shop, the speed can be set at two or more definite rates. Once the motor is set at a definite speed, the speed will remain practically constant regardless of load changes.

Protective Features

The particular application of each motor and control installation must be considered to determine what protective features are required to be installed and maintained.

Overload Protection

Running protection and overload protection refer to the same thing. This protection may be an integral part of the motor or be separate. A controller with electrical overload protection will protect a motor from burning up while allowing the motor to achieve its maximum available power under a range of overload and temperature conditions. An electrical overload on the motor may be caused by mechanical overload on driven machinery, a low line voltage, an open electrical line in a polyphase system resulting in single-phase operation, motor problems such as too badly worn bearings, loose terminal connections, or poor ventilation within the motor.

Open Field Protection

Dc shunt and compound-wound motors can be protected against the loss of field excitation by field loss relays. Other protective arrangements are used with starting equipment for dc and ac synchronous motors. Some sizes of dc motors may race dangerously with the loss of field excitation while other motors may not race due to friction and the fact that they are small.

Open-Phase Protection

Phase failure in a three-phase circuit may be caused by a blown fuse, an open connection, a broken line or other reasons. If phase failure occurs when the motor is at a standstill during attempts to start, the stator currents will rise to a very high value and will remain there, but the motor will remain stationary (not turn). Since the windings are not properly ventilated while the motor is stationary, the heating produced by the high currents may damage them. Dangerous conditions also are possible while the motor is running. When the motor is running and an open-phase condition occurs, the motor may continue to run. The torque will decrease, possibly to the point of motor “stall”; this condition is called *breakdown torque.*

Reversed Phase Protection

If two phases of the supply of a three-phase induction motor are interchanged (phase reversal), the motor will reverse its direction of rotation. In elevator operation and industrial applications, this reversal can result in serious damage. Phase failure and phase reversal relays are safety devices used to protect motors, machines, and personnel from the hazards of open-phase or reversed-phase conditions.

Overtravel Protection

Control devices are used in magnetic starter circuits to govern the starting, stopping, and reversal of electric motors. These devices can be used to control regular machine operation or they can be used as safety emergency switches to prevent the improper functioning of machinery.

Overspeed Protection

Excessive motor speeds can damage a driven machine, materials in the industrial process, or the motor. Overspeed safety protection is provided in control equipment for paper and printing plants, steel mills, processing plants, and the textile industry.

Reversed Current Protection

Accidental reversal of currents in dc controllers can have serious effects. Direct-current controllers used with three-phase alternating-current systems that experience phase failures and phase reversals are also subject to damage. Reverse current protection is an important provision for battery charging and electroplating equipment.

Mechanical Protection

An enclosure may increase the life span and contribute to the trouble-free operation of a motor and

Figure 1–19 Explosion proof enclosure for a magnetic motor starter.

controller. Enclosures with particular ratings such as general purpose, watertight, dustproof, explosionproof, and corrosion resistant are used for specific applications (Figure 1–19). All enclosures must meet the requirements of national and local electrical codes and building codes.

Short Circuit Protection

For large motors with greater than fractional horsepower ratings, short circuit and ground fault protection generally is installed in the same enclosure as the motor-disconnecting means. Overcurrent devices (such as fuses and circuit breakers) are used to protect the motor branch circuit conductors, the motor control apparatus, and the motor itself against sustained overcurrent due to short circuits and grounds, and prolonged and excessive starting currents.

Classification of Automatic Motor Starting Control Systems

The numerous types of automatic starting and control systems are grouped into the following classifications: current limiting acceleration and time delay acceleration.

Current Limiting Acceleration

Current limiting acceleration is also called *compensating time*. It refers to the amount of current or voltage drop required to open and close magnetic switches when used in a motor accelerating controller. The rise and fall of the current or voltage determines a timing period that is used mainly for dc motor control. Examples of types of current limiting acceleration are:

- Counter emf or voltage drop acceleration
- Lockout contactor or series relay acceleration

Time Delay Acceleration

For time delay acceleration, *definite time* relays are used to obtain a preset timing period. Once the period is preset, it does not vary regardless of current or voltage changes occurring during motor acceleration. The following timers and timing systems are used for motor acceleration; some are also used in interlocking circuits for automatic control systems.

- Pneumatic timing
- Motor-driven timers
- Capacitor timing
- Electronic timers

Troubleshooting

One of the primary jobs of an industrial electrician is troubleshooting control circuits. An electrician that is proficient in troubleshooting is sought after by most of industry. The greatest troubleshooting tool an electrician can possess is the ability to read and understand control schematic diagrams. Many of the circuits shown in this text are accompanied by detailed explanations of the operation of the circuit. If the circuit and explanation are studied step by step, the student will have an excellent understanding of control schematics when this text is completed.

Most electricians follow a set procedure when troubleshooting a circuit. If the problem has occurred several times in the past and was caused by the same component each time, most electricians check that component first. If that component proves to be the problem, much time has been saved by not having to trace the entire circuit.

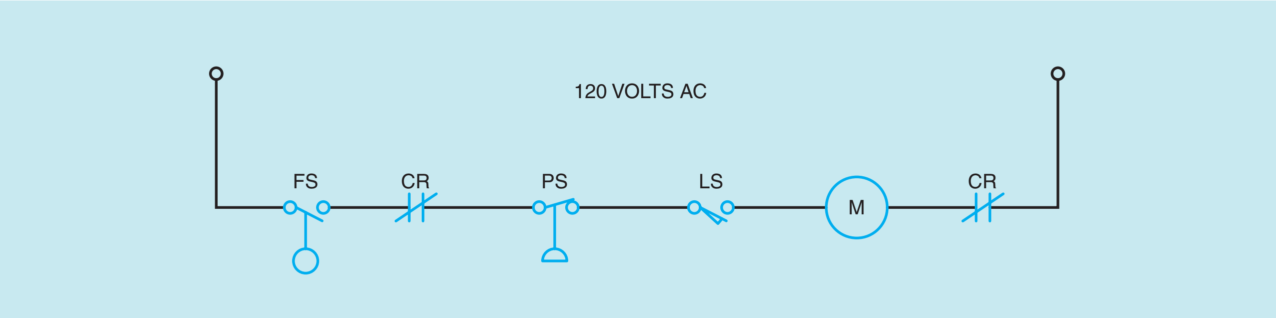


Figure 1–20 Troubleshooting a circuit.

Another method of troubleshooting a circuit is *shotgun* troubleshooting. This method derives its name from the manner in which components are tested. Instead of following the circuit in a logical step-by-step procedure, the electrician quickly checks the major components of the circuit. This approach is used to save time because in many industrial situations an inoperative piece of equipment can cost a company thousands of dollars for each hour it is not working.

When neither of these methods reveals the problem, the electrician must use the control schematic to trace the circuit in a logical step-by-step procedure. The primary tool used to trace a circuit is the volt-ohm-milliammeter (VOM), which measures voltage, current, and resistance. It is often necessary to use jumper leads to bridge open contacts when using the VOM. When a jumper lead is used for this application, it should be provided with short circuit protection. This can be done by connecting a small fuse holder or circuit breaker in series with the jumper lead. In this way if the jumper is accidently shorted, the fuse or circuit breaker will open and protect the rest of the circuit.

When troubleshooting a circuit, most electricians work backward through the circuit. For example, one line of a control schematic is shown in Figure 1–20. M relay coil is connected in series with a normally closed overload contact, a normally open limit switch contact, a normally closed pressure switch contact, a normally closed CR relay contact, and a normally open float switch contact. The problem with the circuit is that M relay coil will not energize. The first test should be to measure the voltage at each end of the circuit to confirm the presence of control voltage. The next procedure is to connect the voltmeter across each of the circuit components to determine which one is open and stopping the current flow to the coil. When the voltmeter is connected across a closed contact, there is no voltage drop, and the meter indicates 0 volts. If the voltmeter is connected across an open contact, the meter indicates the full voltage of the circuit.

Assume in this circuit that the full circuit voltage is indicated when the meter is connected across float switch FS. This reading signals that float switch FS is open. The next step is to determine if the switch is bad or if the liquid lever it is sensing has not risen high enough to close the switch. Once that has been determined, the electrician can correct the problem.

Review Questions

1. What is a controller and what is its function? (Use the Glossary and the information from this unit to answer this question.)
2. What is meant by remote control?
3. To what does current limiting, or compensating time, acceleration refer?
4. List some devices that are used to control a motor automatically. Briefly describe the purpose of each device.

Select the *best* answer for each of the following.

5. The general purpose of motor control is
   a. to start the motor
   b. to stop the motor
   c. to reverse the motor
   d. all of the above

6. A motor may be controlled manually by using a
   a. float switch
   b. pressure switch
   c. toggle switch
   d. time clock

7. A motor may be controlled remotely or automatically by using a
   a. drum controller
   b. thermostat
   c. safety switch
   d. faceplate control

8. Conditions that may affect starting and stopping of motor driven machinery are
   a. fast or slow starts
   b. light or heavy duty starting
   c. frequency of starting and stopping
   d. all of the above

9. Which factor is *not* to be considered for motor speed control when the motor is running?
   a. Constant speed
   b. Varying speed
   c. Multispeed
   d. Starting protection

10. Which is not considered a motor controller protective feature?
    a. Overload
    b. Short circuit
    c. Adjustable speed
    d. Mechanical

11. Which function is not a fundamental job of a motor controller?
    a. Start and stop the motor
    b. Protect the motor, machine, and operator
    c. Reverse, inch, jog, speed control
    d. Motor disconnect switch and starting protection

12. What factors are to be considered when selecting and installing a controller?
    a. Electrical service
    b. Motor
    c. Electrical codes and standards
    d. All of the above

13. Dynamic braking for a dc motor is accomplished by
    a. connecting ac voltage to the armature
    b. maintaining dc current flow through the field and connecting the armature to a load resistor
    c. maintaining dc current flow through the armature and connecting a load resistor to the field
    d. disconnecting dc power from the motor and reconnecting the armature to a load resistor

14. Dynamic braking for an ac motor is accomplished by
    a. disconnecting ac power from the motor leads and reconnecting the motor to a load resistor
    b. reversing the direction of rotation of the motor
    c. connecting dc voltage to the stator leads
    d. connecting a load resistor in series with the motor leads

UNIT 2
SEMICONDUCTORS

OBJECTIVES

After studying this unit, the student will be able to:

- Discuss the atomic structure of conductors, insulators, and semiconductors.
- Discuss how a P-type material is produced.
- Discuss how an N-type material is produced.

Many of the control systems used in today's industry are operated by solid-state devices as well as magnetic and mechanical devices. To install and troubleshoot control systems, an electrician must have an understanding of electronic control devices as well as relays and motor starters. Solid-state devices, such as diodes and transistors, are often called *semiconductors.* The word *semiconductor* refers to the type of material used to make solid-state devices. To understand how solid-state devices operate, one must first study the atomic structure of conductors, insulators, and semiconductors.

Conductors

Conductors are materials that provide easy paths for the flow of electrons. Conductors are generally made from materials that have large, heavy atoms. For this reason, most conductors are metals. The best electrical conductors are silver, copper and aluminum.

Conductors are also made from materials that have only one or two valence electrons in their atoms. (*Valence electrons* are the electrons in the outer orbit of an atom, Figure 2–1). An atom that has only one valence electron makes the best electrical conductor because the electron is held loosely in orbit and is easily given up for current flow.

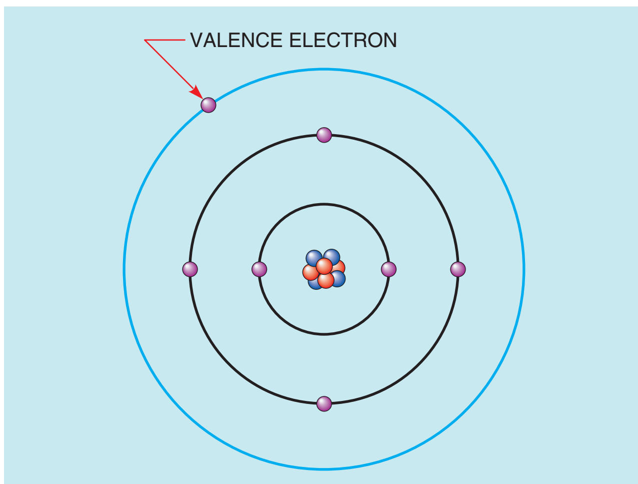


Figure 2–1 Atom of a conductor.

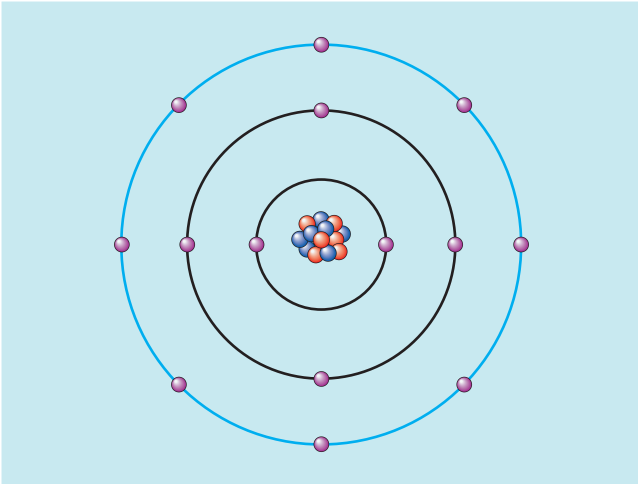


Figure 2–2 Atom of an insulator.

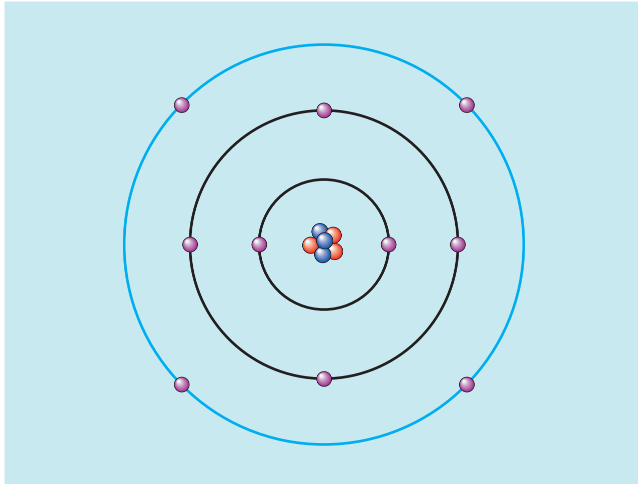


Figure 2–3 Atom of a semiconductor.

Insulators

Insulators are generally made from lightweight materials that have small atoms. The outer orbits of the atoms of insulating materials are filled or almost filled with valence electrons. This means an insulator will have seven or eight valence electrons as in the example in Figure 2–2. Since an insulator has its outer orbit filled or almost filled with valence electrons, the electrons are held tightly in orbit and are not easily given up for current flow.

Semiconductors

Semiconductors, as the word implies, are materials that are neither good conductors nor good insulators. Semiconductors are made from materials that have four valence electrons in their outer orbits (Figure 2–3). Germanium and silicon are the most common semiconductor materials used in the electronics field. Of these materials, silicon is used more often because of its ability to withstand heat.

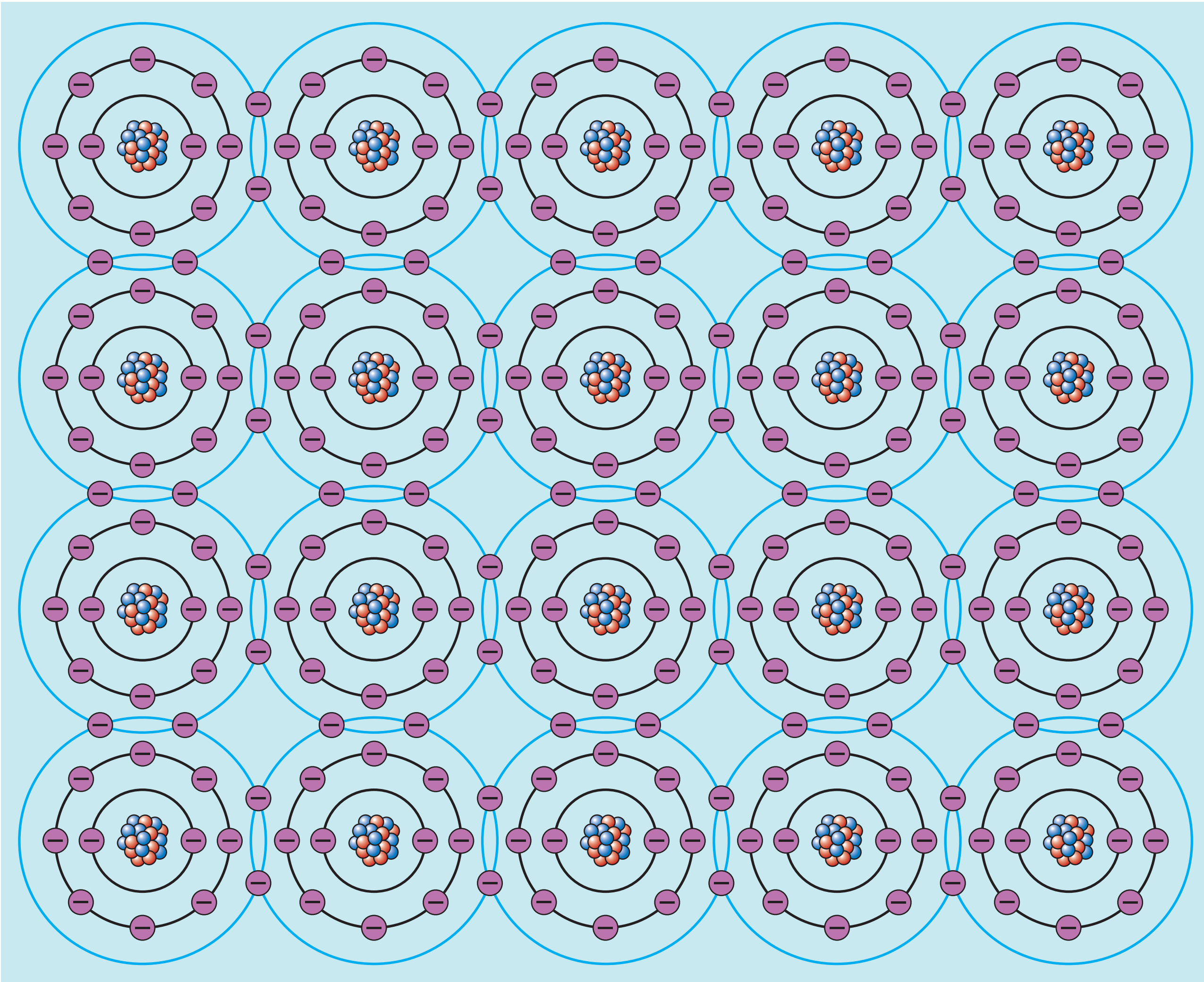


Figure 2–4 Lattice structure of a pure semiconductor material.

When semiconductor materials are refined into a pure form, the molecules arrange themselves into a crystal structure with a definite pattern (Figure 2–4). This type of pattern is called a *lattice structure.* A pure semiconductor material such as silicon has no special properties and will do little more than make a poor conductive material. To make semiconductor material useful in the production of solid-state components, it is

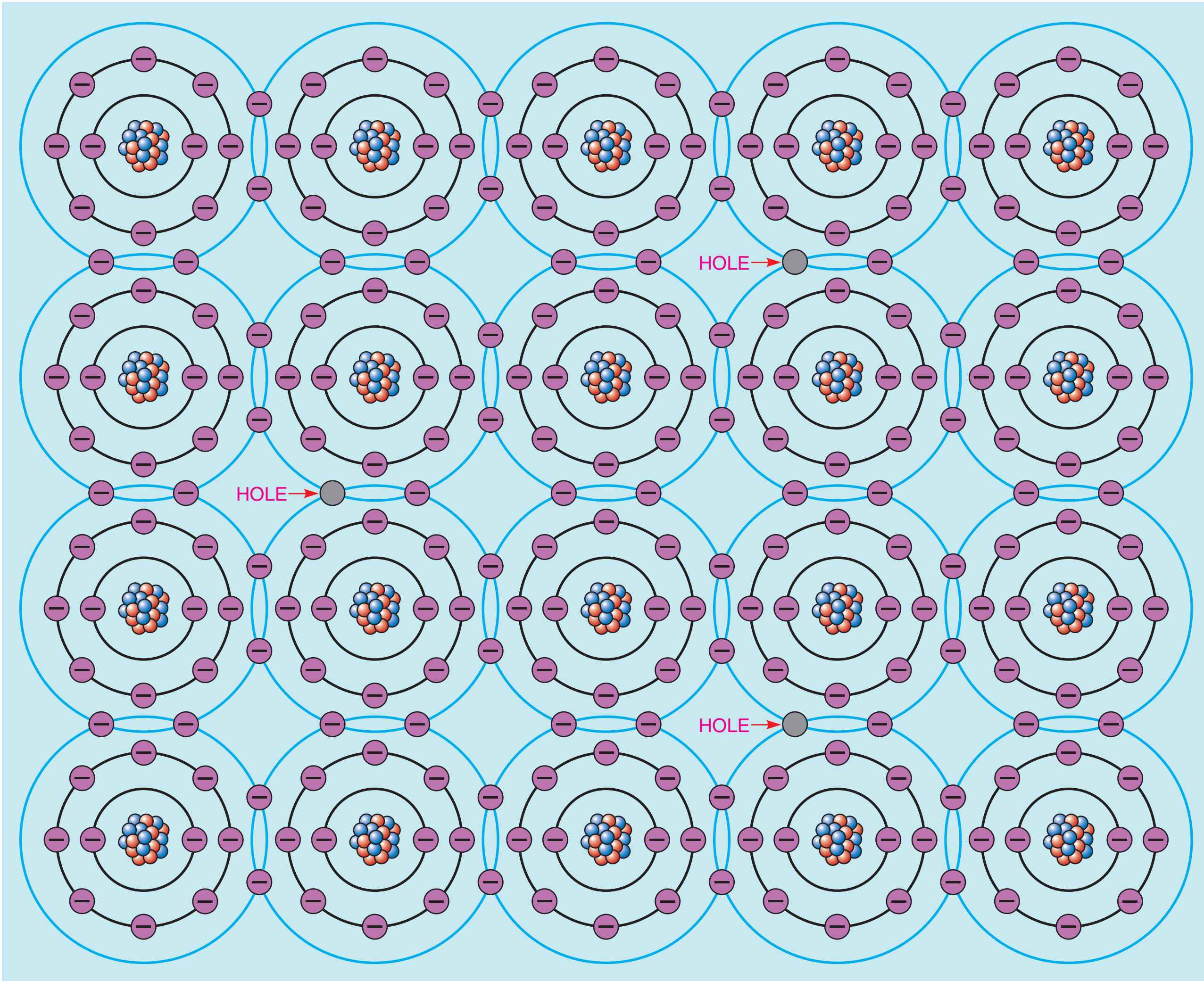


Figure 2–5 Lattice structure of a P-type material.

mixed with an impurity. When pure semiconductor material is mixed with an impurity that has only three valence electrons, such as indium or gallium, the lattice structure changes, leaving a hole in the material (Figure 2–5). This hole is caused by a missing electron. Since the material now lacks an electron, it is no longer electrically neutral. Electrons are negative particles. The hole, which has taken the place of an

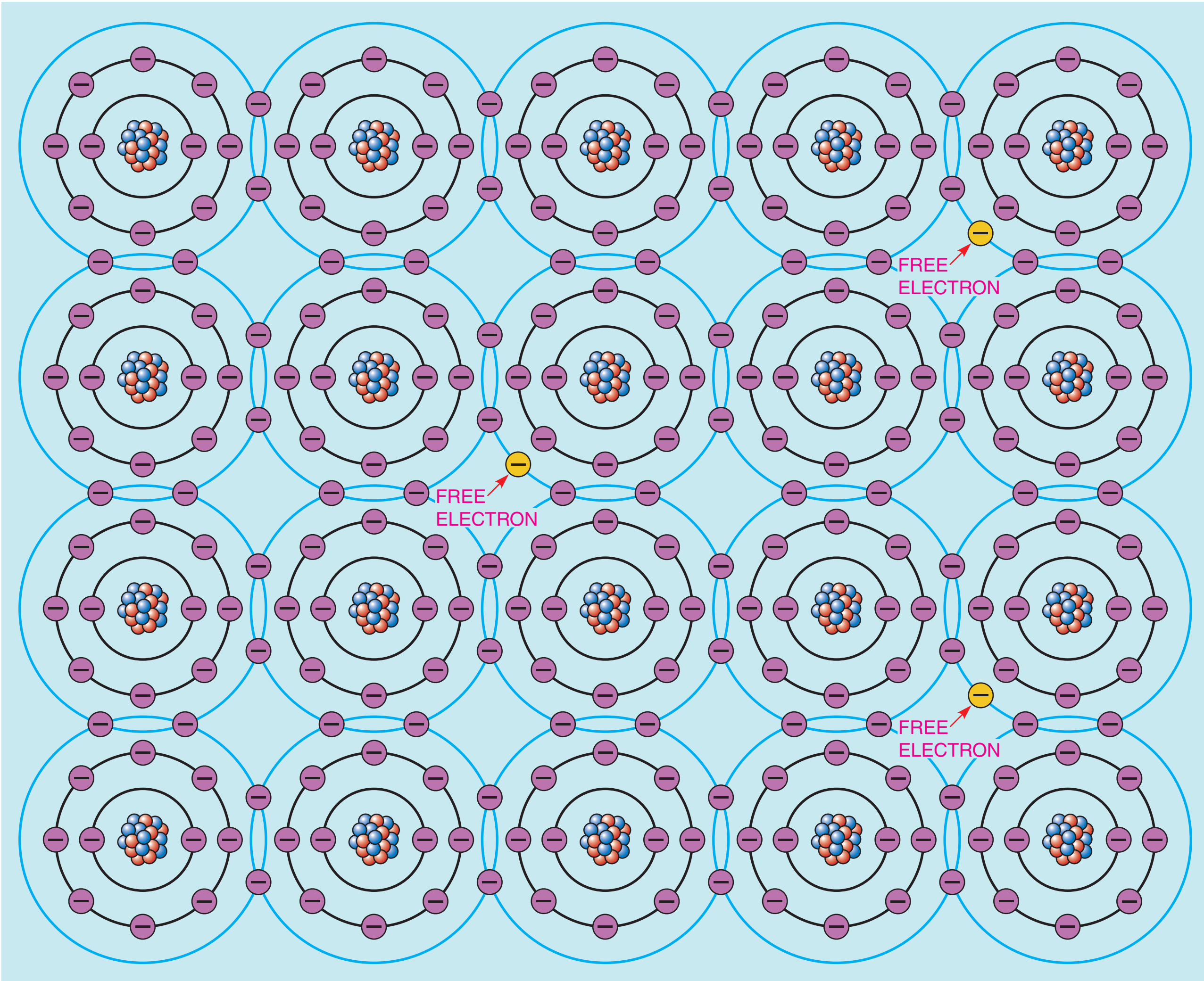


Figure 2–6 Lattice structure of an N-type material.

electron, has a positive charge; therefore, the semiconductor material now has a net positive charge and is called a P-type material.

When a semiconductor material is mixed with an impurity that has five valence electrons, such as arsenic or antimony, the lattice structure has an excess of electrons (Figure 2–6). Since electrons are negative particles, and there are more electrons in the material than there should be, the material has a net negative charge. This material is called an N-type material because of its negative charge.

All solid-state devices are made from combinations of P- and N-type materials. The type of device formed is determined by how the P- and N-type materials are

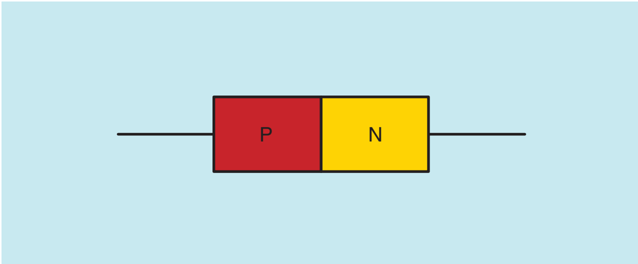


Figure 2–7 The PN junction.

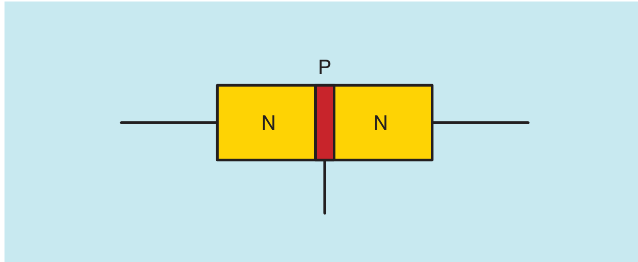


Figure 2–8 The transistor.

connected. The number of layers of material and the thickness of each layer play an important part in determining what type of device is formed. For example, the diode is often called a PN junction because it is made by joining a piece of P-type material and a piece of N-type material (Figure 2–7). The transistor, on the other hand, is made by joining three layers of semiconductor materials (Figure 2–8).

Review Questions

1. The atoms of a material used as a conductor generally contain __________________ valence electrons.
2. The atoms of a material used as an insulator generally contain ____________________ valence electrons.
3. The two materials most often used to produce semiconductor devices are __________________ and ___________________.
4. What is a lattice structure?
5. How is a P-type material made?
6. How is an N-type material made?
7. Which type of semiconductor material can withstand the greatest amount of heat?
8. All electronic components are formed from P-type and N-type materials. What factors determine the kind of components formed?

UNIT 3

THE PN JUNCTION

OBJECTIVES

After studying this unit, the student will be able to:

- Discuss how the PN junction is produced.
- Recognize the schematic symbol for a diode.
- Discuss the differences between the conventional current flow theory and the electron flow theory.
- Discuss how the diode operates in a circuit.
- Identify the anode and cathode leads of a diode.
- Properly connect the diode in an electric circuit.
- Discuss the differences between a half-wave rectifier and a full-wave rectifier.
- Test the diode with an ohmmeter.

The PN Junction

Hundreds of different electronic devices have been produced since the invention of solid-state components. Solid-state devices are made by combining P-type and N-type materials. The device produced is determined by the number of layers of material used, the thickness of the layers of material, and the manner in which the layers are joined.

It is not within the scope of this text to cover even a small portion of these devices. The devices that are covered have been selected because of their frequent use in industry as opposed to communications or computers. These devices are presented in a straightforward, practical manner, and mathematical explanation is used only when necessary.

The PN junction is often called the *diode.* The diode is the simplest of all electronic devices. It is made by joining a piece of P-type material and a piece of N-type material (Figure 3–1). The schematic symbol for a diode is shown in Figure 3–2. The diode operates like an electric check valve in that it permits current to flow through it in only one direction. If the diode is to conduct current, it must be forward biased. The diode is forward biased only when a positive voltage is connected to the anode and a negative voltage is connected to the cathode. If the diode is reverse biased, the negative voltage connected to the anode and the positive

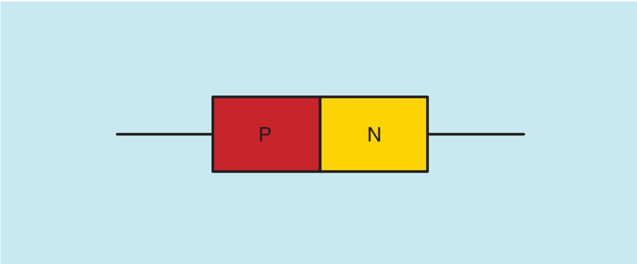


Figure 3–1 The PN junction, or diode.

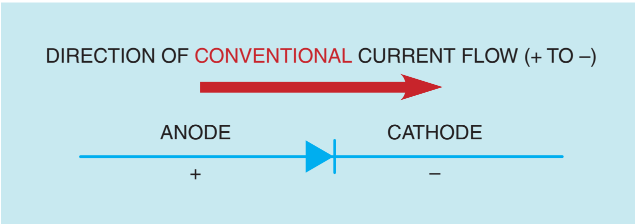


Figure 3–2 Schematic symbol for a diode.

voltage connected to the cathode, it will act like an open switch and no current will flow through the device.

When working with solid-state circuits, it is important to realize that circuits are often explained assuming conventional current flow as opposed to electron flow. The *conventional current flow theory assumes that current flows from positive to negative, while the electron flow theory states that current flows from negative to positive.* Although it has been known for many years that current flows from negative to positive, many electronic circuit explanations assume a positive to negative current flow. There are several reasons for this assumption. One reason is that ground is generally negative and is considered to be 0 volts in an electronic circuit. Any voltage above, or greater, than ground is positive. Most people find it is easier to think of something flowing downhill or from some point above to some point below. Another reason is that all of the arrows in an electronic schematic are pointed in the direction of conventional current flow. The diode shown in Figure 3–2 is forward biased only when a positive voltage is applied to the anode and a negative voltage is applied to the cathode. If the conventional current flow theory is used, current will flow in the direction the arrow is pointing. If the electron theory of current flow is used, current must flow against the arrow.

A common example of the use of the conventional current flow theory is the electrical system of an automobile. Most automobiles use a negative ground system, which means that the negative terminal of the battery is grounded. The positive terminal of the battery is considered to be the "hot" terminal, and it is generally assumed that current flows from the "hot" terminal to ground.

The diode can be tested with an ohmmeter (see Procedure 1 in the Appendix). When the leads of an ohmmeter are connected to a diode, the diode should show continuity in only one direction. For example, assume that when the leads of an ohmmeter are connected to a diode, it shows continuity. If the leads are reversed, the ohmmeter should indicate an open circuit. If the diode shows continuity in both directions, it is shorted. If the ohmmeter indicates no continuity in either direction, the diode is open.

The diode can be used to perform many jobs, but it is most commonly used in industry to construct a *rectifier.* A rectifier is a device that changes, or converts, ac voltage into dc voltage. The simplest type of rectifier is the half-wave rectifier (Figure 3–3). The half-wave rectifier can be constructed using only one diode. It gets its name from the fact that it will rectify only half of the ac waveform applied to it. When the voltage applied to the anode is positive, the diode is forward biased and current flows through the diode, the load resistor, and back to the power supply. When the voltage applied to the anode is negative, the diode is reverse biased and no current will flow. Since the diode permits current to flow through the load resistor in only one direction, the current is direct current.

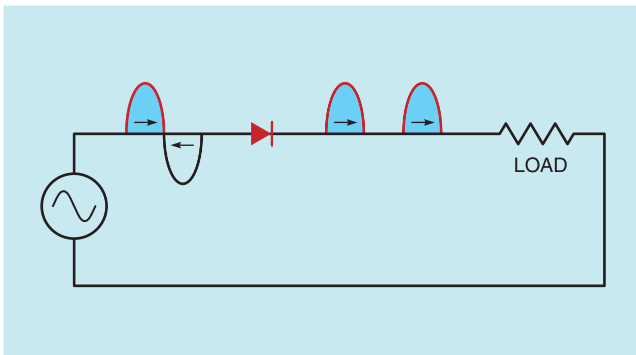


Figure 3–3 Half-wave rectifier.

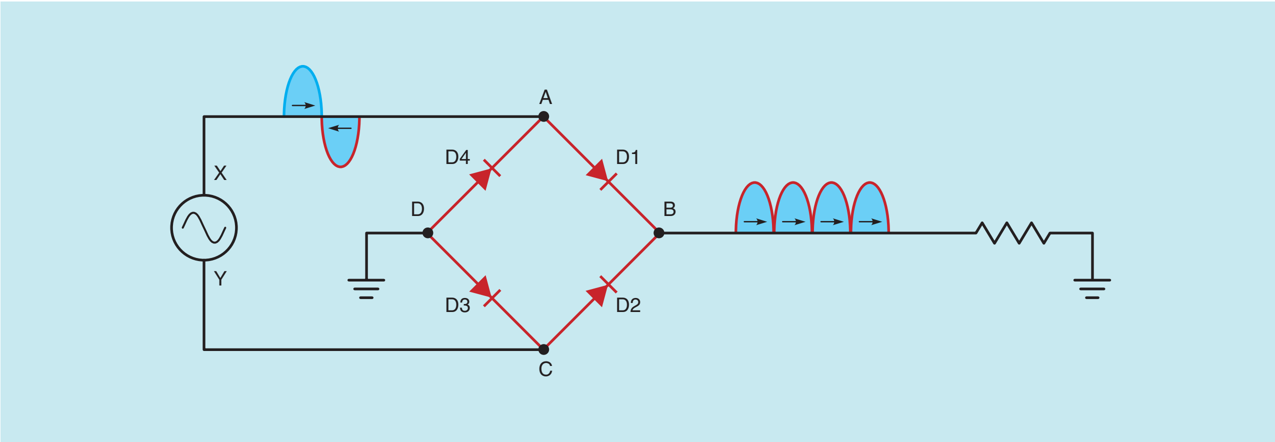


Figure 3–4 Bridge rectifier.

Diodes can be connected to produce full-wave rectification, which means that both halves of the ac waveform are made to flow in the same direction. One type of full-wave rectifier is the bridge rectifier (Figure 3–4). Notice that four diodes are required to construct the bridge rectifier.

To understand the operation of the bridge rectifier shown in Figure 3–4, assume that point X of the ac source is positive and point Y is negative. Current flows to point A of the rectifier. At point A, diode D4 is reverse biased and D1 is forward biased; therefore, the current flows through diode D1 to point B of the rectifier. At point B, diode D2 is reverse biased, so the current must flow through the load resistor to ground. The current returns through ground to point D of the rectifier. At point D, both diodes D3 and D4 are forward biased, but current will not flow from positive to positive. Therefore, the current flows through diode D3 to point C of the bridge, and then to point Y of the ac source, which is negative at this time. Since current flowed through the load resistor during this half cycle, a voltage developed across the resistor.

Now assume that point Y of the ac source is positive and point X is negative. Current flows from point Y to point C of the rectifier. At point C, diode D3 is reverse biased and diode D2 is forward biased. The current flows through diode D2 to point B of the rectifier. At point B, diode D1 is reverse biased, so the current must flow through the load resistor to ground. The current flows from ground to point D of the bridge. At point D, both diodes D3 and D4 are forward biased. Since current will not flow from positive to positive, the current flows through diode D4 to point A of the bridge and then to point X which is now negative. Current flowed through the load resistor during this half cycle, so a voltage developed across the load resistor. Notice that the current flowed in the same direction through the resistor during both half cycles. Bridge rectifiers in single cases are shown in Figure 3–5.

In industry three-phase power is used more often than single-phase power. Six diodes can be connected to form a three-phase bridge rectifier that will change three-phase ac voltage into dc voltage (Figure 3–6).

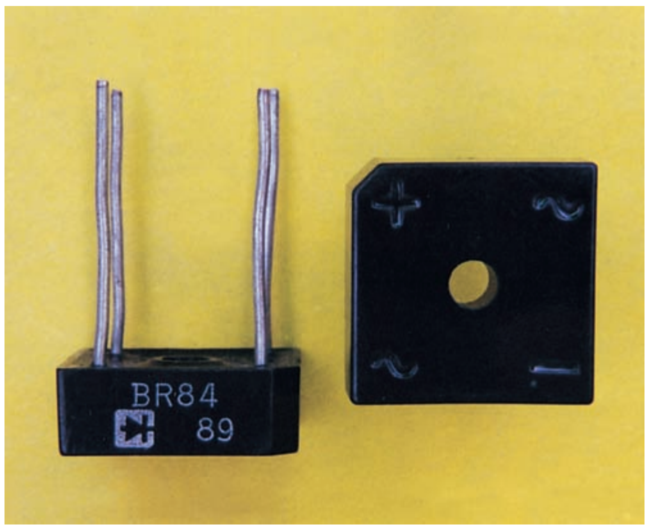


Figure 3–5 Bridge rectifiers in a single case.

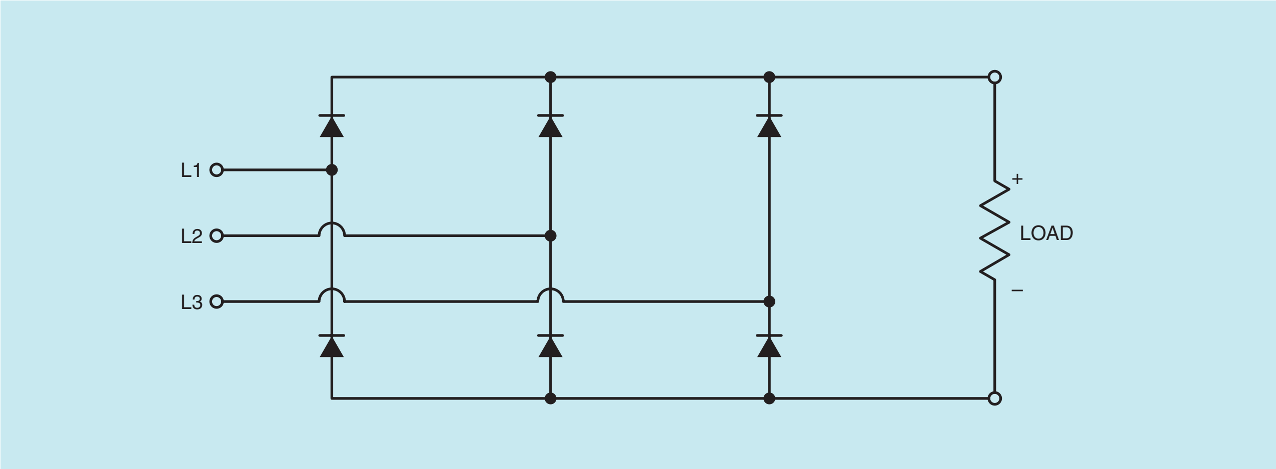


Figure 3–6 Three-phase bridge rectifier.

When the diode is to be connected in a circuit, there must be some means of identifying the anode and the cathode. Diodes are made in different case styles, as shown in Figure 3–7, so there are different methods of identifying the leads. Large stud mounted diodes often have the diode symbol printed on the case to show proper lead identification. Small plastic case diodes often have a line or band around one end of the case (Figure 3–8). This line or band represents the line in front of the arrow on the schematic symbol of the diode. An ohmmeter can always be used to determine the proper lead identification if the polarity of the ohmmeter leads is known. The positive lead of the ohmmeter must be connected to the anode to make the diode forward biased.

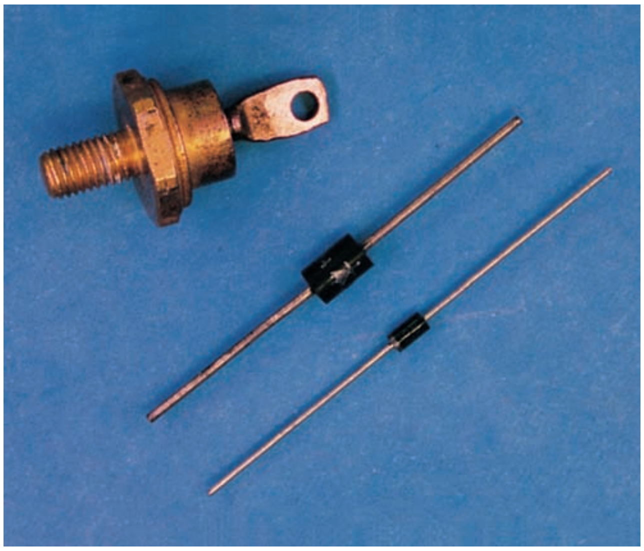


Figure 3–7 Diodes shown in various case styles.

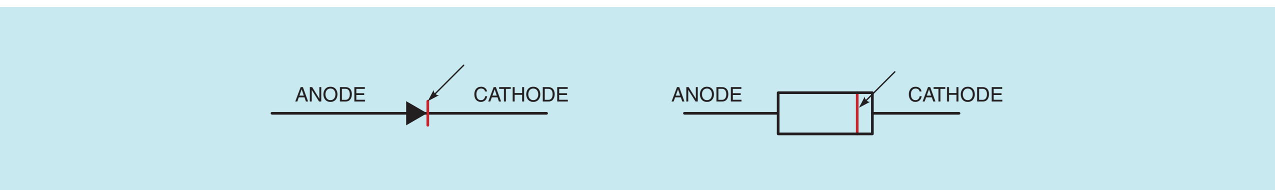


Figure 3–8 Lead identification of a plastic case diode.

Review Questions

1. The PN junction is more commonly known as the ___________________.
2. Draw the schematic symbol for a diode.
3. Explain how a diode operates.
4. Explain the difference between the conventional current flow theory and the electron flow theory.
5. Explain the difference between a half-wave rectifier and a full-wave rectifier.
6. Explain how to test a diode with an ohmmeter.

UNIT 4
THE ZENER DIODE

OBJECTIVES

After studying this unit, the student will be able to:

- Explain the difference between a junction diode and a zener diode.
- Discuss common applications of the zener diode.
- Connect a zener diode in a circuit.

The Zener Diode

The zener diode is a special device designed to be operated with reverse polarity applied to it. When a diode is broken down in the reverse direction, it enters what is known as the *zener region.* Usually, when a diode is broken down into the zener region, it is destroyed; the zener diode, however, is designed to be operated in this region without harming the device.

When the reverse breakdown voltage of a zener diode is reached, the voltage drop of the device remains almost constant regardless of the amount of current flowing in the reverse direction (Figure 4–1). Since the voltage drop of the zener diode is constant, any device connected parallel to the zener will have a constant voltage drop even if the current through the load is changing.

In Figure 4–2, resistor R1 is used to limit the total current of the circuit. Resistor R2 is used to limit the current in the load circuit. Note that the value of R1 is less than the value of R2. This is to ensure that the supply can furnish enough current to operate the load. Note also that the supply voltage is greater than the zener voltage. The supply voltage must be greater than the voltage of the zener diode or the circuit cannot operate.

Resistor R1 and the zener diode form a series circuit to ground. Since the zener diode has a voltage drop of 12 volts, resistor R1 has a voltage drop of 8 volts: (20 volts − 12 volts = 8 volts). Therefore, resistor R1 will permit a maximum current flow in the circuit of .08 amperes or 80 milliamps:

$$\left(\frac{8}{100} = .08\right)$$

The load circuit, which is a combination of R2 and R3, is connected parallel to the zener diode. Therefore, the voltage applied to the load circuit must be the same as the voltage dropped by the zener. If the zener diode maintains a constant 12-volt drop, a constant voltage of 12 volts must be applied to the load circuit.

The maximum current that can flow through the load circuit is .06 amperes or 60 mA:

$$\left(\frac{12\text{ volts}}{200\text{ ohms}} = .06\text{ amps}\right)$$

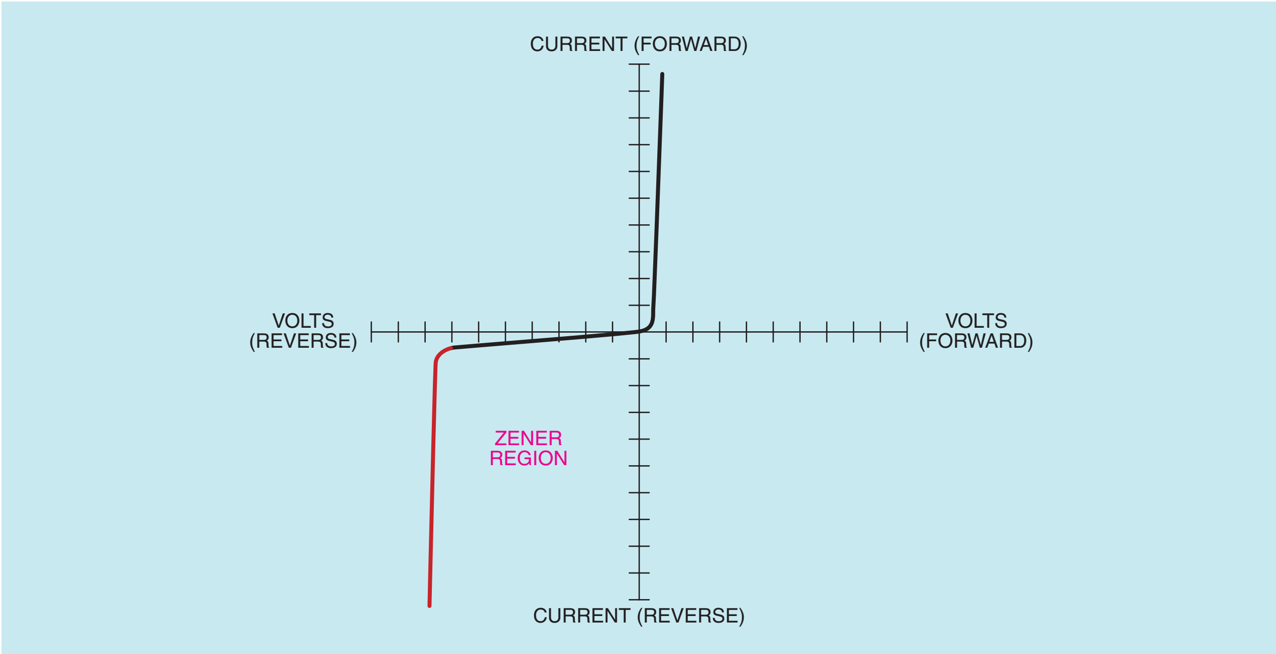


Figure 4–1

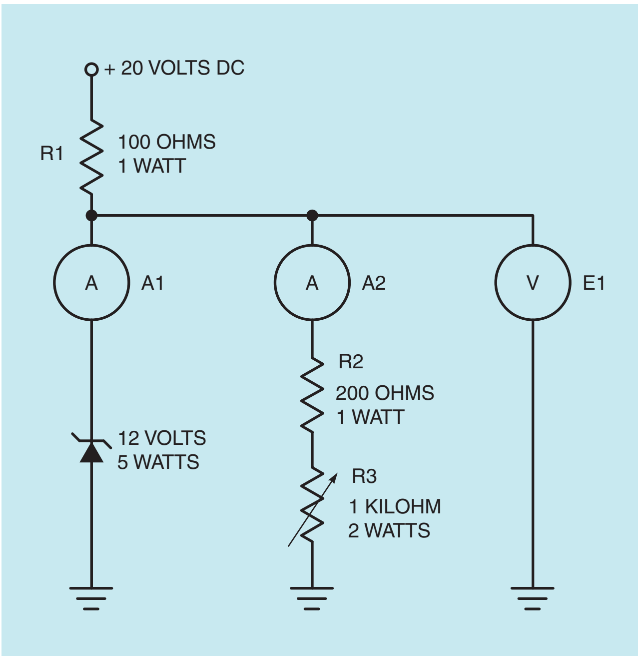


Figure 4–2

Notice that the value of R2 (200 ohms) is used to ensure that there is enough current available to operate the load.

The maximum current allowed into the circuit by resistor R1 is always equal to the sum of the currents passing through the zener diode and the load. For example, when the load is connected parallel to the zener diode as shown in Figure 4–2, and resistor R3 is adjusted to 0 ohms, meter A1 will indicate a current of 20 mA, and meter A2 will indicate a current of 60 mA. Therefore, the maximum current allowed into the circuit by resistor R1 will be 80 mA (20 mA + 60 mA = 80 mA). The voltage value indicated by meter E1 will be the same as the zener voltage value.

If resistor R3 is increased in value to 200 ohms, the resistance of the load will increase to 400 ohms (200 + 200 = 400). Meter A1 will indicate a current of 50 mA and meter A2 will indicate a current of 30 mA. The voltage value indicated by meter E1 will still be the same as the zener voltage value.

The zener diode, therefore, makes a very effective voltage regulator for the load circuit. Although the

current through the load circuit changes, the zener diode forces the voltage across the load circuit to remain at a constant value, and conducts the current not used by the load circuit to ground.

The schematic symbol for a zener diode is shown in Figure 4–3. The zener diode can be tested with an ohmmeter in the same manner as a common junction diode is tested, provided the zener voltage is greater than the battery voltage of the ohmmeter.

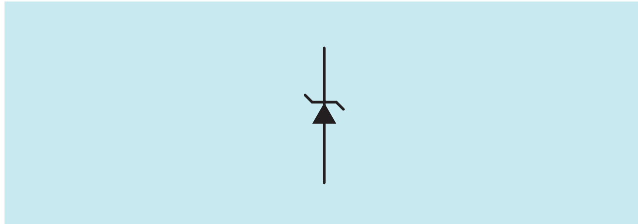


Figure 4–3 Schematic symbol for the zener diode.

Review Questions

1. How is a zener diode connected in a circuit as compared to a common junction diode?
2. What is the primary use of a zener diode?
3. A 5.1-volt zener diode is to be connected to an 8-volt power source. The current must be limited to 50 mA. What value of current-limiting resistor must be connected in series with the zener diode?
4. How is a zener diode tested?
5. In a zener diode circuit, the current-limiting resistor limits the total circuit current to 150 mA. If the load circuit is drawing a current of 90 mA, how much current is flowing through the zener diode?

UNIT 5
THE TRANSISTOR

OBJECTIVES

After studying this unit, the student will be able to:

- Discuss the differences between PNP and NPN transistors.
- Test transistors with an ohmmeter.
- Identify the leads of standard, case-style transistors.
- Discuss the operation of a transistor.
- Connect a transistor in a circuit.

The Transistor

Transistors are made by connecting three pieces of semiconductor material. There are two basic types of transistors: the NPN and the PNP (Figure 5–1). The schematic symbols for these transistors are shown in Figure 5–2. These transistors differ in the manner in which they are connected in a circuit. The NPN transistor must have a positive voltage connected to the collector and a negative voltage connected to the emitter. The PNP must have a positive voltage connected to the emitter and a negative voltage connected to the collector. The base must be connected to the same polarity as the collector to forward bias the transistor. Notice that the arrows on the emitters point in the direction of conventional current flow.

An ohmmeter can be used to test a transistor which will appear to the ohmmeter to be two joined diodes (Figure 5–3). (For an explanation of how to test a transistor, see Procedure 2 in the Appendix.) If the polarity of the output of the ohmmeter leads is known, the transistor can be identified as NPN or PNP. An NPN transistor will appear to an ohmmeter to be two diodes with their anodes connected. If the positive lead of the ohmmeter is connected to the base of the transistor, a diode junction should be seen between the base-collector and the base-emitter. If the negative lead of

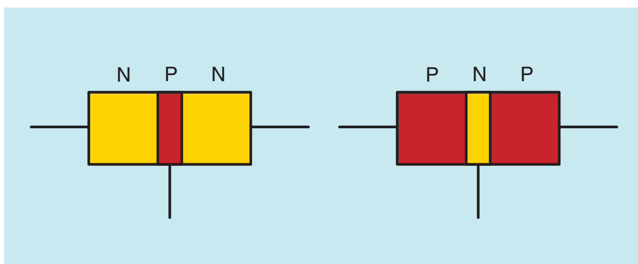


Figure 5–1 Two basic types of transistors.

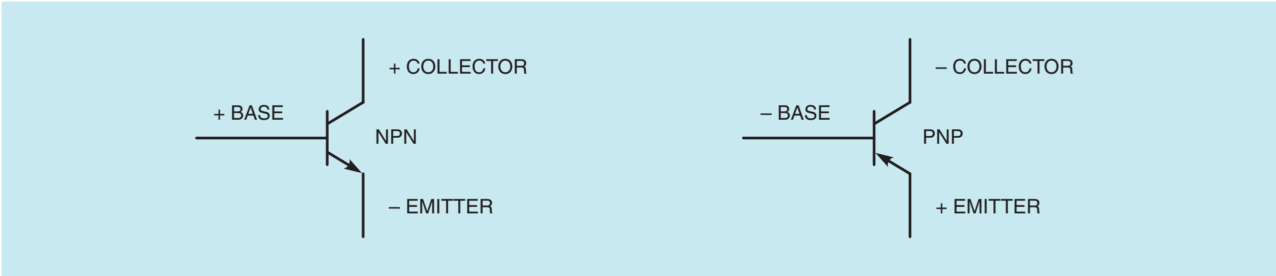


Figure 5–2 Schematic symbols for transistors.

Figure 5–3 Ohmmeter test for transistors.

the ohmmeter is connected to the base of an NPN transistor, there should be no continuity between the base-collector and the base-emitter junction.

A PNP transistor will appear to an ohmmeter to be two diodes with their cathodes connected. If the negative lead of the ohmmeter is connected to the base of the transistor, a diode junction should be seen between the base-collector and the base-emitter. If the positive ohmmeter lead is connected to the base, there should be no continuity between the base-collector or the base-emitter.

The simplest way to describe the operation of a transistor is to say that it operates like an electric valve. Current will not flow through the collector-emitter until current flows through the base-emitter. The amount of base-emitter current, however, is small when compared to the collector-emitter current (Figure 5–4). For example, assume that when 1 milliamp of current flows through the base-emitter junction, 100 mA of current flow through the collector-emitter junction. If this transistor is a linear device, an increase or decrease of base current will cause a similar increase or decrease of collector current. Therefore, if the base current is increased to 2 mA, the collector current will increase to 200 mA. If the base current is decreased to .5 mA, the collector current will decrease to 50 mA. Notice that a small change in the amount of base current can cause a large change in the amount of collector current. This permits a small amount of signal current to operate a larger device such as the coil of a control relay.

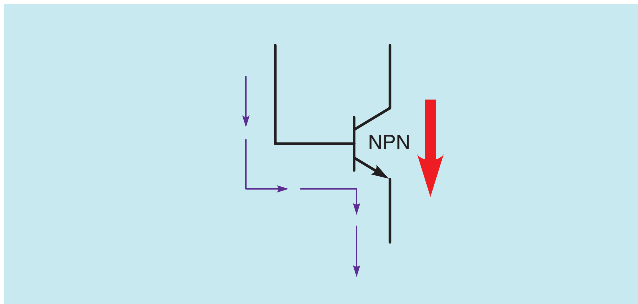


Figure 5–4 A small base current controls a large collector current.

One of the most common applications of the transistor in industry is that of a switch. When used in this manner, the transistor operates like a *digital* device instead of an *analog* device. The term *digital* means a device that has only two states, such as on and off. An *analog* device can be adjusted to different states. An example of this control can be seen in a simple switch connection. A common wall switch is a digital device. It can be used to turn a light on or off. If the simple toggle

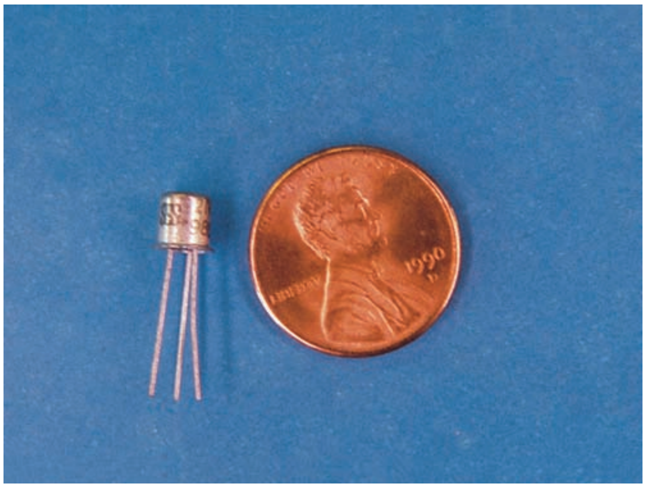


Figure 5–5 TO 18 case transistor.

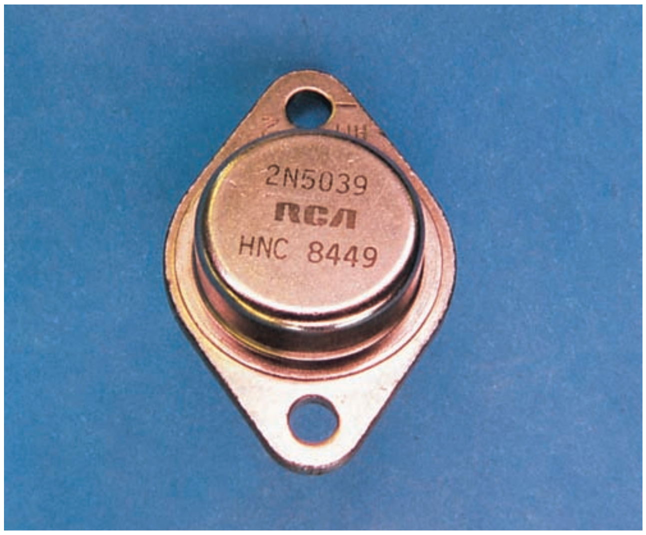


Figure 5–7 TO 3 case transistor.

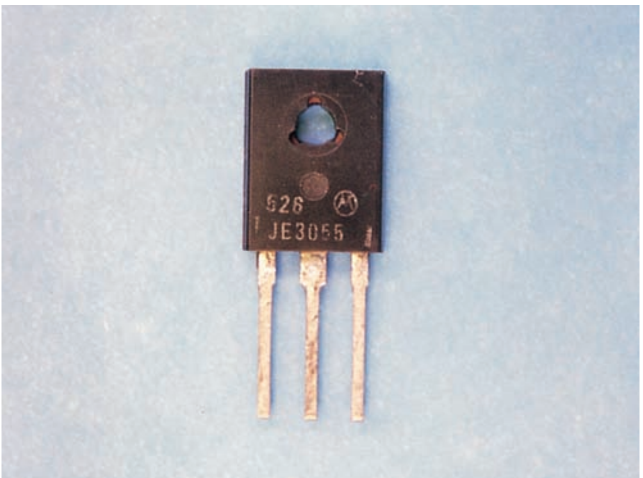


Figure 5–6 TO 220 case transistor.

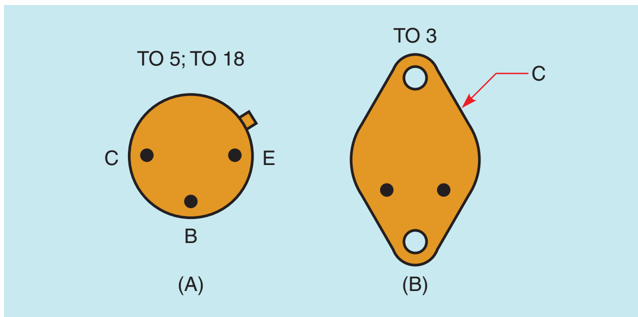


Figure 5–8 Lead identification of transistors.

switch is replaced with a dimmer control, the light can be turned on, off, or it can be adjusted to any position between on and off. The dimmer is an example of analog control.

If no current flows through the base of the transistor, the transistor acts like an open switch and no current can flow through the collector-emitter junction. If enough base current is applied to the transistor to turn it completely on, it acts like a closed switch and permits current to flow through the collector-emitter junction. This is the same action produced by the closing contacts of a relay or motor starter, but, unlike a transistor, a relay or motor starter cannot turn on and off several thousand times a second.

Some case styles of transistors permit the leads to be quickly identified, Figures 5–5, 5–6, and 5–7. The TO 5 and TO 18 cases, and the TO 3 case are in this category. The leads of the TO 5 and TO 18 case transistors can be identified by holding the case of the transistor with the leads facing you as shown in Figure 5–8A. The metal tab on the case of the transistor is closest to the emitter lead. The base and collector leads are positioned as shown.

The leads of a TO 3 case transistor can be identified as shown in Figure 5–8B. When the transistor is held with the leads facing you and down, the emitter is the left lead and the base is the right lead. The case of the transistor is the collector.

Review Questions

1. What are the two basic types of transistors?
2. Explain how to test an NPN transistor with an ohmmeter.
3. Explain how to test a PNP transistor with an ohmmeter.
4. What polarity must be connected to the collector, base, and emitter of an NPN to make it forward biased?
5. What polarity must be connected to the collector, base, and emitter of a PNP transistor to make it forward biased?
6. Explain the difference between an analog device and a digital device.

UNIT 6

THE UNIJUNCTION TRANSISTOR

OBJECTIVES

After studying this unit, the student will be able to:

- Discuss the differences between junction transistors and unijunction transistors.
- Describe the operation of the unijunction transistor (UJT).
- Identify the leads of a UJT.
- Draw the schematic symbol for a UJT.
- Test a UJT with an ohmmeter.
- Connect a UJT in a circuit.

The Unijunction Transistor

The *unijunction transistor (UJT)* is a special transistor that has two bases and one emitter. The unijunction transistor is a digital device because it has only two states, on and off. It is generally classified with a group of devices known as *thyristors.* Thyristors are devices that are turned completely on or completely off. Thyristors include such devices as the SCR, the triac, the diac and the UJT.

The unijunction transistor is made by combining three layers of semiconductor material as shown in Figure 6–1. Figure 6–2 shows the schematic symbol of the UJT with polarity connections and the base diagram.

Current flows in two paths through the UJT. One path is from base #2 to base #1. The other path is through the emitter and base #1. In its normal state, current does not flow through either path until the

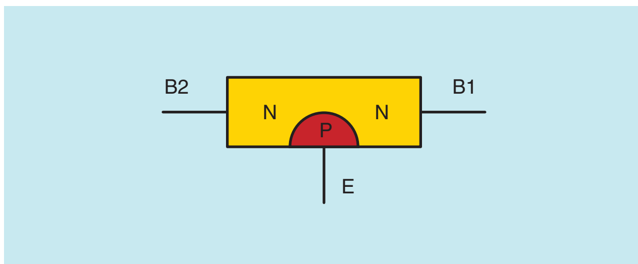


Figure 6–1 The unijunction transistor.

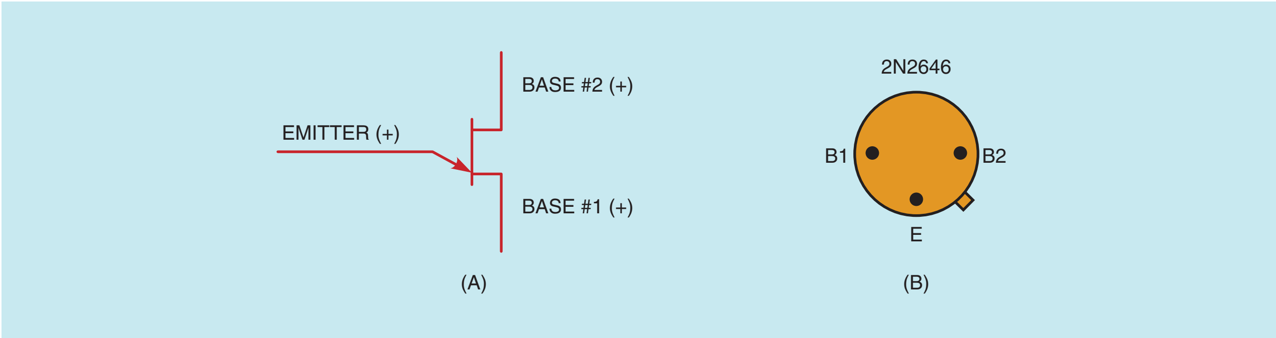


Figure 6–2 The schematic symbol for the unijunction transistor with polarity connections and base diagram.

voltage applied to the emitter is about 10 volts higher than the voltage applied to base #1. When the voltage applied to the emitter is about 10 volts higher than the voltage applied to base #1, the UJT turns on and current flows through the base #1–base #2 path and from the emitter through base #1. Current will continue to flow through the UJT until the voltage applied to the emitter drops to a point that is about 3 volts higher than the voltage applied to base #1. When the emitter voltage drops to this point, the UJT will turn off and will remain off until the voltage applied to the emitter again reaches a level about 10 volts higher than the voltage applied to base #1.

The unijunction transistor is generally connected to a circuit similar to the circuit shown in Figure 6–3. The variable resistor controls the capacitor's rate of charge time. When the capacitor has been charged to about 10 volts, the UJT turns on and discharges the capacitor through the emitter and base #1. When the capacitor has been discharged to about 3 volts, the UJT turns off and permits the capacitor to begin charging again. By varying the resistance connected in series with the capacitor, the amount of time needed for charging the capacitor can be changed, thereby controlling the pulse rate of the UJT (T = RC).

The unijunction transistor can furnish a large output pulse because the output pulse is produced by the discharging capacitor (Figure 6–4). This large output pulse is generally used for triggering the gate of a silicon-controlled rectifier.

The pulse rate is determined by the amount of resistance and capacitance connected to the emitter of the UJT. However, the amount of capacitance that can be connected to the UJT is limited. For instance, most UJTs should not be connected to capacitors larger than 10 μF because the UJT may not be able to handle the current

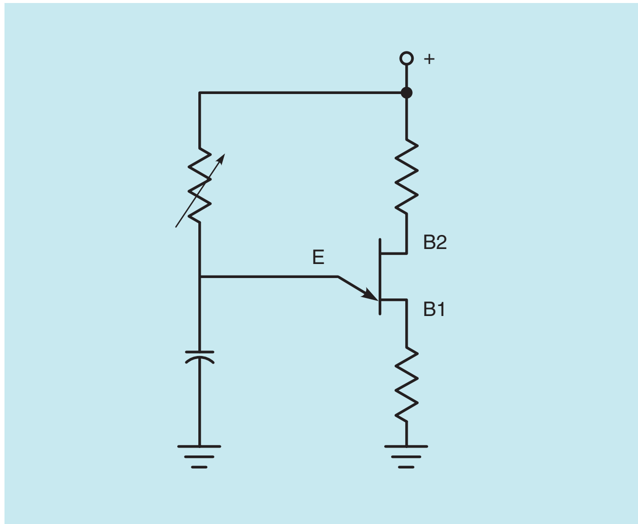


Figure 6–3

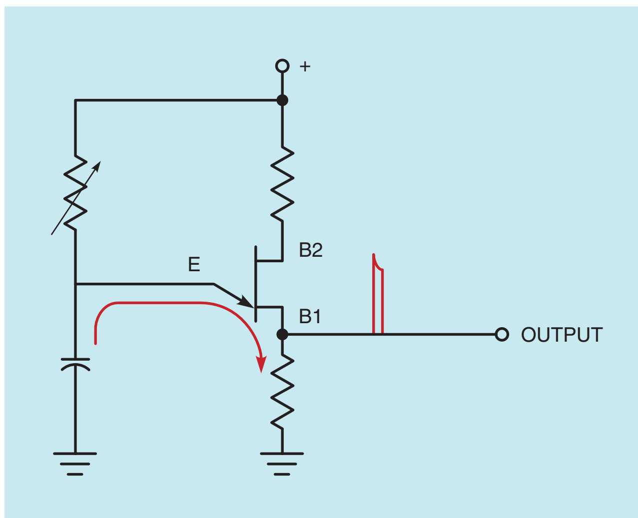


Figure 6–4

spike produced by a larger capacitor, and the UJT could be damaged.

The unijunction transistor can be tested with an ohmmeter in a manner very similar to that used to test a common junction transistor. (For an explanation of how to test a unijunction transistor, see Procedure 3 in the Appendix.)

When testing the UJT with an ohmmeter, the UJT will appear as a circuit containing two resistors connected in series with a diode connected to the junction point of the two resistors as shown in Figure 6–5. If the positive lead of the ohmmeter is connected to the emitter of the UJT, a circuit should be seen between emitter and base 1 and emitter and base 2. If the negative lead of the ohmmeter is connected to the emitter, no circuit should be seen between the emitter and either base. If the ohmmeter leads are connected to the two bases, continuity will be seen between these two leads provided that the output voltage of the ohmmeter is high enough.

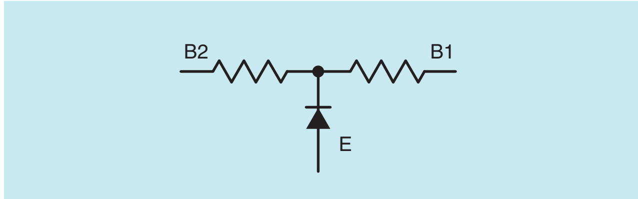


Figure 6–5 Testing a UJT.

Review Questions

1. What do the letters UJT stand for?
2. How many layers of semiconductor material are used to construct a UJT?
3. Briefly explain the operation of the UJT.
4. Draw the schematic symbol for the UJT.
5. Briefly explain how to test a UJT with an ohmmeter.

UNIT 7
THE SCR

OBJECTIVES

After studying this unit, the student will be able to:

- Discuss the operation of an SCR in a dc circuit.
- Discuss the operation of an SCR in an ac circuit.
- Draw the schematic symbol for an SCR.
- Discuss phase shifting.
- Test an SCR with an ohmmeter.
- Connect an SCR in a circuit.

The silicon-controlled rectifier (SCR) is often referred to as a PNPN junction because it is made by joining four layers of semiconductor material (Figure 7–1). The schematic symbol for the SCR is shown in Figure 7–2. Notice that the symbol for the SCR is the same as the symbol for the diode except that a gate lead has been added. Case styles for SCRs are shown in Figure 7–3.

The SCR is a member of a family of devices known as thyristors. Thyristors are digital devices in that they have only two states, on and off. The SCR is used when it is necessary for an electronic device to control a large amount of power. For example, assume that an SCR has been connected in a circuit as shown in Figure 7–4. When the SCR is turned off, it will drop the full voltage of the circuit and 200 volts will appear across the anode and cathode. Although the SCR has a voltage drop of 200 volts, there is no current flow in the circuit. The SCR does not have to dissipate any power in this condition (200 volts $\times$ 0 amperes $=$ 0 watts). When the push

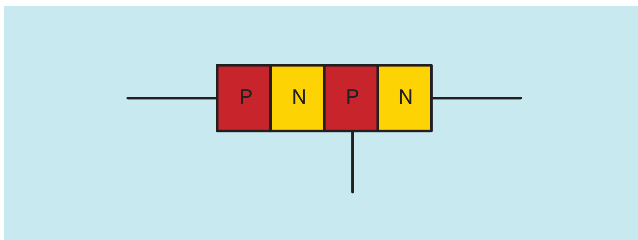


Figure 7–1 The PNPN junction.

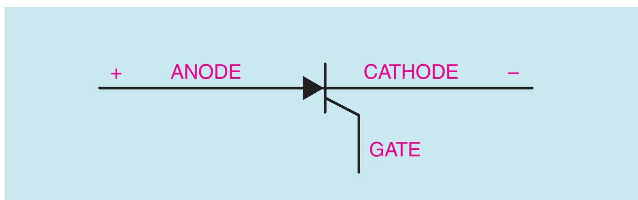


Figure 7–2 The schematic symbol for a silicon-controlled rectifier.

button is pressed, the SCR turns on, producing a voltage drop across its anode and cathode of about 1 volt. The load resistor limits the circuit current to 2 amperes

$$\frac{200 \text{ volts}}{100 \text{ ohms}} = 2 \text{ amperes}$$

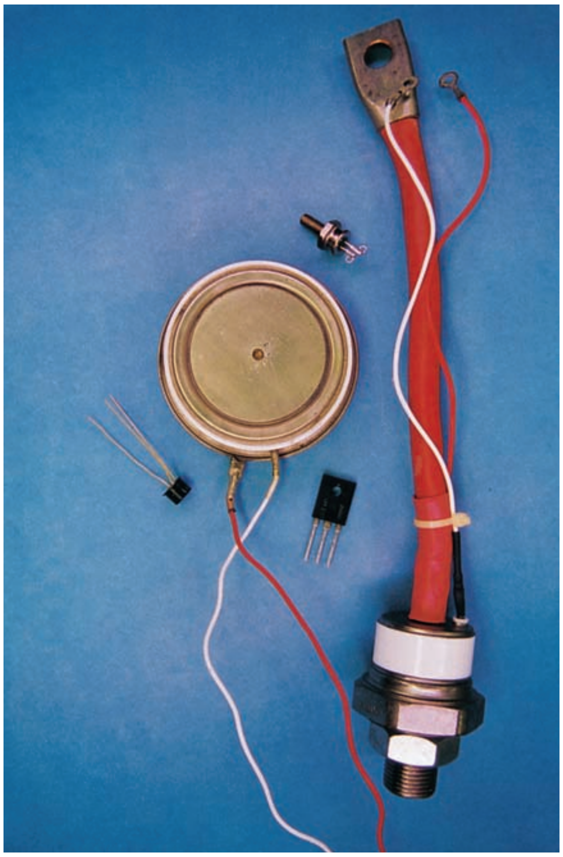


Figure 7–3 SCRs shown in different case styles.

Since the SCR now has a voltage drop of 1 volt and 2 amperes of current flowing through it, it must dissipate 2 watts of heat (1 volt × 2 amperes = 2 watts). Notice that although the SCR is dissipating only 2 watts of power, it is controlling 400 watts of power.

The SCR in a DC Circuit

When an SCR is connected in a dc circuit as shown in Figure 7–4, the gate will turn the SCR on, but it will not turn the SCR off. To turn the anode-cathode section of the SCR on, the gate must be connected to the same polarity as the anode. Once the gate has turned the SCR on, the SCR will remain on until the current flowing through the anode-cathode section drops to a low enough level to permit the device to turn off. The amount of current required to keep the SCR turned on is called the *holding current.*

In Figure 7–5 assume that resistor R1 has been adjusted to its highest value and resistor R2 has been adjusted to its lowest or 0 value. When switch S1 is closed, no current will flow through the anode-cathode section of the SCR because resistor R1 prevents the amount of current needed to trigger the device from flowing through the gate-cathode section of the SCR. If the value of resistor R1 is slowly decreased, current flow through the gate-cathode section will slowly increase. When the gate reaches a certain level, assume 5 mA for this SCR, the SCR will fire, or turn on. When the SCR fires, current will flow through the anode-cathode section and the voltage drop across the device will be about 1 volt. Once the SCR is turned on, the gate has no control over the device. It could be

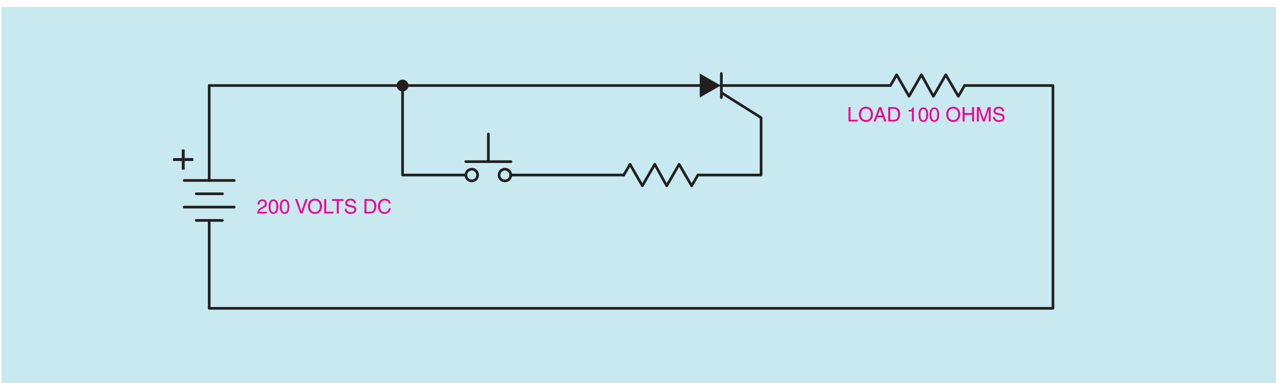


Figure 7–4 The SCR is turned on by the gate.

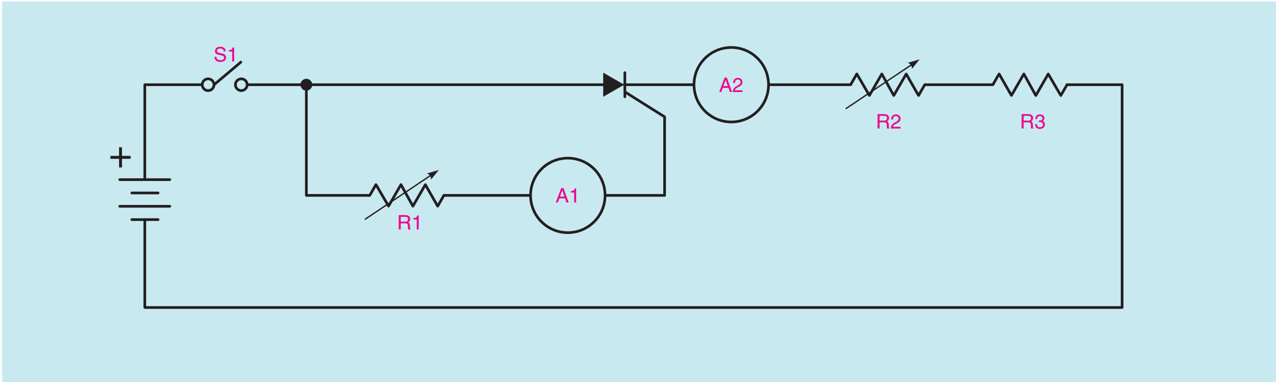


Figure 7–5 Operation of an SCR in a dc circuit.

disconnected from the anode without affecting the circuit. When the SCR fires, the anode-cathode section becomes a short circuit and current flow is limited by resistor R3.

Now assume that resistor R2 is slowly increased in value. When the resistance of R2 is slowly increased, the current flow through the anode-cathode section will slowly decrease. Assume that when the current flow through the anode-cathode section drops to 100 mA, the device suddenly turns off and the current flow drops to 0. This SCR requires 5 mA of gate current to turn it on, and has a holding current value of 100 mA.

The SCR in an AC Circuit

The SCR is a rectifier; when it is connected in an ac circuit, the output is direct current. The SCR operates in the same manner in an ac circuit as it does in a dc circuit. The difference in operation is caused by the ac waveform falling back to 0 at the end of each half cycle. When the ac waveform drops to 0 at the end of each half cycle, the SCR turns off. This means that the gate must retrigger the SCR for each cycle it is to conduct (Figure 7–6).

Assume that the variable resistor connected to the gate has been adjusted to permit 5 mA of current to flow when the voltage applied to the anode reaches its peak value. When the SCR turns on, current will begin flowing through the load resistor when the ac waveform is at its positive peak. Current will continue to flow through the load until the decreasing voltage of the sine wave causes the current to drop below the holding current level of 100 mA. When the current through the anode-cathode section drops below 100 mA, the SCR turns off and all current flow stops. The SCR will remain turned off when the ac waveform goes into its negative half cycle because during this half cycle the SCR is reverse biased and cannot be fired.

If the resistance connected in series with the gate is reduced, a current of 5 mA will be reached before the

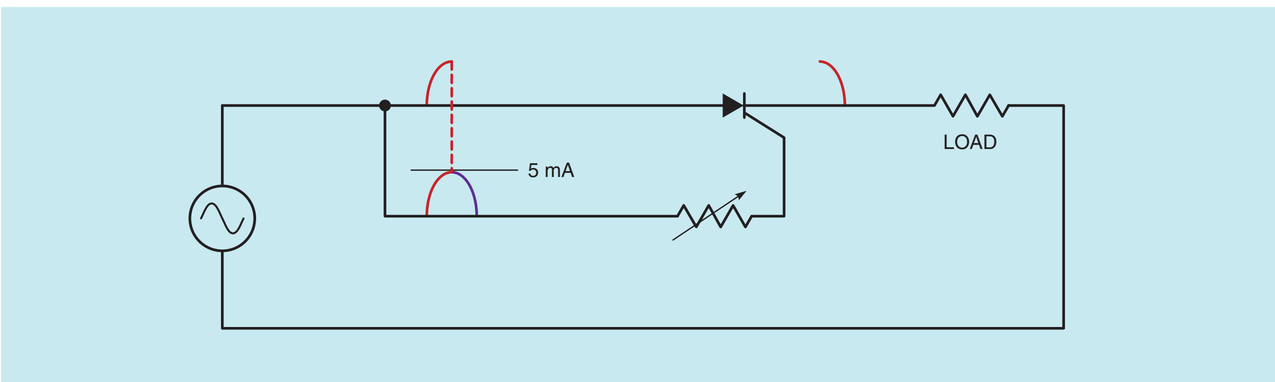


Figure 7–6 The SCR fires when the ac waveform reaches peak value.

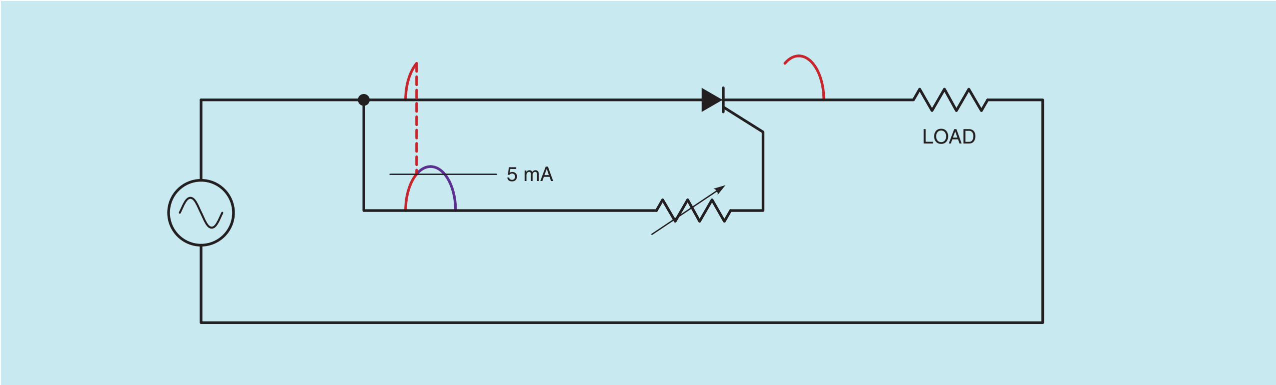


Figure 7–7 The SCR fires before the ac waveform reaches peak value.

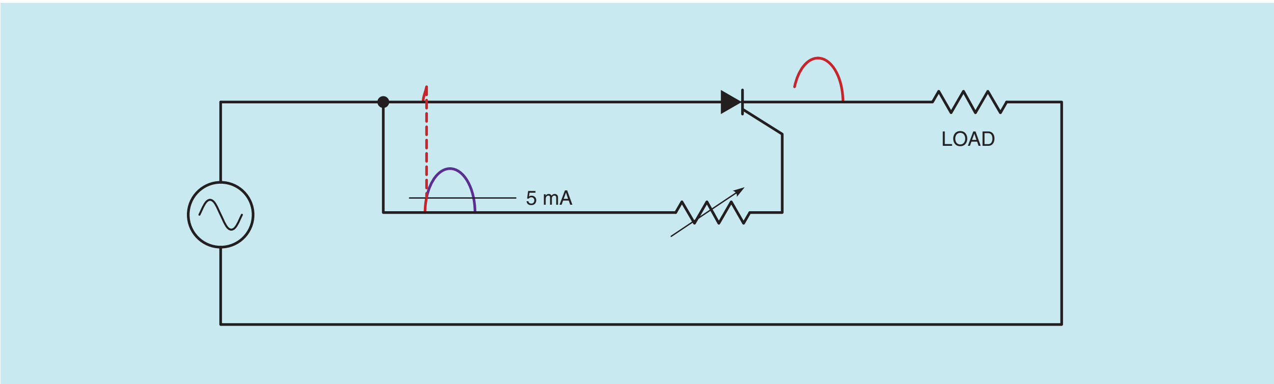


Figure 7–8 The SCR fires earlier than in Figure 7–7.

ac waveform reaches its peak value (Figure 7–7). This will cause the SCR to fire earlier in the cycle. Since the SCR fires earlier in the cycle, current is permitted to flow through the load resistor for a longer period of time, which produces a higher average voltage drop across the load. If the resistance of the gate circuit is reduced again as shown in Figure 7–8, the 5 mA of gate current needed to fire the SCR will be reached earlier than in Figure 7–7. Current will begin flowing through the load sooner than before, which will permit a higher average voltage to be dropped across the load.

Notice that this circuit enables the SCR to control only half of the positive waveform. The latest the SCR can be fired in the cycle is when the ac waveform is at 90° or peak. If a lamp were used as the load for this circuit, it would burn at half brightness when the SCR first turned on. This control would permit the lamp to be operated from half brightness to full brightness, but it could not be operated at a level less than half brightness.

Phase Shifting the SCR

The SCR can control all of the positive waveform through the use of *phase shifting*. As the term implies, phase shifting means to shift the phase of one thing in reference to another. In this instance, the voltage applied to the gate must be shifted out of phase with the voltage applied to the anode. Although there are several methods used for phase shifting an SCR, it is beyond the scope of this text to cover all of them. The basic principles are the same for all of the methods, however, so only one method is covered.

To phase shift an SCR, the gate circuit must be unlocked or separated from the anode circuit. The circuit shown in Figure 7–9 will accomplish this. A 24-volt, center-tapped transformer is used to isolate the gate circuit from the anode circuit. Diodes Dl and D2 are used to form a two-diode type of full-wave rectifier to operate the UJT circuit. Resistor R1 is used to

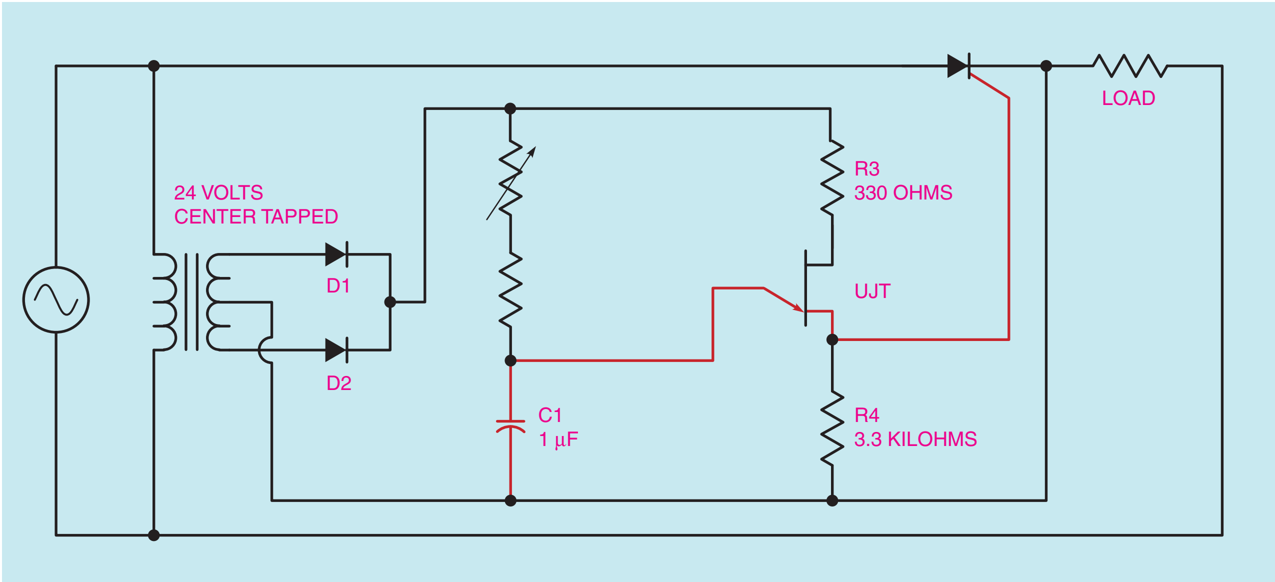


Figure 7–9 UJT phase shift for an SCR. SCR gate current is provided by the discharging capacitor when the UJT fires.

determine the pulse rate of the UJT by controlling the charge time of capacitor C1. Resistor R2 is used to limit the current through the emitter of the UJT if resistor R1 is adjusted to 0 ohms. Resistor R3 limits current through the base 1–base 2 section when the UJT turns on. Resistor R4 permits a voltage spike or pulse to be produced across it when the UJT turns on and discharges capacitor C1. The pulse produced by the discharge of capacitor C1 is used to trigger the gate of the SCR.

Since the pulse of the UJT is used to provide a trigger for the gate of the SCR, the SCR can be fired at any time regardless of the voltage applied to the anode. This means that the SCR can now be fired as early or late during the positive half cycle as desired because the gate pulse is determined by the charge rate of capacitor C1. The voltage across the load can now be adjusted from 0 to the full applied voltage.

Testing the SCR

The SCR can be tested with an ohmmeter (see Procedure 4 in the Appendix). To test the SCR, connect the positive output lead of the ohmmeter to the anode and the negative lead to the cathode. The ohmmeter should indicate no continuity. Touch the gate of the SCR to the anode. The ohmmeter should indicate continuity through the SCR. When the gate lead is removed from the anode, conduction may stop or continue depending on whether the ohmmeter is supplying enough current to keep the device above its holding current level. If the ohmmeter indicates continuity through the SCR before the gate is touched to the anode, the SCR is shorted. If the ohmmeter will not indicate continuity through the SCR after the gate has been touched to the anode, the SCR is open.

Review Questions

1. What do the letters SCR stand for?
2. If an SCR is connected to an ac circuit, will the output voltage be ac or dc?
3. Briefly explain how an SCR operates when connected to a dc circuit.
4. How many layers of semiconductor material are used to construct an SCR?
5. SCRs are members of a family of devices known as thyristors. What is a thyristor?
6. Briefly explain why thyristors have the ability to control large amounts of power.
7. What is the average voltage drop of an SCR when it is turned on?
8. Explain why an SCR must be phase shifted.

UNIT 8
THE DIAC

OBJECTIVES

After studying this unit, the student will be able to:

- Draw the schematic symbol for a diac.
- Discuss the operation of a diac.
- Connect a diac in a circuit.

The Diac

The *diac* is a special-purpose, bidirectional diode. The primary function of the diac is to phase shift a triac. The operation of the diac is very similar to that of a unijunction transistor, except that the diac is a two-directional device. The diac has the ability to operate in an ac circuit while the UJT can operate only in a dc circuit.

There are two schematic symbols for the diac (Figure 8–1). Both of these symbols are used in electronic schematics to illustrate the use of a diac. Therefore, you should make yourself familiar with both symbols.

The diac is a voltage sensitive switch that can operate on either polarity (Figure 8–2). Voltage applied to the diac must reach a predetermined level before the diac will activate. For this example, assume that the predetermined level is 15 volts. When the voltage reaches 15 volts, the diac will turn on, or fire. When the diac fires, it displays a negative resistance, which means that it will conduct at a lower voltage than the voltage needed to turn it on. In this example, assume that the voltage drops to 5 volts when the diac conducts. The diac will remain on until the applied voltage drops below its conduction level, which is 5 volts (Figure 8–3).

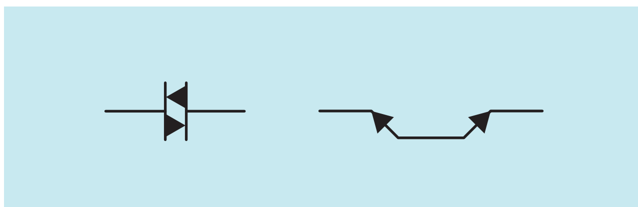


Figure 8–1 Schematic symbols for the diac.

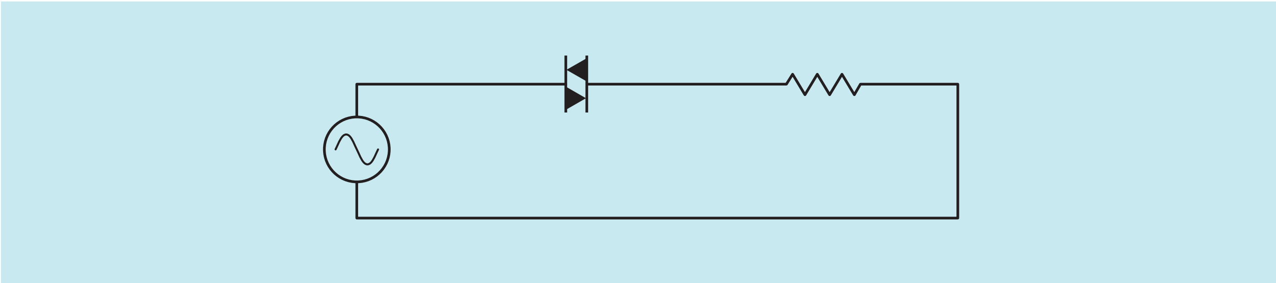


Figure 8–2 The diac can operate on either polarity.

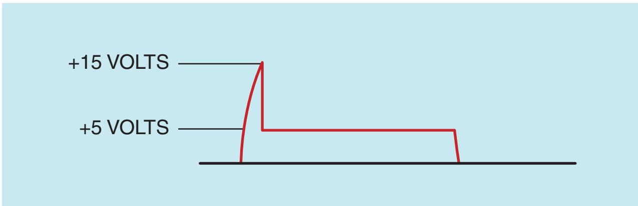


Figure 8–3 The diac operates until the applied voltage falls below its conduction level.

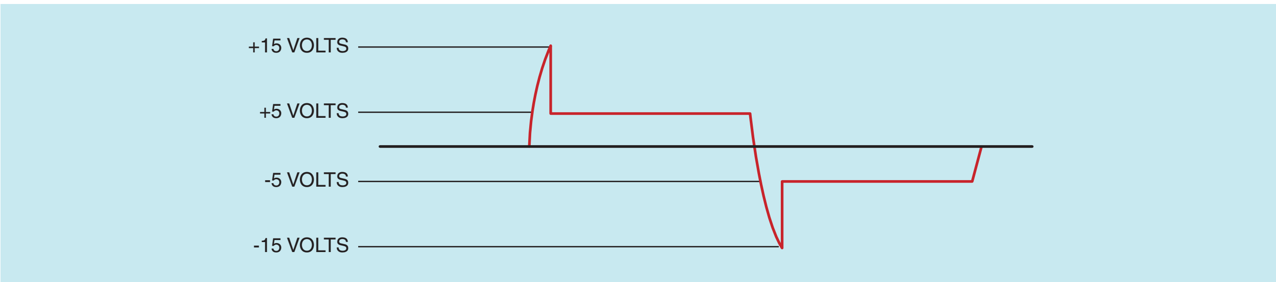


Figure 8–4 The diac will conduct on either half of the alternating current.

Since the diac is a bidirectional device, it will conduct on either half cycle of the alternating current applied to it (Figure 8–4). Note that the diac operates in the same manner on both halves of the ac cycle. The simplest way to summarize the operation of the diac is to say that it is a voltage sensitive ac switch.

Review Questions

1. Briefly explain how a diac operates.
2. Draw the two schematic symbols used to represent the diac.
3. What is the major use of the diac in industry?
4. When a diac first turns on, does the voltage drop, remain at the same level, or increase to a higher level?

UNIT 9
THE TRIAC

OBJECTIVES

After studying this unit, the student will be able to:

- Draw the schematic symbol for a triac.
- Discuss the similarities and differences between SCRs and triacs.
- Discuss the operation of a triac in an ac circuit.
- Discuss phase shifting a triac.
- Connect a triac in a circuit.
- Test a triac with an ohmmeter.

The triac is a PNPN junction connected parallel to an NPNP junction. Figure 9–1 illustrates the semiconductor arrangement of a triac. The triac operates in a manner similar to that of two connected SCRs (Figure 9–2). The schematic symbol for the triac is shown in Figure 9–3.

When an SCR is connected in an ac circuit, the output voltage is direct current. When a triac is connected in an ac circuit, the output voltage is alternating current. Since the triac operates like two SCRs that are connected and facing in opposite directions, it will conduct both the positive and negative half cycles of ac current.

When a triac is connected in an ac circuit as shown in Figure 9–4, the gate must be connected to the same polarity as MT2. When the ac voltage applied to MT2 is positive, the SCR, which is forward biased, will conduct. When the voltage applied to MT2 is negative, the other SCR is forward biased and will conduct that half of the waveform. Since one of the SCRs is forward biased for each half cycle, the triac will conduct ac current as long as the gate lead is connected to MT2.

The triac, like the SCR, requires a certain amount of gate current to turn it on. Once the triac has been triggered by the gate, it will continue to conduct until the current flowing through MT2–MT1 drops below the holding current level.

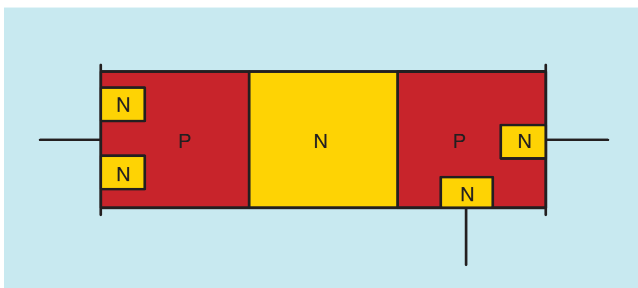


Figure 9–1 The semiconductor arrangement of a triac.

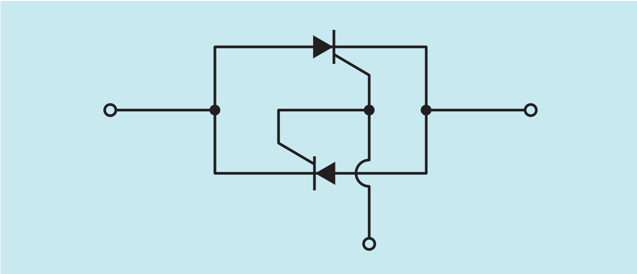


Figure 9–2 The triac operates in a manner similar to two SCRs with a common gate.

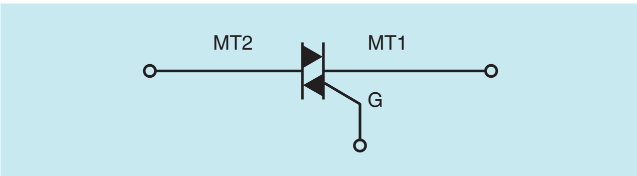


Figure 9–3 The schematic symbol for a triac.

The Triac Used as an AC Switch

The triac is a member of the thyristor family, which means that it has only two states of operation, on and off. When the triac is turned off, it drops the full applied voltage of the circuit at 0 amps of current flow. When the triac is turned on, it has a voltage drop of about 1 volt and circuit current must be limited by the load connected to the circuit.

The triac has become very popular in industrial circuits as an ac switch. Since it is a thyristor, it has the ability to control a large amount of voltage and current. There are no contacts to wear out, it is sealed against dirt and moisture, and it can operate thousands of times per second. The triac is used as the output device of many solid-state relays which will be covered later. Two types of triacs are shown in Figures 9–5 and 9–6.

The Triac Used for AC Voltage Control

The triac can be used to control ac voltage (Figure 9–7). If a variable resistor is connected in series with the gate, the point at which the gate current is high enough to fire the triac can be adjusted. The resistance can be adjusted to permit the triac to fire when the ac waveform reaches its peak value. This will cause half of the ac voltage to be dropped across the triac and half to be dropped across the load.

If the gate resistance is reduced, the amount of gate current needed to fire the triac will be obtained before the ac waveform reaches its peak value. This means that less voltage will be dropped across the triac and more voltage will be dropped across the load. This circuit permits the triac to control only one half of the ac waveform applied to it. If a lamp is used as the load, it can be controlled from half brightness to full brightness. If an attempt is made to adjust the lamp to operate at less than half brightness, it will turn off.

Phase Shifting the Triac

To obtain complete voltage control, the triac, like the SCR, must be phase shifted. Several methods can be used to phase shift a triac, but only one will be covered in this unit. In Figure 9–8, a diac is used to phase shift the triac. Resistors Rl and R2 are connected in series with capacitor C1. Resistor R1 is a variable resistor used to control the charge time of capacitor C1. Resistor R2

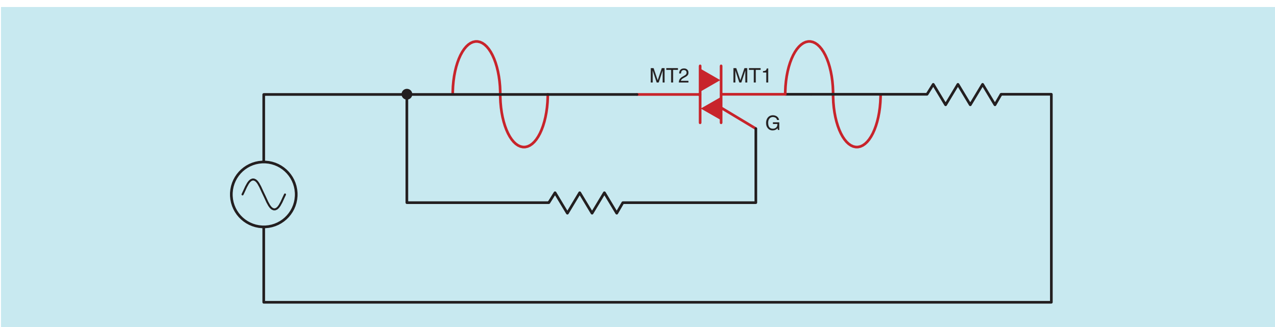


Figure 9–4 The triac conducts both halves of the ac waveform.

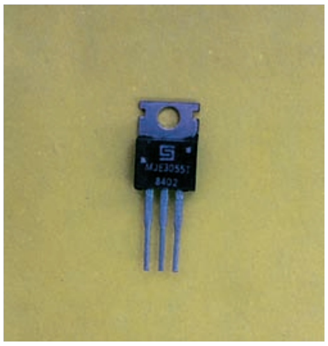


Figure 9–5 The triac used for low power applications.

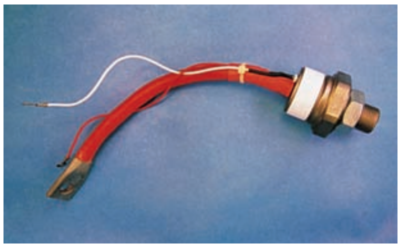


Figure 9–6 The triac shown in a stud mount case.

is used to limit current if resistor R1 is adjusted to 0 ohms. Assume that the diac connected in series with the gate of the triac will turn on when capacitor C1 has been charged to 15 volts. When the diac turns on, capacitor C1 will discharge through the gate of the triac. This permits the triac to fire, or turn on. Since the diac is a bidirectional device, it will permit a positive or negative pulse to trigger the gate of the triac.

When the triac fires, there is a voltage drop of about 1 volt across MT2 and MT1. The triac remains on until the ac voltage drops to a low enough value to permit the triac to turn off. Since the phase shift circuit is connected parallel to the triac, once the triac turns on, capacitor C1 cannot begin charging again until the triac turns off at the end of the ac cycle.

Notice that the pulse applied to the gate is controlled by the charging of capacitor C1, not the amplitude of voltage. If the correct values are chosen, the triac can be fired at any point in the ac cycle applied to it. The triac can now control the ac voltage from 0 to the full voltage of the circuit. A common example of this type of triac circuit is the light dimmer control used in many homes.

Testing the Triac

The triac can be tested with an ohmmeter (see Procedure 5 in the Appendix). To test the triac, connect the ohmmeter leads to MT2 and MT1. The ohmmeter should indicate no continuity. If the gate lead is touched to MT2, the triac should turn on and the ohmmeter should indicate continuity through the triac. When the gate lead is released from MT2, the triac may continue to conduct or it may turn off depending on whether the ohmmeter supplies enough current to keep the device above its holding current level. This tests one half of the triac.

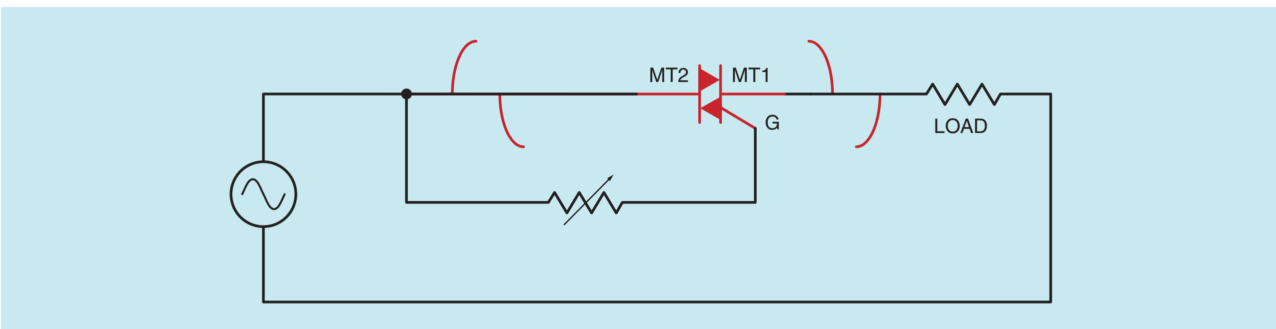


Figure 9–7 The triac controls half of the ac applied voltage.

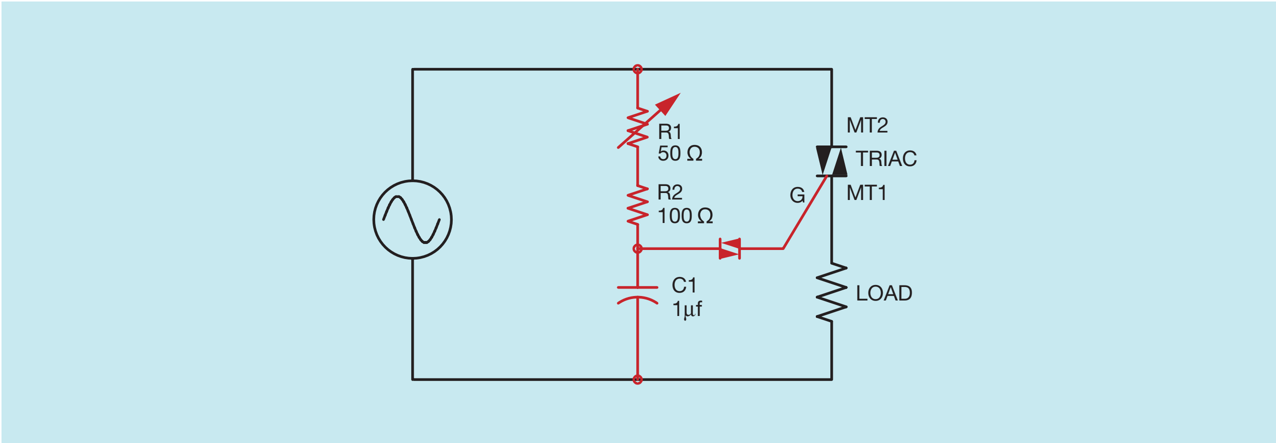


Figure 9–8 Phase shift circuit for a triac. When the diac turns on, gate current is supplied to the triac by the discharge of capacitor C1.

To test the other half of the triac, reverse the connection of the ohmmeter leads. The ohmmeter should indicate no continuity. If the gate is touched again to MT2, the ohmmeter should indicate continuity through the device. The other half of the triac has been tested.

Review Questions

1. Draw the schematic symbol for a triac.
2. When a triac is connected in an ac circuit, is the output ac or dc?
3. The triac is a member of what family of devices?
4. Briefly explain why a triac must be phase shifted.
5. What electronic component is frequently used to phase shift the triac?
6. When the triac is being tested with an ohmmeter, which other terminal should the gate be connected to if the ohmmeter is to indicate continuity?

UNIT 10

THE 555 TIMER

OBJECTIVES

After studying this unit, the student will be able to:

- Describe the operation of the 555 timer.
- Discuss the uses of the 555 timer.
- Connect the timer as an oscillator.
- Connect the 555 timer as an on-delay timer.

The 555 timer is an eight-pin integrated circuit that has become one of the most popular electronic devices used in industrial electronic circuits. The reason for the 555's popularity is its tremendous versatility. The 555 timer is used in circuits that require a time delay function, and is also used as an oscillator to provide the pulses needed to operate computer circuits.

The 555 timer is most often housed in an eight-pin, in-line integrated circuit (IC) (Figures 10–1 and 10–2). This package has a notch at one end, or a dot by one pin, which is used to identify pin #1. Once pin #1 has been identified, the other pins are numbered as shown in Figure 10–1. The 555 timer operates on voltages that range from about 3 to 16 volts. Following is an explanation of each pin and its function.

Pin #1 ***Ground***—This pin is connected to circuit ground.

Pin #2 ***Trigger***—Pin #2 must be connected to a voltage that is less than ⅓ Vcc (the applied voltage) to trigger the unit. This usually is done by

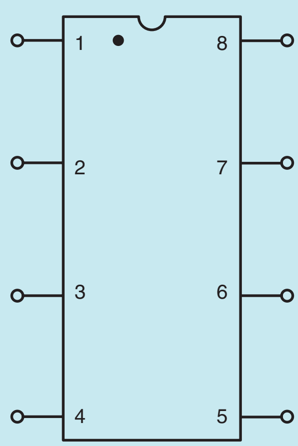


Figure 10–1 After pin #1 has been identified, the other pins are numbered as shown.

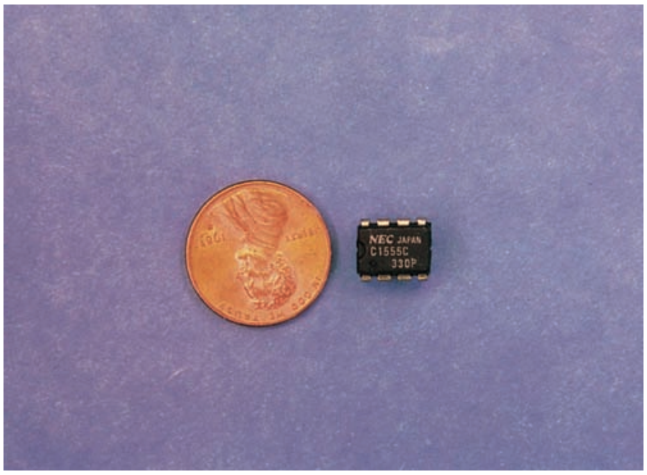


Figure 10–2 An eight-pin, in-line, integrated circuit.

connecting pin #2 to ground. The connection to ⅓ Vcc or ground must be momentary. If pin #2 is not removed from ground, the unit will not operate.

Pin #3 ***Output***—The output turns on when Pin #2 is triggered and turns off when the discharge is turned on.

Pin #4 ***Reset***—When this pin is connected to Vcc, it permits the unit to operate. When it is connected to ground, it activates the discharge and keeps the timer from operating.

Pin #5 ***Control Voltage***—If this pin is connected to Vcc through a variable resistor, the on time is longer, but the off time is not affected. If pin #5 is connected to ground through a variable resistor, the on time is shorter, and the off time is still not affected. If pin #5 is not to be used in the circuit, it is usually taken to ground through a small capacitor. This helps to keep circuit noise from "talking" to pin #5.

Pin #6 ***Threshold***—When the voltage across the capacitor connected to pin #6 reaches ⅔ the value of Vcc, the discharge turns on and the output turns off.

Pin #7 ***Discharge***—When pin #6 turns the discharge on, it discharges the capacitor connected to pin #6. The discharge remains turned on until pin #2 retriggers the timer. The discharge then turns off and the capacitor connected to pin #6 begins charging again.

Pin #8 ***Vcc***—Pin #8 is connected to Vcc.

(For the following explanation, assume that pin #2 is connected to pin #6. This permits the unit to be retriggered by the discharge each time it turns on and discharges the capacitor to ⅓ the value of Vcc.)

The 555 timer operates on a percentage of the applied voltage. This permits the time setting to remain constant even if the applied voltage changes. For example, when the capacitor connected to pin #6 reaches ⅔ of the applied voltage, the discharge turns on and discharges the capacitor until it reaches ⅓ of the applied voltage. If the applied voltage of the timer is connected to 12 volts dc, ⅔ of the applied voltage is 8 volts and ⅓ is 4 volts. This means that when the voltage across the capacitor connected to pin #6 reaches 8 volts, pin #7 will turn on until the capacitor is discharged to ⅓ the value of Vcc, or 4 volts, and will then turn off (Figure 10–3).

If the voltage is lowered to 6 volts at Vcc, ⅔ of the applied voltage is 4 volts and ⅓ of the applied voltage is 2 volts. Pin #7 will now turn on when the voltage across the capacitor connected to pin #6 reaches 4 volts and will turn off when the voltage across the capacitor drops to 2 volts.

The formula for a RC time constant is (Time = Resistance × Capacitance). Notice that there is no mention of voltage in the formula. This means that it will take the same amount of time to charge the capacitor regardless of whether the circuit is connected to 12 volts

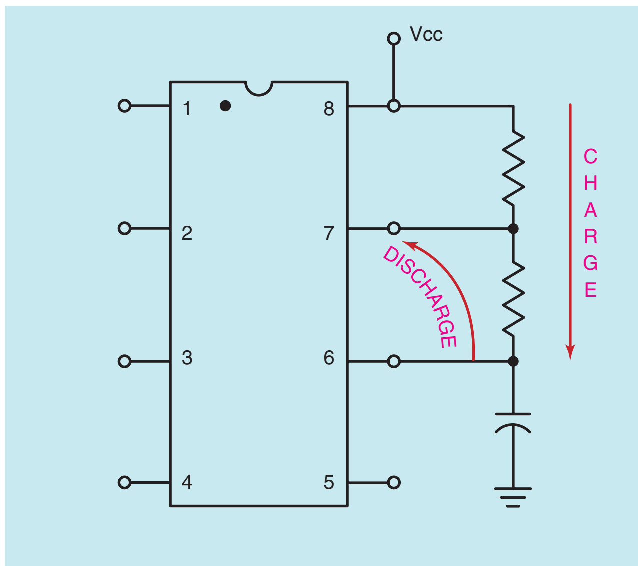


Figure 10–3 The charge and discharge is determined by a percentage of the applied voltage.

or to 6 volts. If the time it takes for the voltage of the capacitor connected to pin #6 to reach ⅔ of Vcc when the timer has an applied voltage of 12 volts is measured, it will be the same as the amount of time it takes when the applied voltage is only 6 volts. The timing of the circuit remains the same even if the voltage changes.

The circuit shown in Figure 10–4 is used to explain the operation of the 555 timer. In Figure 10–4, a normally closed switch, S1, is connected between the discharge, pin #7, and the ground, pin #1. A normally open switch, S2, is connected between the output, pin #3, and Vcc, pin #8.

The dotted line drawn between these two switches shows mechanical connection. This means that these switches operate together. If S1 opens, S2 closes at the same time. If S2 opens, S1 closes. Pin #2, the trigger, and pin #6, the threshold, are used to control these switches. The trigger can close switch S2, and the threshold can close S1.

To begin the analysis of this circuit, assume that switch S1 is closed and switch S2 is open as shown in Figure 10–4. When the trigger is connected to a voltage that is less than ⅓ of Vcc, it causes switch S2 to close and switch S1 to open. When switch S2 closes, voltage is supplied to the output at pin #3. When switch S1 opens, the discharge is no longer connected to ground, and capacitor C1 begins to charge through resistors R1 and R2. When the voltage across C1 reaches ⅔ of Vcc, the threshold, pin #6, causes switch S1 to close and switch S2 to open. When switch S2 opens, the output turns off. When switch S1 closes, the discharge, pin #7, is connected to ground. Capacitor C1 then discharges through resistor R2. The timer will remain in this position until the trigger is again connected to a voltage that is less than ⅓ of Vcc.

If the trigger is connected permanently to a voltage less than ⅓ of Vcc, switch S2 will be held closed and switch S1 will be held open. This, of course, will stop the operation of the timer. As stated previously, the trigger must be a momentary pulse, not a continuous connection, in order for the 555 timer to operate.

Circuit Applications

The Oscillator

The 555 timer can perform a variety of functions. It is commonly used as an oscillator. The 555 timer has become popular for this application because it is so easy to use.

The 555 timer shown in Figure 10–5 has pin #2 connected to pin #6. This permits the timer to retrigger itself at the end of each time cycle. When the applied voltage is turned on, capacitor C1 is discharged and has a voltage of 0 volts across it. Since pin #2 is connected to pin #6, and the voltage at that point is less than ⅓ of Vcc, the timer will trigger. When the timer is triggered, two things happen at the same time: the output turns on, and the discharge turns off. When the discharge at

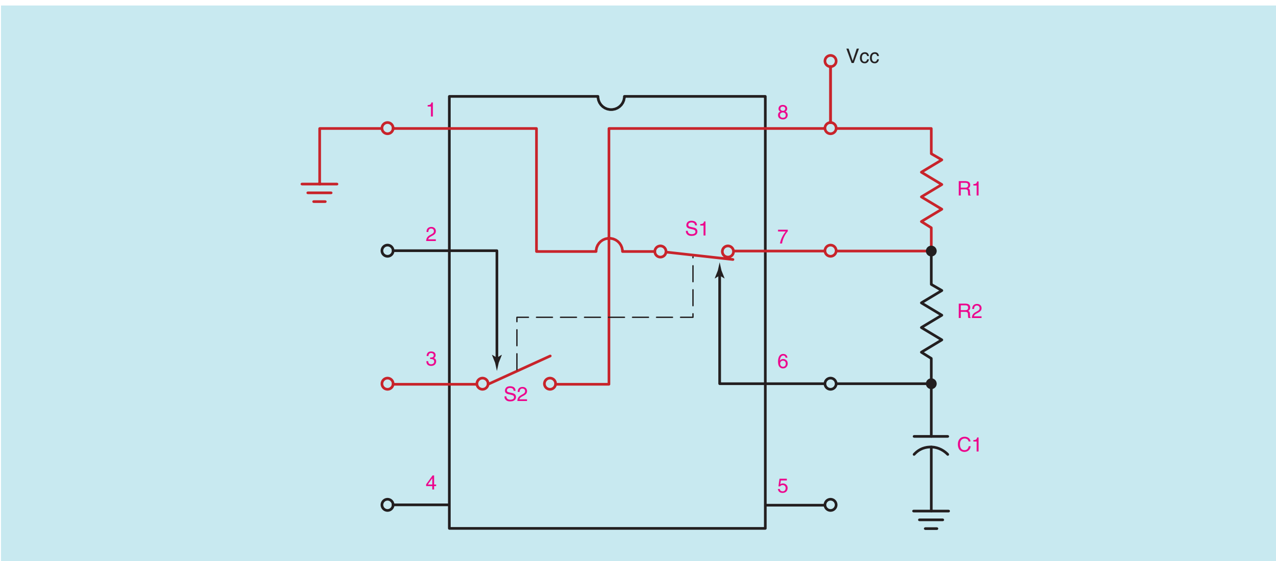


Figure 10–4 A simple circuit illustrates how the timer works.

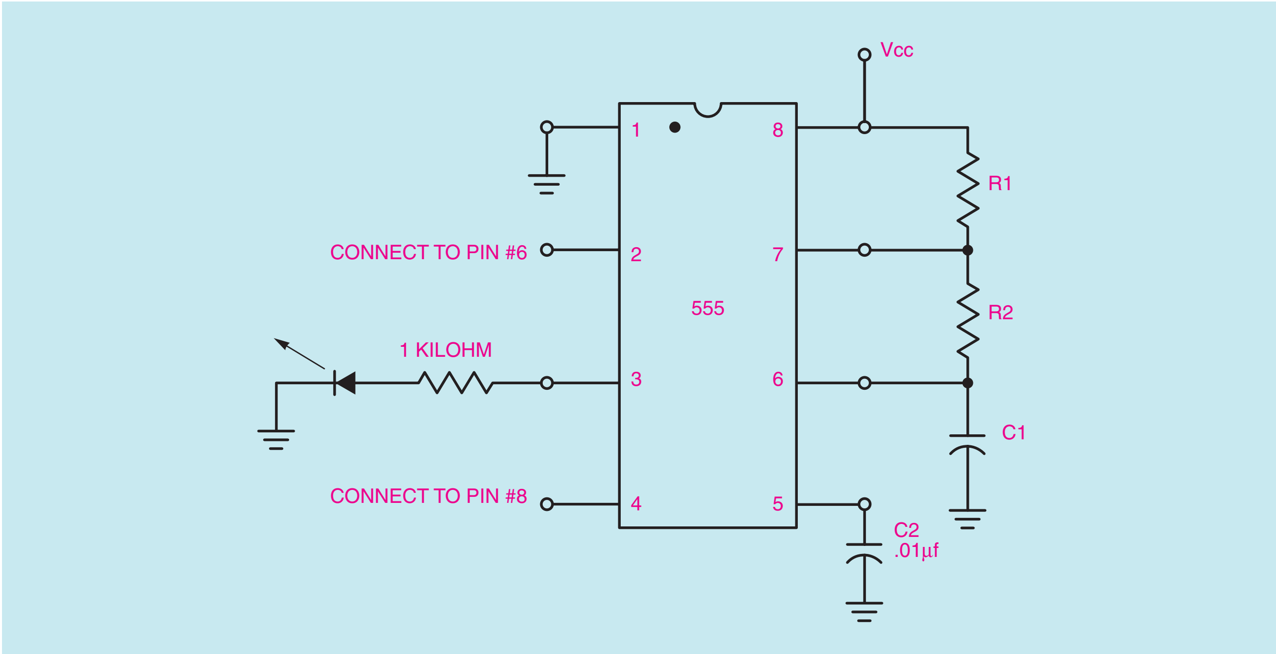


Figure 10–5 555 timer connected as a simple oscillator.

pin #7 turns off, capacitor C1 charges through resistors R1 and R2. The amount of time it takes for capacitor C1 to charge is determined by the capacitance of the capacitor and the combined resistance of R1 and R2.

When capacitor C1 is charged to a voltage that is ⅔ of Vcc, the output turns off, and the discharge at pin #7 turns on. When the discharge turns on, capacitor C1 discharges through resistor R2 to ground. The amount of time it takes C1 to discharge is determined by the capacitance of capacitor C1 and the resistance of R2. When capacitor C1 is discharged to a voltage that is ⅓ of Vcc, the timer is retriggered by pin #2 causing the output to turn on and the discharge to turn off. When the discharge turns off, capacitor C1 begins charging again.

The amount of time required to charge capacitor C1 is determined by the combined resistance of R1 and R2. The discharge time, however, is determined by the value of R2 (Figure 10–6).

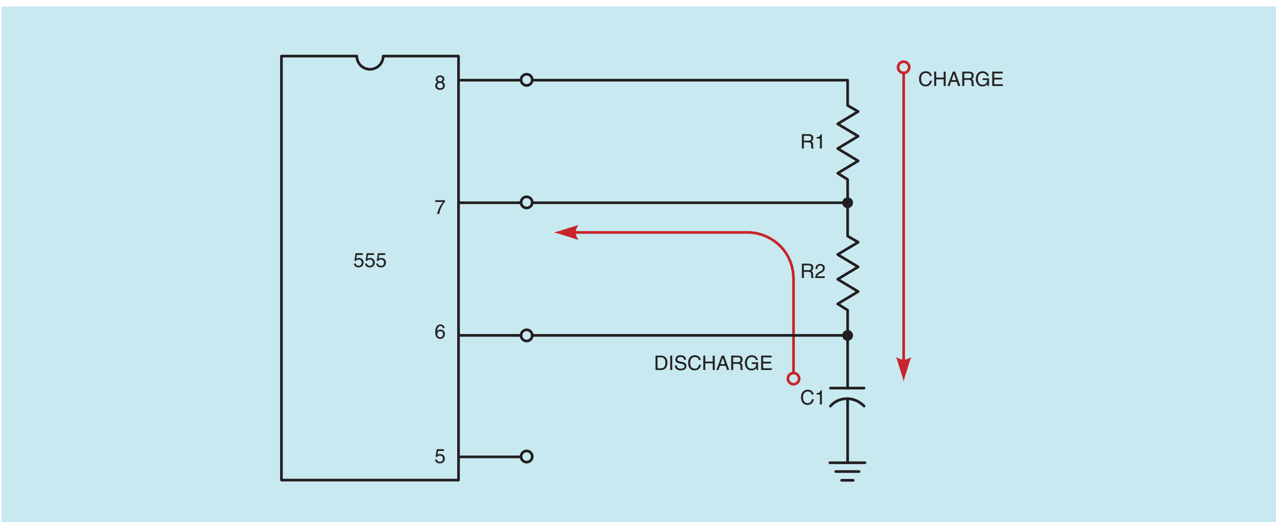


Figure 10–6 Charge time of C1 is determined by resistors R1 and R2. Discharge time of C1 is determined by resistor R2.

Since the timer's output is turned on while capacitor C1 is charging, and turned off while C1 is discharging, the on time of the output is longer than the off time. If the value of resistor R2 is much greater than the value of resistor R1, this condition is not too evident. For example, if resistor R1 has a value of 1 kilohm and R2 has a value of 100 kilohms, the resistance connected in series with the capacitor during charging is 101 kilohms. The resistance connected in series with the capacitor during discharge is 100 kilohms. In this circuit, the difference between the charge time and the discharge time of the capacitor is 1%. If an oscilloscope is connected to the output of the timer, a waveform similar to the waveform shown in Figure 10–7 will be seen.

Assume that the value of resistor R1 is changed to 100 kilohms and the value of resistor R2 remains at 100 kilohms. In this circuit, the resistance connected in series with the capacitor during charging is 200 kilohms. The resistance connected in series with the capacitor during discharge, however, is 100 kilohms. Therefore, the discharge time is 50% of the charge time. This means that the output of the timer will be turned on twice as long as it will be turned off. An oscilloscope connected to the output of the timer would display a waveform similar to the one shown in Figure 10–8.

Although this condition can exist, the 555 timer has a provision for solving the problem. Pin #5, the control voltage pin, can give complete control of the output voltage. If a variable resistor is connected between pin #5 and Vcc, the on time of the output can be lengthened to any value desired. If a variable resistor is connected between pin #5 and ground, the on time of the output can be shortened to any value desired. Since the on time of the timer is adjusted by connecting resistance to pin #5, the off time is set by the values of C1 and R2.

The output frequency of the unit is determined by the values of capacitor C1 and resistors R1 and R2. The 555 timer will operate at almost any frequency desired. It is used in many industrial electronic circuits that require the use of a square wave oscillator.

The On-Delay Timer

In this circuit, the 555 timer is used to construct an on-delay relay. The 555 produces accurate time delays which can range from seconds to hours depending on the values of resistance and capacitance used in the circuit. In Figure 10–9, transistor Q1 is used to switch relay coil K1 on or off. A transistor is used to control the relay because the 555 timer may not be able to supply the current needed to operate it.

Transistor Q2 is used as a stealer transistor to steal the base current from transistor Q1. As long as transistor Q2 is turned on by the output of the timer, transistor Q1 is turned off.

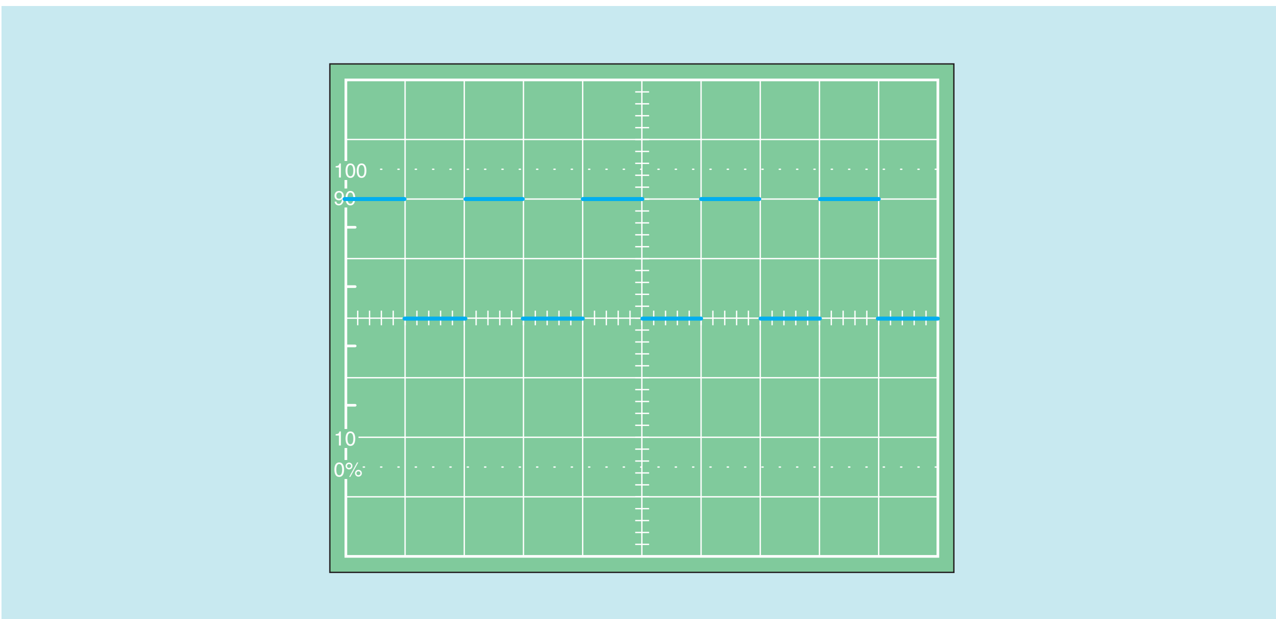


Figure 10–7 Waveform produced when an oscilloscope is connected to the output of the 555 timer. (Reproduced by permission of Tektronix, Inc., copyright © 1983.)

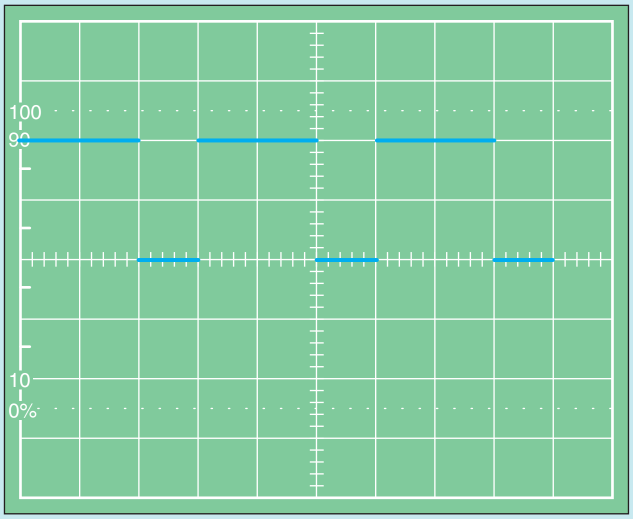


Figure 10–8 A different waveform is produced when the value of one of the resistors is changed. (Reproduced by permission of Tektronix, Inc., copyright © 1983.)

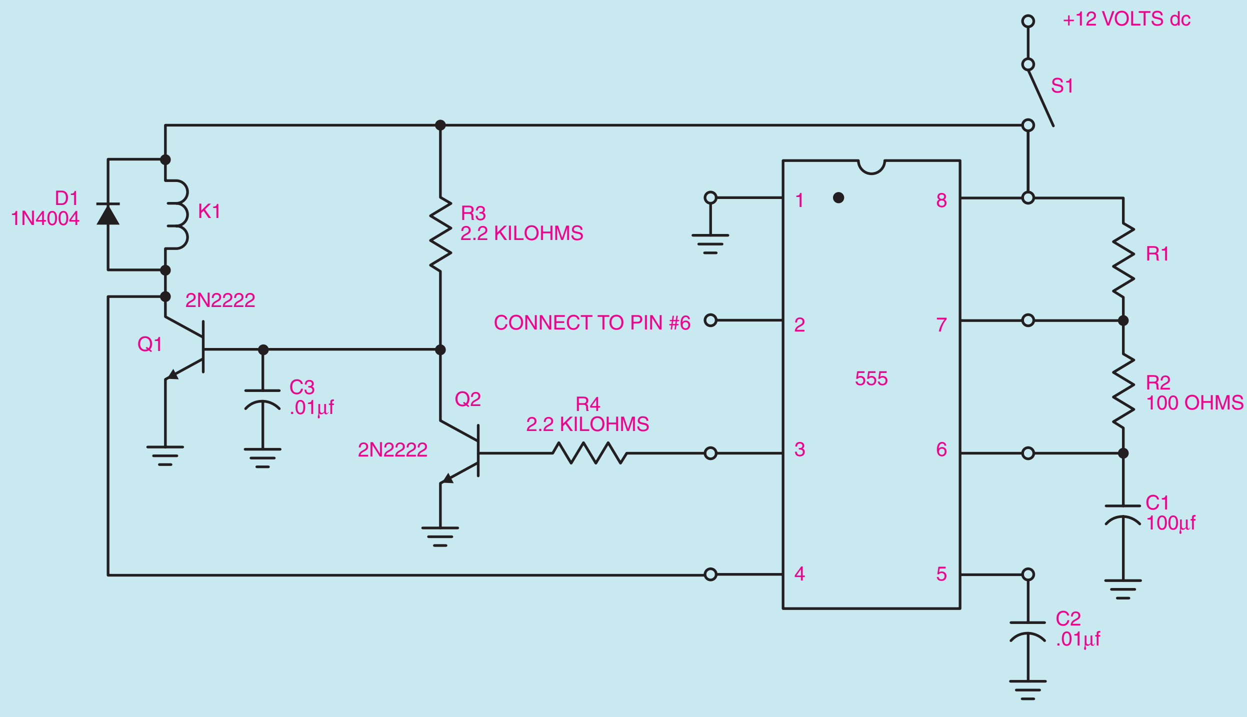


Figure 10–9 On-delay timer.

Capacitor C3 is connected from the base of transistor Q1 to ground. Capacitor C3 acts as a short time-delay circuit. When Vcc is turned on by switch S1, capacitor C3 is discharged. Before transistor Q1 can be turned on, capacitor C3 must be charged through resistor R3. This charging time is only a fraction of a second, but it ensures that transistor Q1 will not turn on before the output of the timer can turn transistor Q2 on. Once transistor Q2 has been turned on, it will hold transistor Q1 off by stealing its base current.

Diode Dl is used as a kickback or freewheeling diode to kill the spike voltage induced into the coil of relay K1 when switch S1 is opened. Resistor R3 limits the base current to transistor Q1 and resistor R4 limits the base current to transistor Q2.

Pin #4, the reset pin, is used as a latch in this circuit. When power is applied at Vcc, transistor Q1 is turned off. Since transistor Q1 is off, most of the applied voltage is dropped across the transistor, causing about 12 volts to appear at the collector of the transistor. Since pin #4 is connected to the collector of transistor Q1, 12 volts is applied to pin #4. For the timer to operate, pin #4 must be connected to a voltage that is greater than ⅔ of Vcc. When pin #4 is connected to a voltage that is less than ⅓ of Vcc, it turns on the discharge and keeps the timer from operating. When transistor Q1 turns on, the collector of the transistor drops to ground or 0 volts. Pin #4 is also connected to ground, which prevents the timer from further operation. Since the timer can no longer operate, the output remains turned off, which permits transistor Q1 to remain turned on.

Capacitor C1 and resistors R1 and R2 are used to set the amount of time delay. Resistor R2 should be kept at a value of about 100 ohms. The job of resistor R2 is to limit the current when capacitor C1 discharges. Resistor R2 has a relatively low value to enable capacitor C1 to discharge quickly. The time setting can be changed by changing the value of resistor R1.

To understand the operation of the circuit, assume that switch S1 is open and all capacitors are discharged. When switch S1 is closed, pin #2, which is connected to 0 volts, triggers the timer. When the timer is triggered, the output activates transistor Q2 which steals the base current from transistor Q1. Transistor Q1 remains off as long as transistor Q2 is on. When capacitor C1 has been charged to ⅔ of Vcc, the discharge turns on and the output of the timer turns off. When the output turns transistor Q2 off, transistor Q1 is supplied with base current through resistor R3 and turns on relay coil K1. When transistor Q1 is turned on, the voltage applied to the reset pin, #4, is changed from 12 volts to 0 volts. This causes the reset to lock the discharge on and the output off. Therefore, when transistor Q1 is turned on, switch S1 must be reopened to reset the circuit.

Review Questions

1. How is pin #1 of an in-line, integrated circuit identified?
2. A 555 timer is connected to produce a pulse at the output once each second. The timer is connected to 12 volts dc. If the voltage is reduced to 8 volts dc, the 555 will continue to operate at the same pulse rate. Explain why the timer will operate at the same pulse rate when the voltage is reduced.
3. What is the range of voltage the 555 timer will operate on?
4. Explain the function of the control voltage, pin #5, when the timer is being used as an oscillator.
5. Explain what happens to the output and discharge pins of the 555 timer when the trigger, pin #2, is connected to a voltage that is less than ⅓ of Vcc.
6. Explain what happens to the output and discharge pins when the threshold, pin #6, is connected to a voltage that is greater than ⅔ of Vcc.
7. Refer to figure 10–6. The values of what components determine the length of time the output will be turned on?
8. The values of what components determine the amount of time the output will remain turned off?
9. Explain the operation of pin #4 on the 555 timer.
10. What is a stealer transistor?

UNIT 11

THE OPERATIONAL AMPLIFIER

OBJECTIVES

After studying this unit, the student will be able to:

- Discuss the operation of the operational amplifier (op amp).
- List the major types of connections for operational amplifiers.
- Connect a level detector circuit using an op amp.
- Connect an oscillator using an op amp.

The operational amplifier, like the 555 timer, has become a very common component in industrial electronic circuits. The operational amplifier, or op amp, is used in hundreds of applications. Different types of op amps are available for different types of circuits. Some op amps use bipolar transistors for input while others use field-effect transistors. The advantage of field-effect transistors is that they have an extremely high input impedance that can be several thousand megohms. As a result of this high input impedance, the amount of current needed to operate the amplifier is small. In fact, op amps that use field-effect transistors for the inputs are generally considered to require no input current.

The ideal amplifier would have an input impedance of infinity. With an input impedance of infinity, the amplifier would not drain power from the signal source; therefore, the strength of the signal source would not be affected by the amplifier. The ideal amplifier would also have zero output impedance. With zero output impedance, the amplifier could be connected to any load resistance without causing a voltage drop inside the amplifier. If it had no internal voltage drop, the amplifier would utilize 100% of its gain. Finally, the ideal amplifier would have unlimited gain. This would enable it to amplify any input signal as much as desired.

Although the ideal amplifier does not exist, the op amp is close. In this unit the operation of an old op amp, the 741, is described as typical of all operational amplifiers. Other op amps may have different characteristics of input and output impedance, but the basic theory of operation is the same for all of them.

The 741 op amp uses bipolar transistors for the inputs. The input impedance is about 2 megohms, the output impedance is about 75 ohms, and the open loop, or maximum gain, is about 200,000. The 741 is impractical for use with such a high gain, so negative feedback (discussed later) is used to reduce the gain. For example, assume that the amplifier has an output voltage

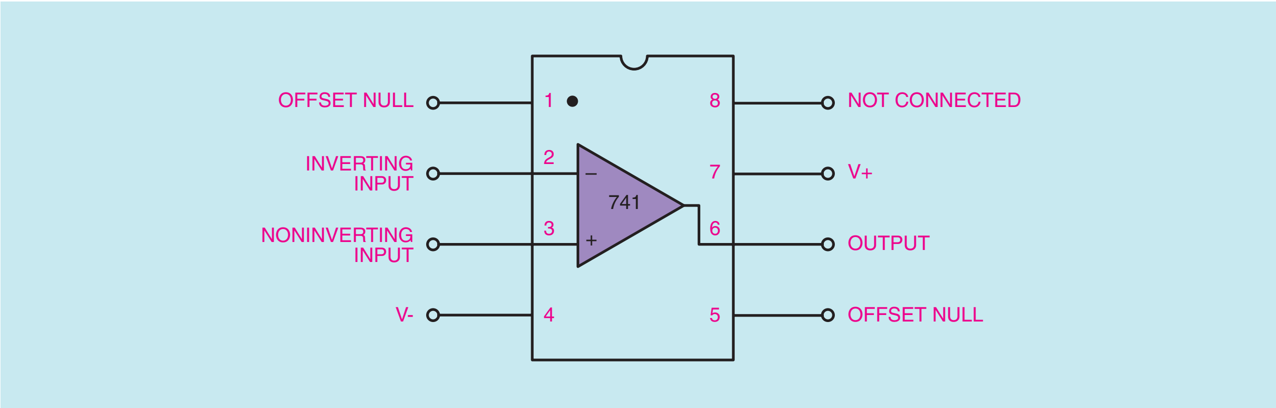


Figure 11–1 The 741 operational amplifier.

of 15 volts. If the input signal voltage is greater than 1/200,000 of the output voltage, or 75 microvolts,

$$\left(\frac{15}{200{,}000} = .000075\right)$$

the amplifier will be driven into saturation at which point it will not operate.

The 741 operational amplifier is usually housed in an eight-pin, in-line, integrated circuit package (Figure 11–1). The op amp has two inputs, the *inverting input* and the *noninverting input.* These inputs are connected to a differential amplifier that amplifies the difference between the two voltages. If both of these inputs are connected to the same voltage, say by grounding both inputs, the output should be 0 volts. In actual practice, however, unbalanced conditions within the op amp may cause a voltage to be produced at the output. Since the op amp has a very high gain, a slight imbalance of a few microvolts at the input can produce several millivolts at the output. To counteract any imbalance, pins #1 and #5 are connected to the offset null which is used to produce 0 volts at the output. These pins are adjusted after the 741 is connected in a working circuit. To make the adjustments, a 10 kilohm potentiometer is connected across pins #1 and #5, and the wiper is connected to the negative voltage (Figure 11–2).

Pin #2 is the inverting input. When a signal voltage is applied to this input, the output is inverted. For example, if a positive ac voltage is applied to the inverting input, the output will be a negative voltage (Figure 11–3).

Pin #3 is the noninverting input. When a signal voltage is applied to the noninverting input, the output voltage is the same polarity. For example, if a positive ac voltage is applied to the noninverting input, the output voltage will be positive also (Figure 11–4).

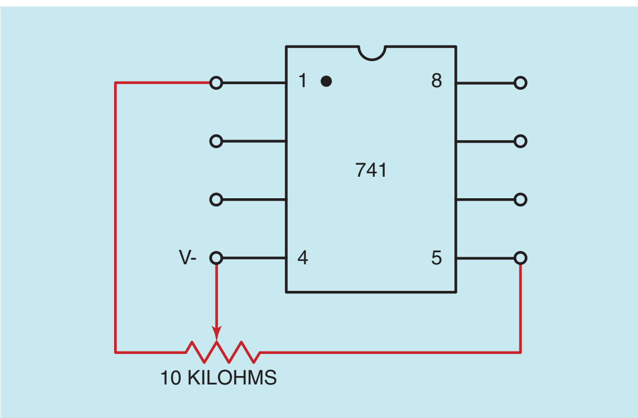


Figure 11–2 The offset null connection.

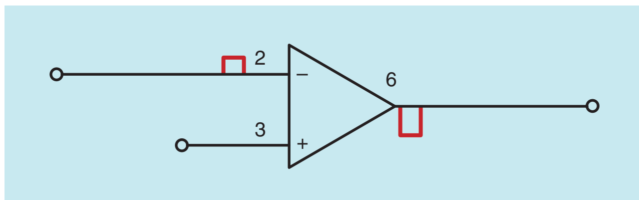


Figure 11–3 Inverting output.

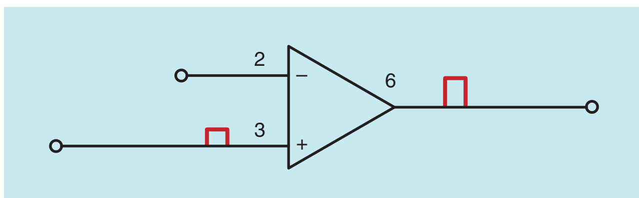


Figure 11–4 Noninverted output.

Operational amplifiers are usually connected to above and below ground power supplies. Although there are some circuit connections that do not require an above and below ground power supply, these are the exception instead of the rule. Pins #4 and #7 are the voltage input pins. Pin #4 is connected to the negative, or below ground, voltage and pin #7 is connected to the positive, or above ground, voltage.

The 741 operates on voltages that range from about 4 volts to 16 volts. Generally, the operating voltage for the 741 is 12 to 15 volts plus and minus. The 741 has a maximum power output rating of about 500 milliwatts.

Pin #6 is the output and pin #8 is not connected.

As stated previously, the open loop gain of the 741 operational amplifier is about 200,000. Since this amount of gain is not practical for most applications, something must be done to reduce the gain to a reasonable level. One of the great advantages of the op amp is the ease with which the gain can be controlled (Figure 11–5). The amount of gain is controlled by a negative feedback loop. This is accomplished by feeding a portion of the output voltage back to the inverting input. Since the output voltage is always opposite in polarity to the inverting input voltage, the amount of output voltage fed back to the input tends to reduce the input voltage. Negative feedback affects the operation of the amplifier in two ways: it reduces the gain, and it makes the amplifier more stable.

The gain of the amplifier is controlled by the ratio of resistor R2 to resistor R1. If a noninverting amplifier is used, the formula

$$\frac{R1 + R2}{R1}$$

is used to calculate the gain. If resistor R1 is 1 kilohm and resistor R2 is 10 kilohms, the gain of the amplifier is 11

$$\left(\frac{11{,}000}{1{,}000} = 11\right)$$

If the op amp is connected as an inverting amplifier, the input signal will be out of phase with the feedback voltage of the output. This will cause a reduction in the input voltage applied to the amplifier and in the gain. The formula

$$\left(\frac{R2}{R1}\right)$$

is used to compute the gain of an inverting amplifier. If resistor R1 is 1 kilohm and resistor R2 is 10 kilohms, the gain of the inverting amplifier is 10

$$\left(\frac{10{,}000}{1{,}000} = 10\right)$$

As a general rule, the 741 operational amplifier is not operated above a gain of about 100 because it tends to become unstable at high gains. If more gain is desired, it is obtained by using more than one amplifier (Figure 11–6). The output of one amplifier is fed into the input of another amplifier.

Another general rule for operating the 741 op amp is the total feedback resistance (R1 + R2) is kept at more than 1,000 ohms and less than 100,000 ohms. These rules apply to the 741 operational amplifier but may not apply to other operational amplifiers.

Basic Circuits

Op amps are generally used in three basic circuits that are used to build other circuits. One of these basic circuits is the voltage follower. In this circuit, the output of the op amp is connected directly back to the inverting input Figure 11–7. Since there is a direct

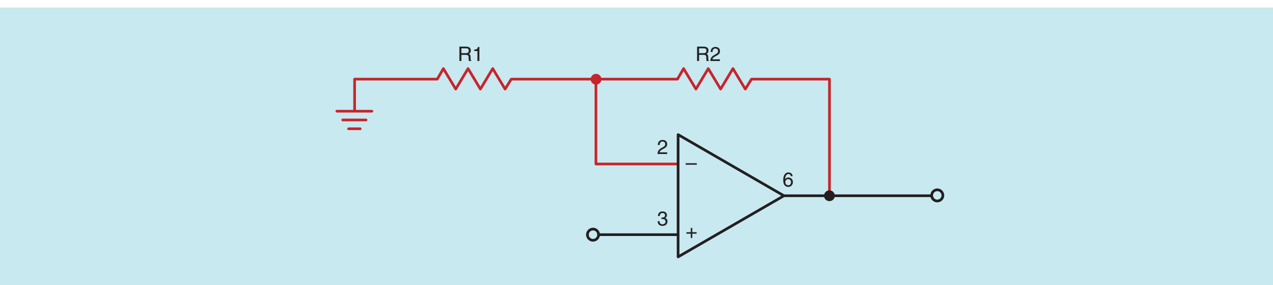


Figure 11–5 Negative feedback connection.

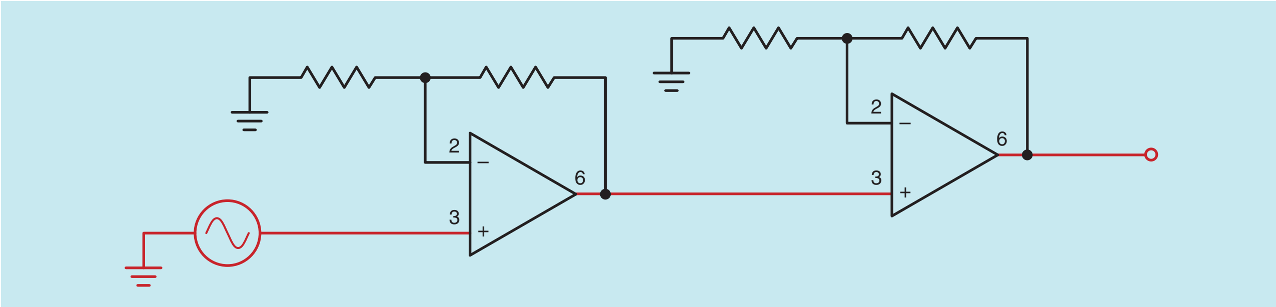


Figure 11–6 Two operational amplifiers are used to obtain a higher gain.

connection between the output of the amplifier and the inverting input, the gain of this circuit is 1. For example, if a signal voltage of .5 volts is connected to the noninverting input, the output voltage will be .5 volts also. You may wonder why anyone would want an amplifier that doesn't amplify. Actually, this circuit does amplify something. It amplifies the input impedance by the amount of the open loop gain. If the 741 has an open loop gain of 200,000 and an input impedance of 2 megohms, this circuit will give the amplifier an input impedance of 200 k × 2 meg or 400,000 megohms. This circuit connection is generally used for impedance matching purposes.

The second basic circuit is the noninverting amplifier (Figure 11–8). In this circuit, the output voltage has the same polarity as the input voltage. If the input voltage is positive, the output voltage will be positive also. The formula

$$\frac{R1 + R2}{R1}$$

is used to calculate the amount of gain in the negative feedback loop.

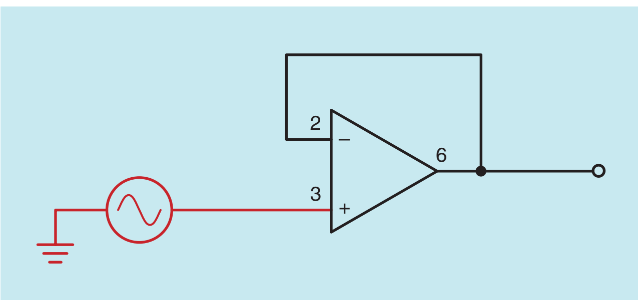


Figure 11–7 Voltage follower connection.

The third basic circuit is the inverting amplifier (Figure 11–9). In this circuit the output voltage is opposite in polarity to the input voltage. If the input signal is positive, the output voltage will be negative at the same instant in time. The formula

$$\frac{R2}{R1}$$

is used to calculate the amount of gain in this circuit.

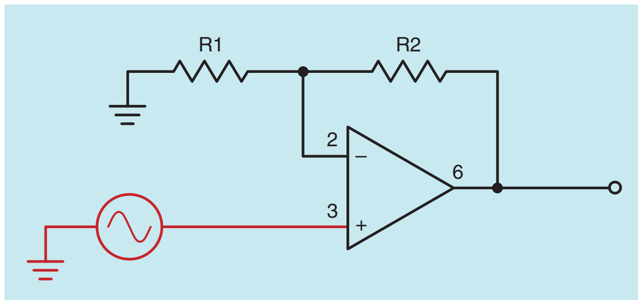


Figure 11–8 Noninverting amplifier connection.

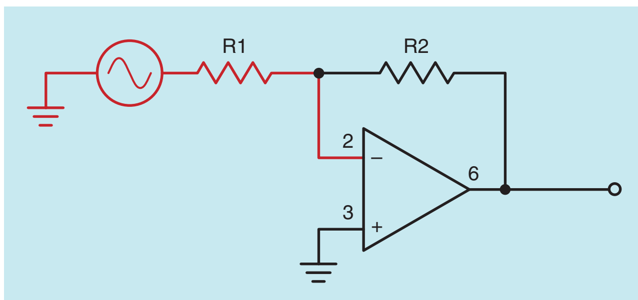


Figure 11–9 Inverting amplifier connection.

Circuit Applications

The Level Detector

The operational amplifier is often used as a level detector or comparator. In this type of circuit, the 741 op amp is used as an inverted amplifier to detect when one voltage becomes greater than another (Figure 11–10). This circuit does not use above and below ground power supplies. Instead, it is connected to a power supply that has a single positive and negative output.

During normal operation, the noninverting input of the amplifier is connected to a zener diode which produces a constant positive voltage at the noninverting input of the amplifier. This constant positive voltage is used as a reference. As long as the noninverting input is more positive than the inverting input, the output of the amplifier is high.

A light-emitting diode (LED), D1, is used to detect a change in the polarity of the output. As long as the output of the op amp is high, the LED is turned off. When the output of the amplifier is high, the LED has equal voltage applied to its anode and cathode. Since both the anode and cathode are connected to +12 volts, there is no potential difference and, therefore, no current flow through the LED.

If the voltage at the inverting input becomes more positive than the reference voltage applied to pin #3, the output voltage will fall to about +2.5 volts. The output voltage of the op amp will not fall to 0 or ground in this circuit because the op amp is not connected to a voltage that is below ground. To enable the output voltage to fall to 0 volts, pin #4 must be connected to a voltage below ground. When the output drops, a potential of about 9.5 volts (12 – 2.5 = 9.5) is produced across R1 and D1. The lowering of potential causes the LED to turn on, which indicates that the op amp's output has changed from high to low.

In this type of circuit, the op amp appears to be a digital device in that the output seems to have only two states, high and low. But, the op amp is not a digital device. This circuit only makes it appear to be digital. In figure 11–10, there is no negative feedback loop connected between the output and the inverting input. Therefore, the amplifier uses its open loop gain, which is about 200,000 for the 741, to amplify the voltage difference between the inverting input and the noninverting input. If the voltage applied to the inverting input becomes 1 millivolt more positive than the reference voltage applied to the noninverting input, the amplifier will try to produce an output that is 200 volts more negative than its high state voltage (.001 × 200,000 = 200). The output voltage of the amplifier cannot be driven 200 volts more negative, though, because only 12 volts are applied to the circuit. Therefore, the output voltage reaches the lowest voltage it can and goes into saturation. This causes the op amp to act like a digital device.

If the zener diode is replaced with a voltage divider as shown in Figure 11–11, the reference voltage can be set to any value by adjusting the variable resistor. For example, if the voltage at the noninverting input is set for 3 volts, the output of the op amp will go

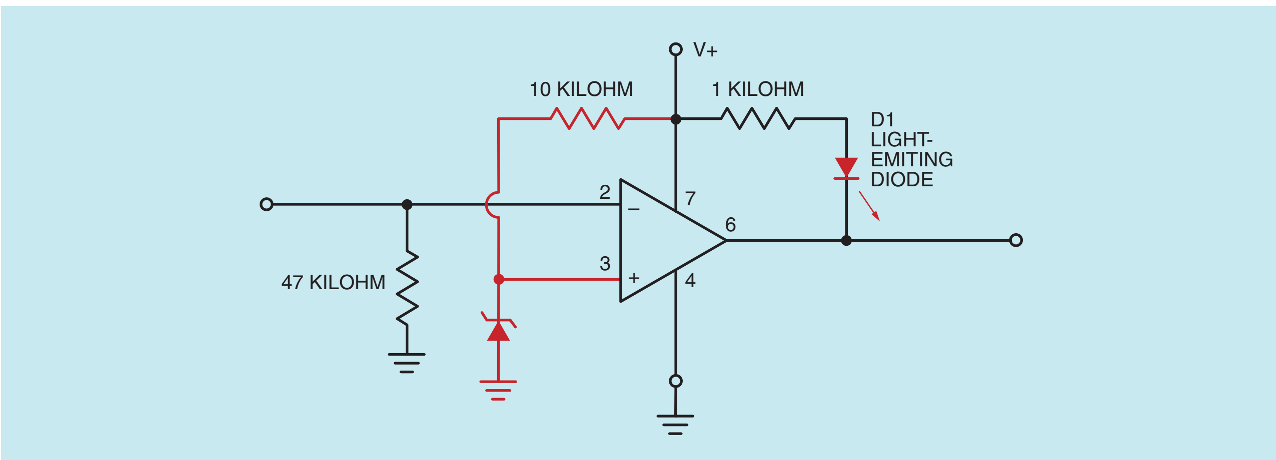


Figure 11–10 Inverting level detector.

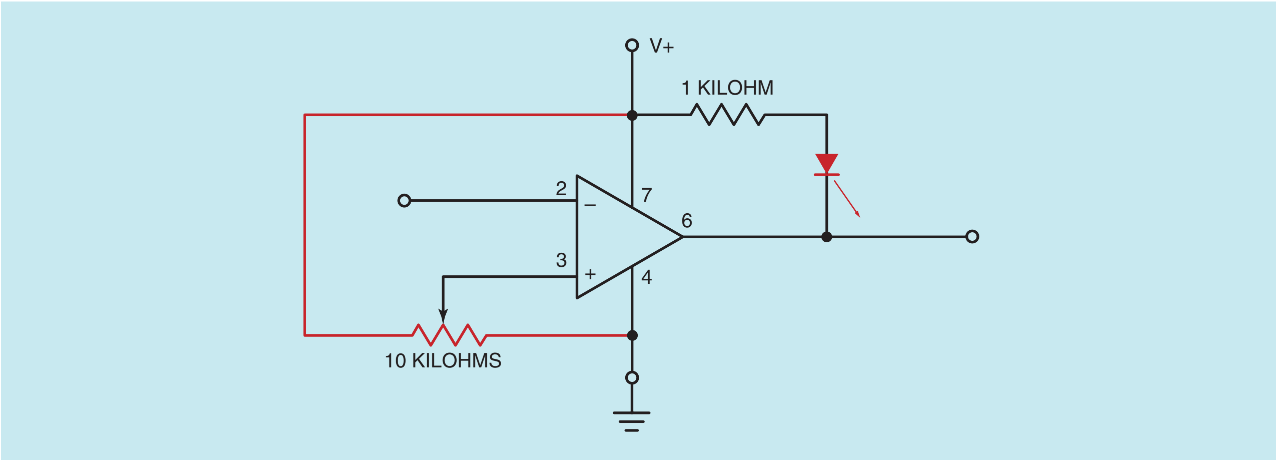


Figure 11–11 Adjustable inverting level detector.

low when the voltage applied to the inverting input becomes greater than +3 volts. If the voltage at the noninverting input is set for 8 volts, the output voltage will go low when the voltage applied to the inverting input becomes greater than +8 volts. In this circuit the output of the op amp can be manipulated through the adjustment of the noninverting input.

In the two circuits just described, the op amp's output shifted from a high level to a low level. There may be occasions, however, when the output must be changed from a low level to a high level. This can be accomplished by connecting the inverting input to the reference voltage, and the noninverting input to the voltage being sensed (Figure 11–12). In this circuit, the zener diode is used to supply a positive reference voltage to the inverting input. As long as the voltage at the inverting input is more positive than the voltage at the noninverting input, the output voltage of the op amp will be low. If the voltage applied to the noninverting input becomes more positive than the reference voltage, the output of the op amp will become high.

Depending on the application, this circuit could cause a small problem. As stated previously, since this circuit does not use an above and below ground power supply, the low output voltage of the op amp is about +2.5 volts. This positive output voltage could cause any other devices connected to the op amp's output to be on when they should be off. For instance, if the LED shown in Figure 11–12 is used, it will glow dimly even when the output is in the low state.

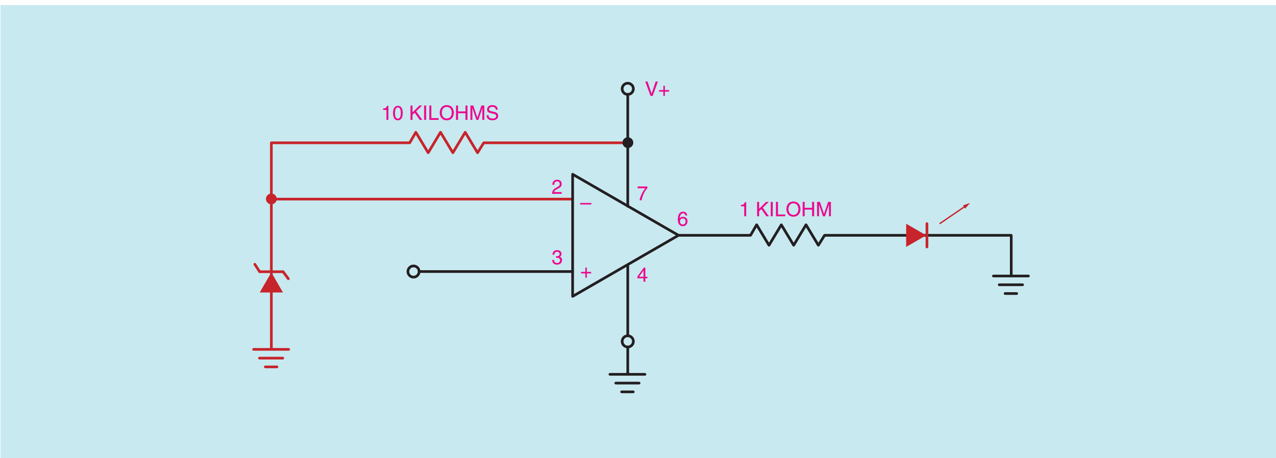


Figure 11–12 Noninverting level detector.

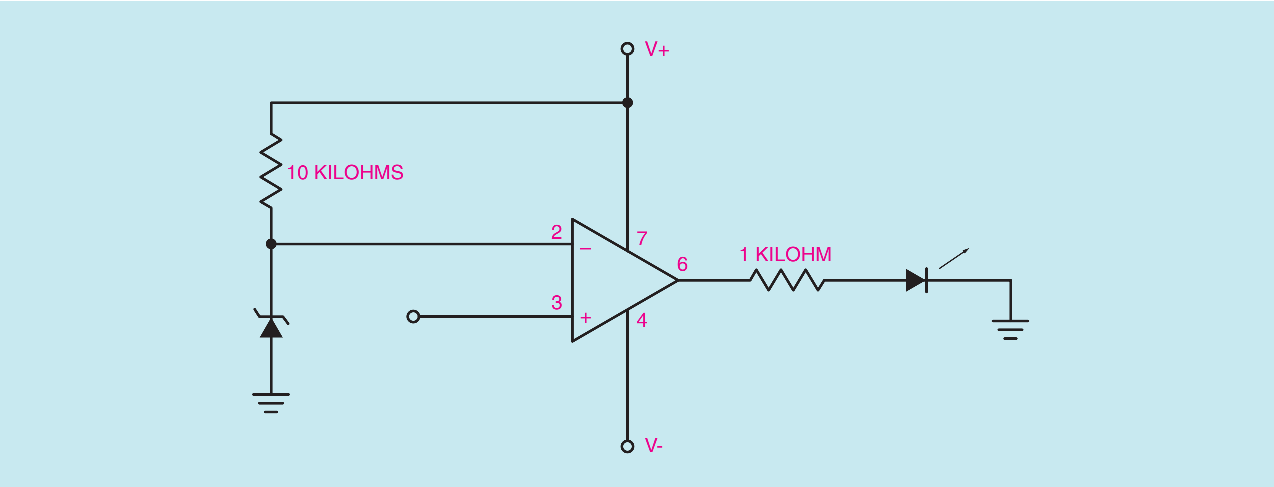


Figure 11–13 Below ground power connection permits the output voltage to become negative.

One way to correct this problem is to connect the op amp to an above and below ground power supply as shown in Figure 11–13. In this circuit, the output voltage of the op amp is negative or below ground as long as the voltage applied to the inverting input is more positive than the voltage applied to the noninverting input. When the output voltage of the op amp is negative with respect to ground, the LED is reverse biased and cannot operate. If the voltage applied to the noninverting input becomes more positive than the voltage applied to the inverting input, the output of the op amp will become positive and the LED will turn on.

Another method of correcting the output voltage problem is shown in Figure 11–14. In this circuit, the op amp is connected again to a power supply that has a single positive and negative out put. A zener diode, D2, is connected in series with the output of the op amp and the LED. The voltage value of diode D2 is greater than the output voltage of the op amp in its low state, but less than the output voltage of the op amp in its high state. For instance, assume that the value of zener diode D2 is 5.1 volts. If the output voltage of the op amp in its low state is 2.5 volts, diode D2 will not conduct. If the output voltage becomes +12 volts when the op amp

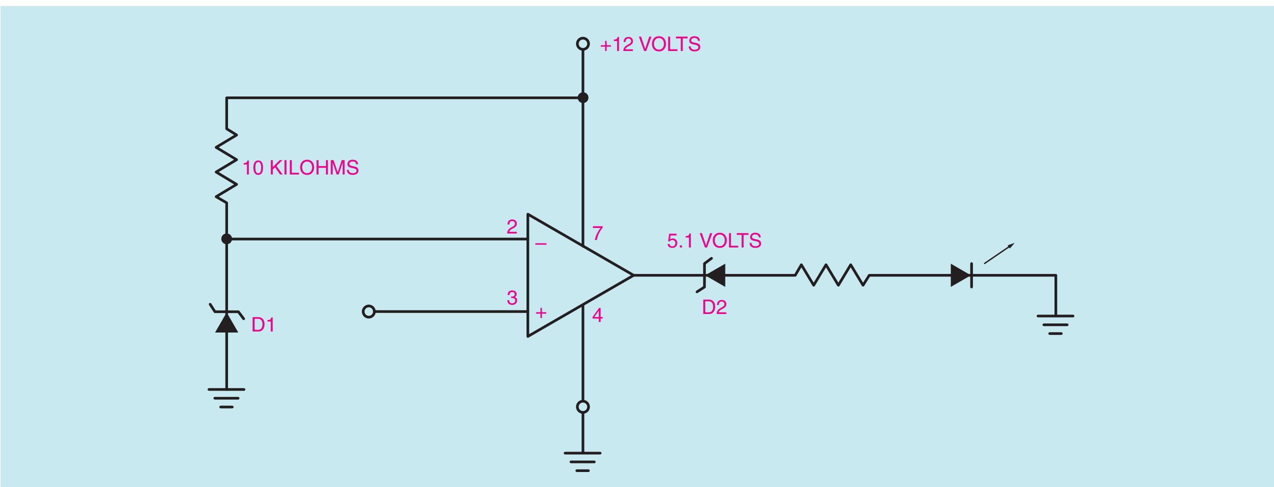


Figure 11–14 A zener diode is used to keep the output turned off.

switches to its high state, diode D2 will turn on and conduct current to the LED. The zener diode, D2, keeps the LED completely off until the op amp switches to its high state providing enough voltage to overcome the reverse voltage drop of the zener diode.

In the preceding circuits, an LED was used to indicate the output state of the amplifier. Keep in mind that the LED is used only as a detector, while the output of the op amp can be used to control almost anything. For example, the output of the op amp can be connected to the base of a transistor as shown in Figure 11–15. The transistor can then control the coil of a relay which could, in turn, control almost anything.

The Oscillator

The operational amplifier can be used as an oscillator. The simple circuit shown in Figure 11–16 produces a square wave output. However, this circuit is impractical because it depends on a slight imbalance in the op amp, or random circuit noise to start the oscillator. A voltage difference of a few millivolts between the two inputs is all that is needed to raise or lower the output of the amplifier. For example, if the inverting input becomes slightly more positive than the noninverting input, the output will go low or become negative. When the output is negative, capacitor CT charges through

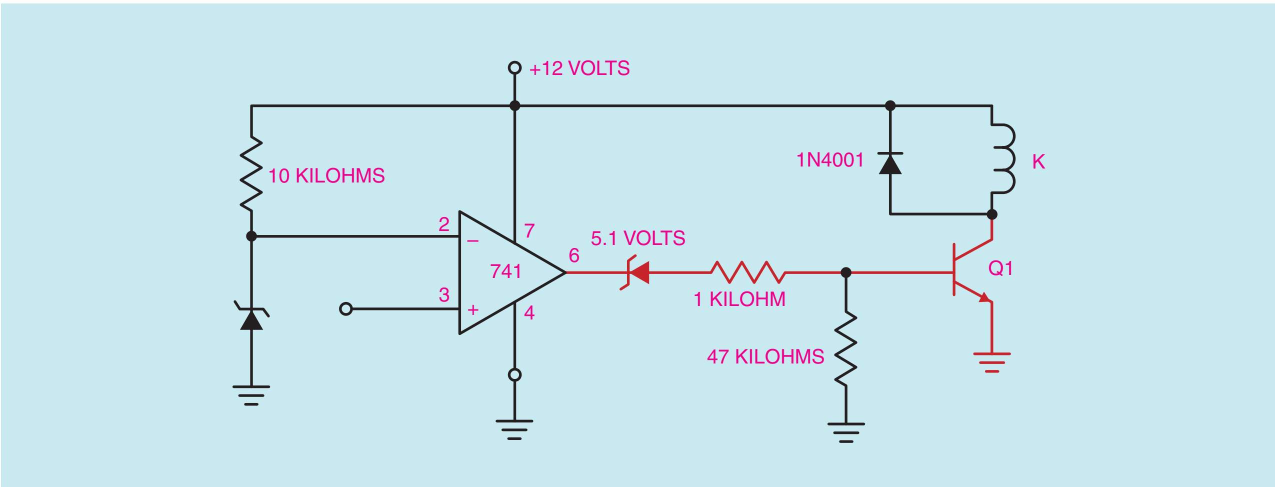


Figure 11–15 The operational amplifier supplies the base current for a switching transistor.

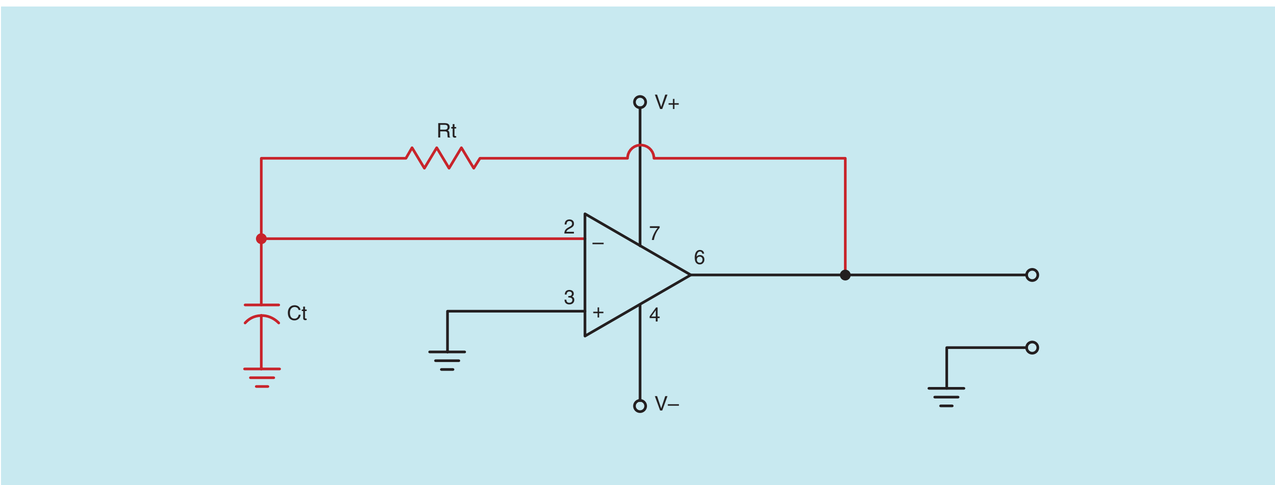


Figure 11–16 A simple square wave oscillator.

resistor RT to the negative value of the output voltage. When the voltage applied to the inverting input becomes slightly more negative than the voltage applied to the noninverting input, the output changes to a high, or positive, value of voltage. When the output is positive, capacitor CT charges through resistor RT toward the positive output voltage.

This circuit would work well if there were no imbalance in the op amp, and if the op amp were shielded from all electrical noise. In practical application, however, there is generally enough imbalance in the amplifier or enough electrical noise to send the op amp into saturation, which stops the operation of the circuit.

The problem with this circuit is that a millivolt difference between the two inputs is enough to drive the amplifier's output from one state to the other. This problem can be corrected by the addition of a hysteresis loop connected to the noninverting input as shown in Figure 11–17. Resistors R1 and R2 form a voltage divider for the noninverting input. These resistors generally have equal value. To understand the circuit operation, assume that the inverting input is slightly more positive than the noninverting input. This causes the output voltage to be negative. Also assume that the output voltage is negative 12 volts as compared to ground. If resistors R1 and R2 have equal value, the noninverting input is driven to −6 volts by the voltage divider. Capacitor CT begins to charge through resistor RT to the value of the output voltage. When capacitor CT has been charged to a value slightly more negative than the −6 volts applied to the noninverting input, the op amp's output rises to +12 volts above ground. When the output of the op amp changes from −12 volts to +12 volts, the voltage applied to the noninverting input changes from −6 volts to +6 volts. Capacitor CT now begins to charge through resistor RT to the positive voltage of the output. When the voltage applied to the inverting input becomes more positive than the voltage applied to the noninverting input, the output changes to −12 volts. The voltage applied to the noninverting input is driven from +6 volts to −6 volts, and capacitor CT again begins to charge toward the negative output voltage of the op amp.

The addition of the hysteresis loop has greatly changed the operation of the circuit. The voltage differential between the two inputs is now volts instead of millivolts. The output frequency of the oscillator is determined by the values of CT and RT. The period of one cycle can be computed by using the formula T = 2RC.

The Pulse Generator

The operational amplifier can be used as a pulse generator. The difference between an oscillator and a pulse generator is the period of time the output is on compared to the period of time it is low or off. For instance, an oscillator is generally considered to produce a waveform that has positive and negative pulses of equal voltage and time (Figure 11–18). The positive value of voltage is the same as the negative value, and the positive and negative cycles are turned on for the same amount of time. This waveform is produced when

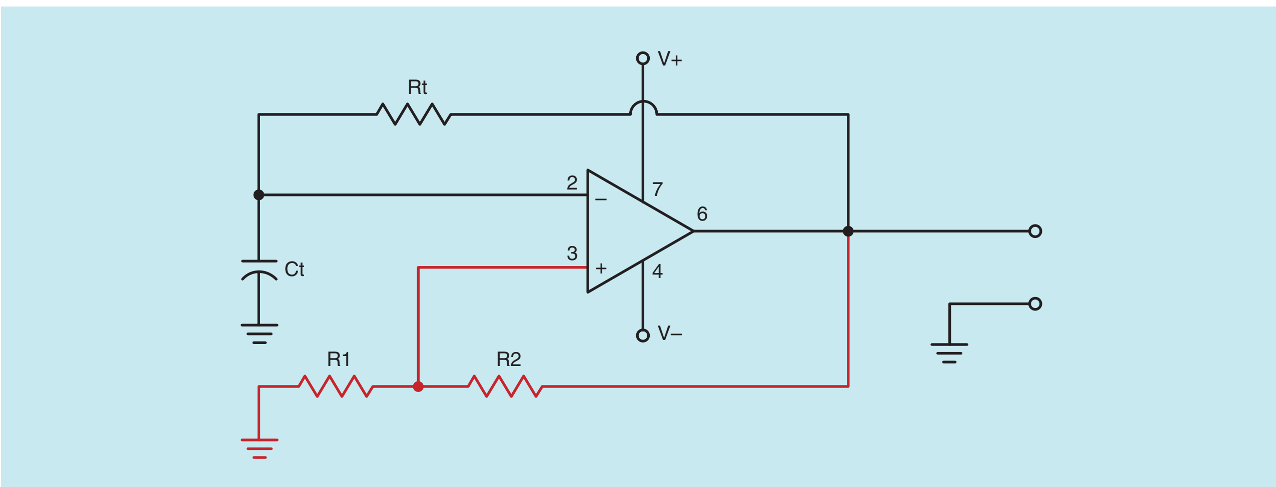


Figure 11–17 A square wave oscillator using a hysteresis loop.

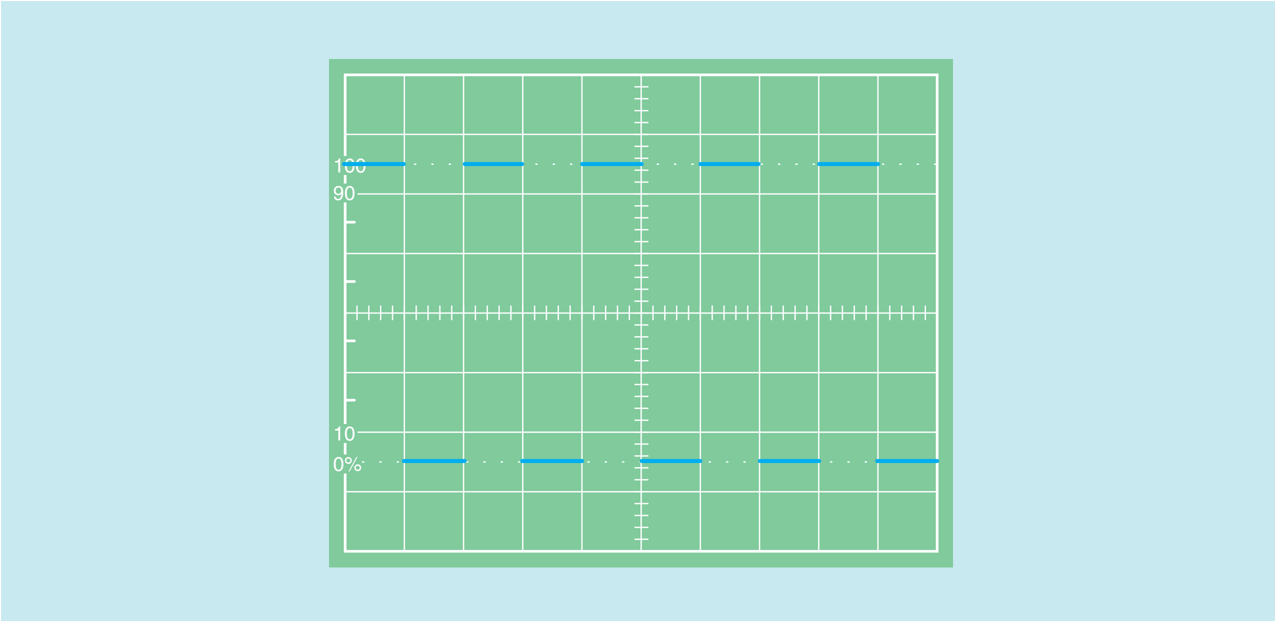


Figure 11–18 Output of an oscillator. (Reproduced by permission of Tektronix, Inc., copyright © 1983.)

an oscilloscope is connected to the output of a square wave oscillator.

If the oscilloscope is connected to a pulse generator, however, a waveform similar to the one shown in Figure 11–19 will be produced. The positive value of voltage is the same as the negative value just as it was in Figure 11–18, but the positive pulse is of a much shorter duration than the negative pulse.

The 741 operational amplifier can easily be changed from a square wave oscillator to a pulse generator (Figure 11–20). The pulse generator circuit is the same basic circuit as the square wave oscillator with the

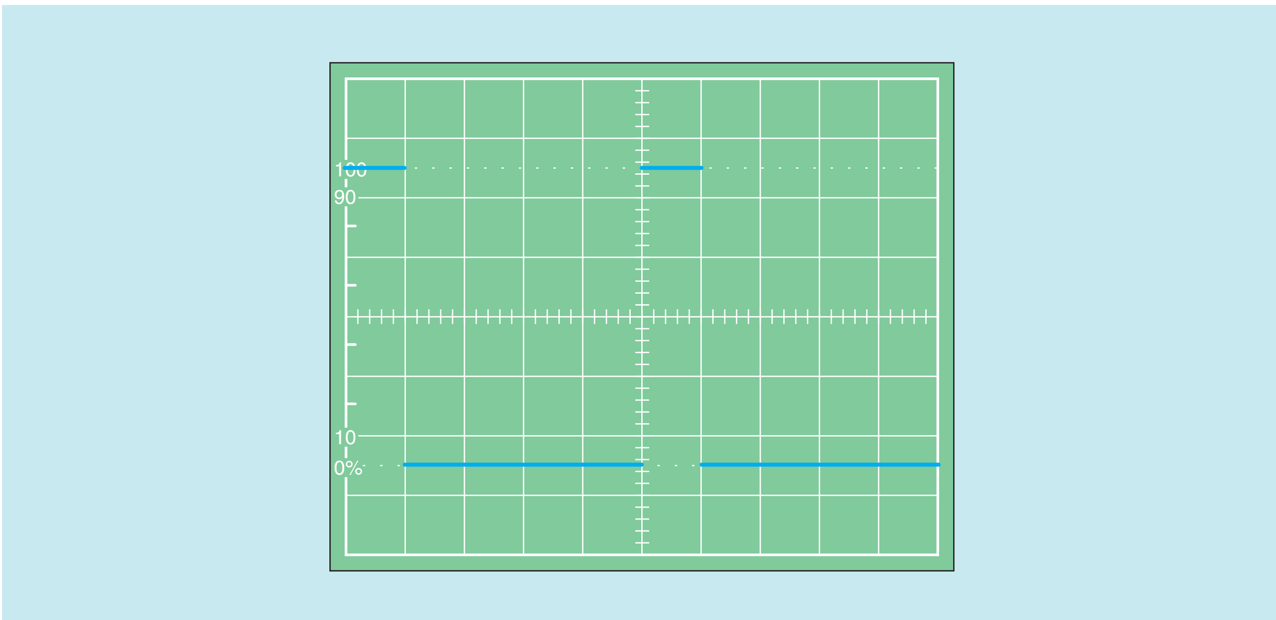


Figure 11–19 Output of a pulse generator. (Reproduced by permission of Tektronix, Inc., copyright © 1983.)

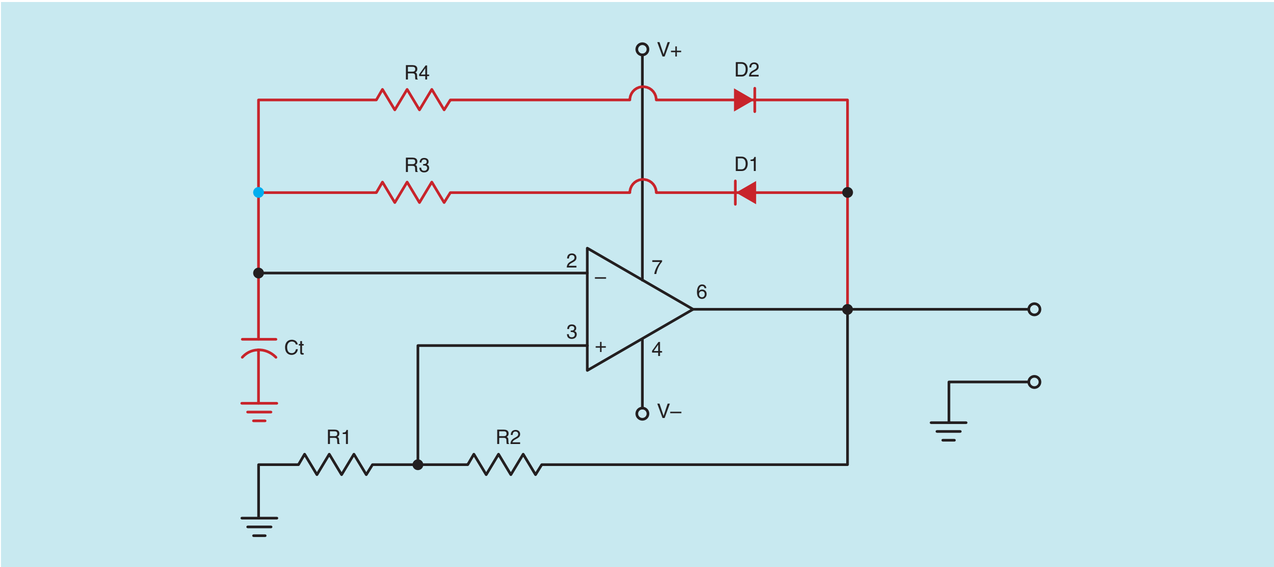


Figure 11–20 Pulse generator circuit.

addition of resistors R3 and R4, and diodes D1 and D2. This circuit permits capacitor CT to charge at a different rate when the output is high, or positive, than when the output is low, or negative. For instance, assume that the voltage of the op amp's output is −12 volts. When the output voltage is negative, diode D1 is reverse biased and no current can flow through resistor R3. Therefore, capacitor CT must charge through resistor R4 and diode D2 which is forward biased. When the voltage applied to the inverting input becomes more negative than the voltage applied to the noninverting input, the output voltage of the op amp rises to +12 volts. When the output voltage is +12 volts, diode D2 is reverse biased and diode D1 is forward biased. Therefore, capacitor CT begins charging toward the +12 volts through resistor R3 and diode D1. The amount of time the output of the op amp is low is determined by the value of CT and R4, and the amount of time the output remains high is determined by the value of CT and R3. The ratio of the amount of time the output voltage is high to the amount of time it is low can be determined by the ratio of resistor R3 to resistor R4.

Review Questions

1. When the voltage connected to the inverting input is more positive than the voltage connected to the noninverting input, will the output be positive or negative?
2. What is the input impedance of a 741 operational amplifier?
3. What is the average open loop gain of the 741 operational amplifier?
4. What is the average output impedance of the 741 operational amplifier?
5. Operational amplifiers are commonly used in what three connections?
6. When the operational amplifier is connected as a voltage follower, it has a gain of 1 (one). If the input voltage is not amplified, what is?
7. Name two effects of negative feedback.
8. Refer to Figure 11–8. If resistor R1 is 200 ohms and resistor R2 is 10 kilohms, what is the gain of the amplifier?
9. Refer to Figure 11–9. If resistor R1 is 470 ohms and resistor R2 is 47 kilohms, what is the gain of the amplifier?
10. What is the purpose of the hysteresis loop when the op amp is used as an oscillator?

Section 2

MOTOR STARTERS AND PILOT DEVICES

UNIT 12

FRACTIONAL AND INTEGRAL HORSEPOWER MANUAL MOTOR STARTERS

OBJECTIVES

After studying this unit, the student will be able to:

- Match simple schematic diagrams with the appropriate manual motor starters.
- Connect manual fractional horsepower motor starters for automatic and manual operation.
- Connect integral horsepower manual starters.
- Explain the principles of operation of manual motor starters.
- List common applications of manual starters.
- Read and draw simple schematic diagrams.
- Briefly explain how motors are protected electrically.

Fractional Horsepower Manual Motor Starters

One of the simplest types of motor starters is an on-off, hand-operated, snap action switch. A toggle lever is mounted on the front of the starter (Figure 12–1). The motor is connected directly across the line voltage when the handle is turned to the START position. This situation usually is not objectionable with motors rated at one horsepower (hp) or less. Since a motor may draw up to a 600% current surge on starting, larger motors should not be connected directly across the line on start-up. Such a connection would result in large line surges that may disrupt power services or cause voltage fluctuations that impede the normal operation of other equipment. Proper motor starters for larger motors are discussed later.

Fractional horsepower (FHP = 1hp or less) manual motor starters are used whenever it is desired to provide

Figure 12–1 Open-type manual starter with overload protection for use with single-phase motors. This resembles a light switch with an overload heater attached. (Courtesy Square D Company.)

overload protection for a motor as well as "off" and "on" control of small ac single-phase or dc motors. Electrical codes require that fractional horsepower motors be provided with overload protection whenever they are started automatically or by remote control. Basically, a manual starter is an *on-off* switch with motor overload protection.

Since manual starters are hand-operated mechanical devices (requiring no electrical coil), the contacts remain closed and the lever stays in the ON position in the event of a power failure. As a result, the motor automatically restarts when the power returns. Therefore, low-voltage protection is not possible with manually operated starters. This automatic restart action is an advantage when the starter is used with motors that run continuously, such as those used on unattended pumps, blowers, fans, and refrigeration processes. This saves the maintenance electrician from running around the plant to restart all these motors after the power returns. On the other hand, the automatic restart feature is a disadvantage on lathes and machines that may be a danger to products, machinery, or people. It is definitely a safety factor to be observed.

The compact construction of the manual starter means that it requires little mounting space and can be installed on the driven machinery and in various other places where the available space is limited. The unenclosed, or open starter, can be mounted in a standard switch or conduit box installed in a wall and can be covered with a standard flush, single-gang switchplate. The ON and OFF positions are clearly marked on the operating lever, which is very similar to a standard lighting toggle switch lever (Figure 12–1).

Application

Fractional horsepower manual starters have thermal overload protection (Figures 12–1 and 12–2). When an overload occurs, the starter handle automatically moves to the center position to signify that the contacts have opened and the motor is no longer operating. The starter contacts cannot be reclosed until the overload relay is reset manually. The relay is reset by moving the handle to the full OFF position after allowing about two minutes for the heater to cool. Should the circuit trip open again, the fault should be located and corrected.

Fractional horsepower manual starters are provided in several different types of enclosures as well as the open type to be installed in a switch-box, flush in the wall, or on the surface. Enclosures are obtained to shield the live starter circuit components from accidental contact, for mounting in machine cavities, to protect

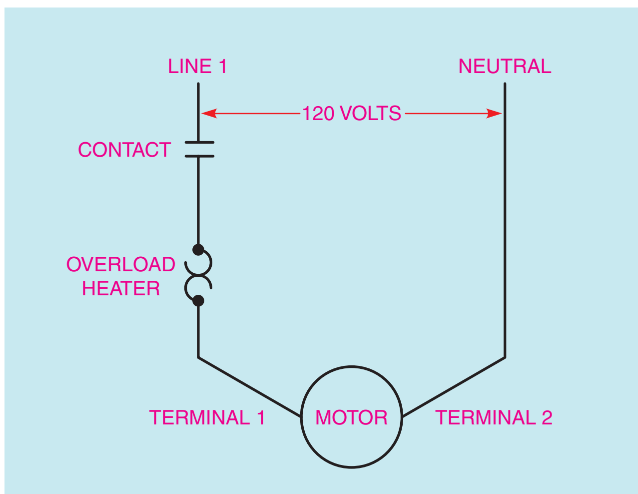


Figure 12–2 Diagram of single-pole manual starter shown in Figure 12–1.

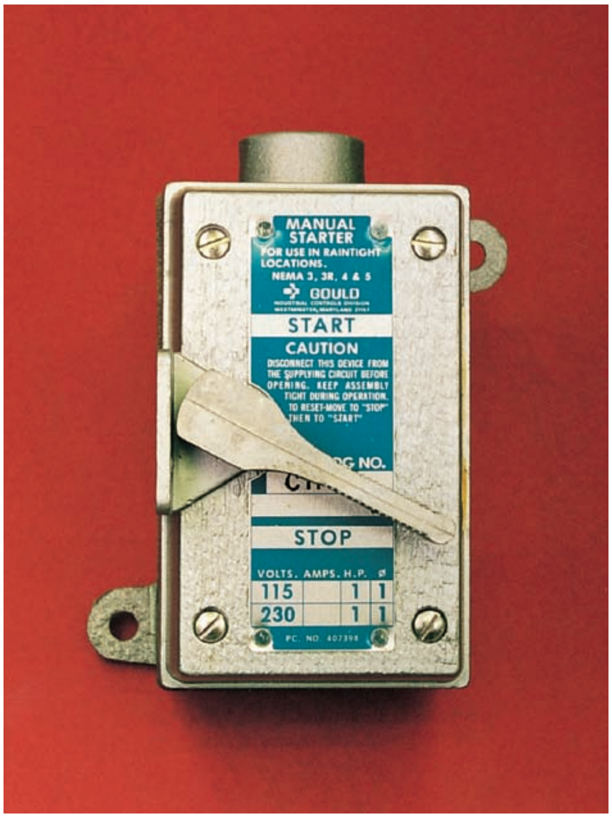


Figure 12–3 Watertight and dusttight manual starter enclosure.

the starter from dust and moisture (Figure 12–3) or to prevent the possibility of an explosion when the starter is used in hazardous locations. These different types of enclosures will be discussed in more detail in Unit 13.

Automatic and Remote Operation

Common applications of manual starters provide control of small machine tools, fans, pumps, oil burners, blowers, and unit heaters. Almost any small motor should be controlled with a starter of this type. However, the contact capacity of the starter must be sufficient to make and break the full motor current. Automatic control devices such as pressure switches, float switches, or thermostats rated to carry motor current may be used with fractional horsepower manual starters.

The schematic diagram shown in Figure 12–4 illustrates a fractional horsepower motor controlled automatically by a float switch that is remotely connected in the small motor circuit as long as the manual starter contact is closed. When the float is up, the pump motor starts.

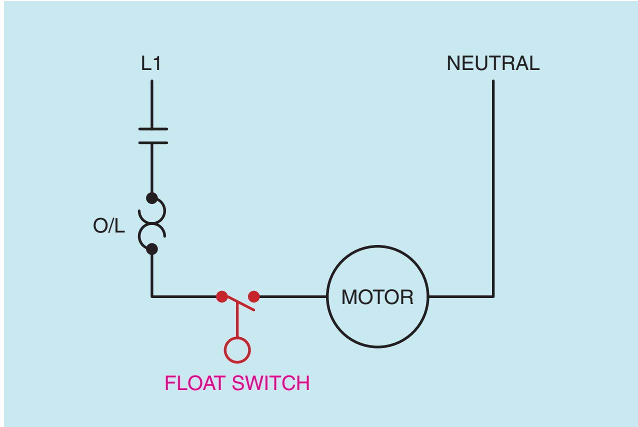


Figure 12–4 Automatic control with FHP-single-pole, single-phase manual starter for fractional hp motor without selector switch.

In Figures 12–5 and 12–6, the selector switch must be turned to the automatic position if the float switch is to take over an automatic operation, such as sump pumping. A liquid-filled sump raises the float, closes the normally open electrical contact, and starts the motor. When the motor pumps the sump or tank empty, the float lowers and breaks electrical contact with the motor thus stopping the motor. This cycle of events will repeat when the sump fills again, automatically, without a human operator.

Note that a double-pole starter is used in Figure 12–5. This type of starter is required when both lines to the motor must be broken such as for 230 volts,

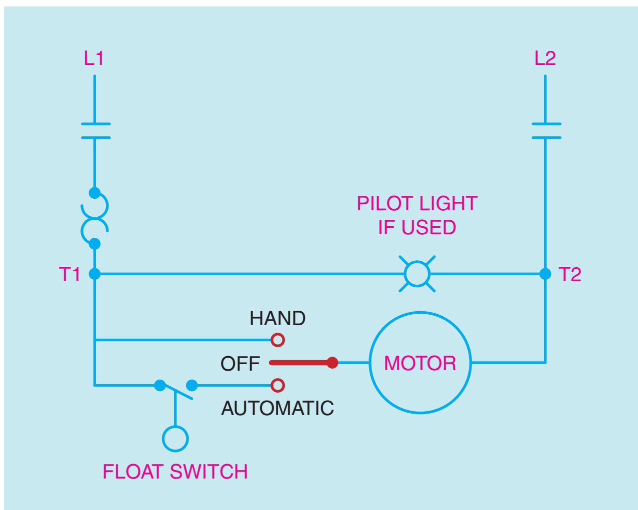


Figure 12–5 Manual FHP-double-pole, single-phase starter with automatic control for fractional hp motor using selector switch (see Figure 12–6).

Figure 12–6 Selector switch with manual-off-automatic.

Figure 12–7 Three-phase line voltage manual starter. No low voltage protection. (Courtesy Square D Company.)

single phase. The double-pole starter is also recommended for heavy-duty applications because of its higher interrupting capacity and longer contact life, when using a two-pole motor starter on 115 volts. Normally, the single-pole motor starter is used for 115 volts.

Manual Push-Button Line Voltage Starters

Manual push-button line voltage starters are integral horsepower motor starters (not fractional). Generally, manual push-button starters may be used to control single-phase motors rated up to 5 hp, polyphase motors rated up to 10 hp and dc current motors rated up to 2 hp. They are available in two-pole for single-phase and three-pole for polyphase motors. A typical manual three-phase push-button starter and diagram are shown in Figures 12–7 and 12–8.

When an overload relay trips, the starter mechanism unlatches, opening the contacts to stop the motor. The contacts cannot be reclosed until the starter mechanism has been reset by pressing the STOP button, after allowing time for the thermal unit to cool.

These starters are designed for infrequent starting of small ac motors. This manual starter provides overload protection also, but cannot be used where low or undervoltage protection is required or for remote or automatic operation.

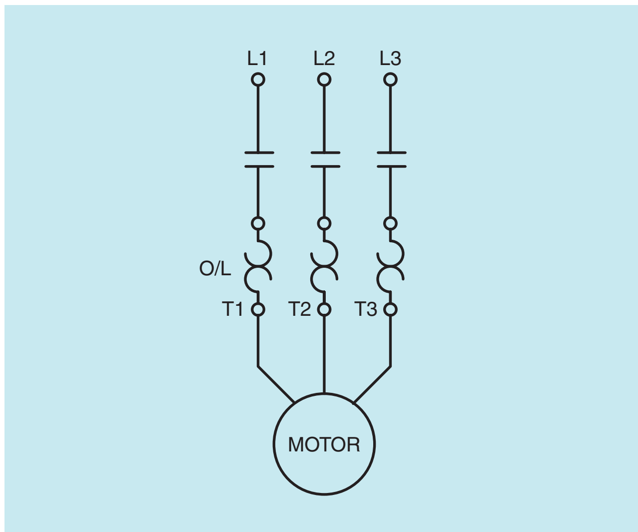


Figure 12–8 Wiring diagram for the three-pole line voltage, push-button manual starter seen in Figure 12–7.

Manual Starter with Low Voltage Protection

Integral horsepower manual starters with low voltage protection (LVP) prevent automatic start-up of motors after a power loss. This is accomplished with a continuous-duty electrical solenoid which is energized whenever the line-side voltage is present (Figure 12–9A and Figure 12–9B). If the line voltage

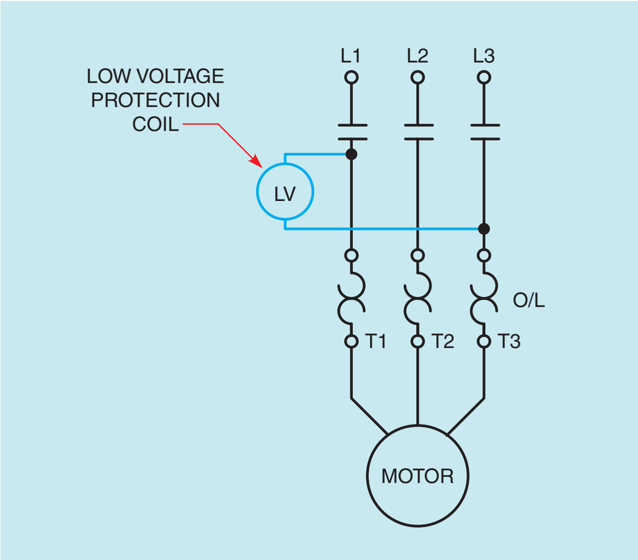


Figure 12–9A Wiring diagram for integral hp manual starter with low-voltage protection.

Figure 12–9B Manual starter with low voltage protection. (Courtesy Square D Company.)

is lost or disconnected, the solenoid de-energizes, opening the starter contacts. The contacts will not automatically re-close when the line voltage is restored. To close the contacts to restart the motor again, the device must be manually reset. This manual starter will not function unless the line terminals are energized. This starter should not be confused with magnetic starters described in the next unit. This is *not* a magnetic starter, but a lower cost starter.

Applications

Typical applications include conveyor lines, grinders, metal working machinery, mechanical power presses, mixers, woodworking machinery and wherever job specifications and standards require low-voltage protection, or wherever machine operator safety could be in jeopardy.

Therefore, this manually operated, push-button starter with low-voltage protection is a method of protecting an operator from injury using automatic restart of a machine upon resumption of voltage, after a power failure. This is normally accomplished with a magnetic starter with electrical (three-wire) control.

Thermal Overload Protection

Thermal overload units are widely used on both the fractional and integral horsepower manual starters for protection of motors from sustained electrical overcurrents that could result from overloading of the driven machine or from excessively low line voltage.

Heater elements that are closely calibrated to the full load current of the motor are used on the solder-pot and the thermo-bimetallic types of overload relays. On the solder-pot overload relays, the heating of the element causes alloy elements to melt when there is a motor overload due to excess current in the circuit. When the alloy melts, a spring-loaded ratchet is rotated and trips open a contact which then opens the supply circuit to the motor starter coil. This stops the motor. On the bimetallic overload relays, the heating from the thermal element causes the bimetallic switch to open, opening the supply circuit and thereby stopping the motor.

Normal motor starting currents and momentary overloads will not cause thermal relays to trip because of their inverse-time characteristics. However, continuous overcurrent through the heater unit raises the temperature of the alloy elements. When the melting point is reached, the ratchet is released and the switch mechanism is tripped to open the line or lines to the motor. The switch mechanism is trip-free, which means that it is impossible to hold the contacts closed against an overload.

Only one overload relay is required in either the single-pole or double-pole motor starter, since the starter is intended for use on dc or single-phase ac service. When the line current is excessively high, these relays offer protection against continued operation. Relays with meltable alloy elements are nontemperable and give reliable overload protection. Repeated

tripping does not cause deterioration nor does it affect the accuracy of the trip point.

Many types of overload relay heater units are available so that the proper one can be selected on the basis of the actual full-load current rating of the motor. The applicable relay heater units for a particular overload relay are interchangeable and are accessible from the front of the starter. Since the motor current is connected in series with the heater element, the motor will not operate unless the relay unit has the heater installed. Overload units may be changed without disconnecting the wires from the starter or removing the starter from the enclosure. However, the disconnect switch and starter should be turned off first for safety reasons. Additional instruction on motor overload protection is given in Unit 13.

Review Questions

1. If the contacts on a manual starter cannot be closed immediately after a motor overload has tripped them open, what is the probable reason?
2. If the handle of an installed motor starter is in the center position, what condition does this indicate?
3. How may a manual starter be installed or used for an automatic operation?
4. What does trip-free mean?
5. If overload heating elements are not installed in the starter, what is the result?

Select the *best* answer for each of the following.

6. A fractional horsepower manual motor starter
   a. starts and stops motors under one horsepower
   b. has a toggle switch type of handle and size
   c. has no low-voltage protection
   d. does all of these
7. An automatic operation is used with
   a. integral hp manual starters
   b. push-button manual starters
   c. FHP manual starters with a pressure switch
   d. fractional horsepower manual starters
8. Normally, low voltage (or under voltage) protection is achieved with
   a. a push-button manual starter
   b. a toggle switch handle starter
   c. both a and b
   d. a push-button manual starter with energized coil
9. Low voltage protection is used mainly for
   a. fans
   b. air compressors
   c. pumps
   d. protection of the operator
10. Thermal overload protection
    a. aids motor warm-up
    b. prevents motors from freezing
    c. protects motors and conductors from mechanical damage
    d. provides electrical protection of motors

UNIT 13
MAGNETIC LINE VOLTAGE STARTERS

OBJECTIVES

After studying this unit, the student will be able to:

- Identify common magnetic motor starters and overload relays.
- Describe the construction and operating principles of magnetic switches.
- Describe the operating principle of a solenoid.
- Troubleshoot magnetic switches.
- Select starter protective enclosures for particular applications.

Magnetic control means the use of electromagnetic energy to close switches. Line voltage (across the line) magnetic starters are electromechanical devices that provide a safe, convenient, and economic means of full voltage starting and stopping motors. In addition, these devices can be controlled remotely. They are used when a full-voltage starting torque may be applied safely to the driven machinery and when the current inrush resulting from across-the-line starting is not objectionable to the power system. Control for these starters is usually provided by pilot devices such as push buttons, float switches, timing relays, and more as discussed in Section 3. Automatic control is obtained from the use of some of these pilot devices.

Magnetic vs. Manual Starters

Using manual control, the starter must be mounted so that it is easily within reach of the machine operator. With magnetic control, pushbutton stations are mounted nearby, but automatic control pilot devices can be mounted almost anywhere on the machine. The push buttons and automatic pilot devices can be connected by control wiring into the coil circuit of a remotely mounted starter, possibly closer to the motor to shorten the power circuit.

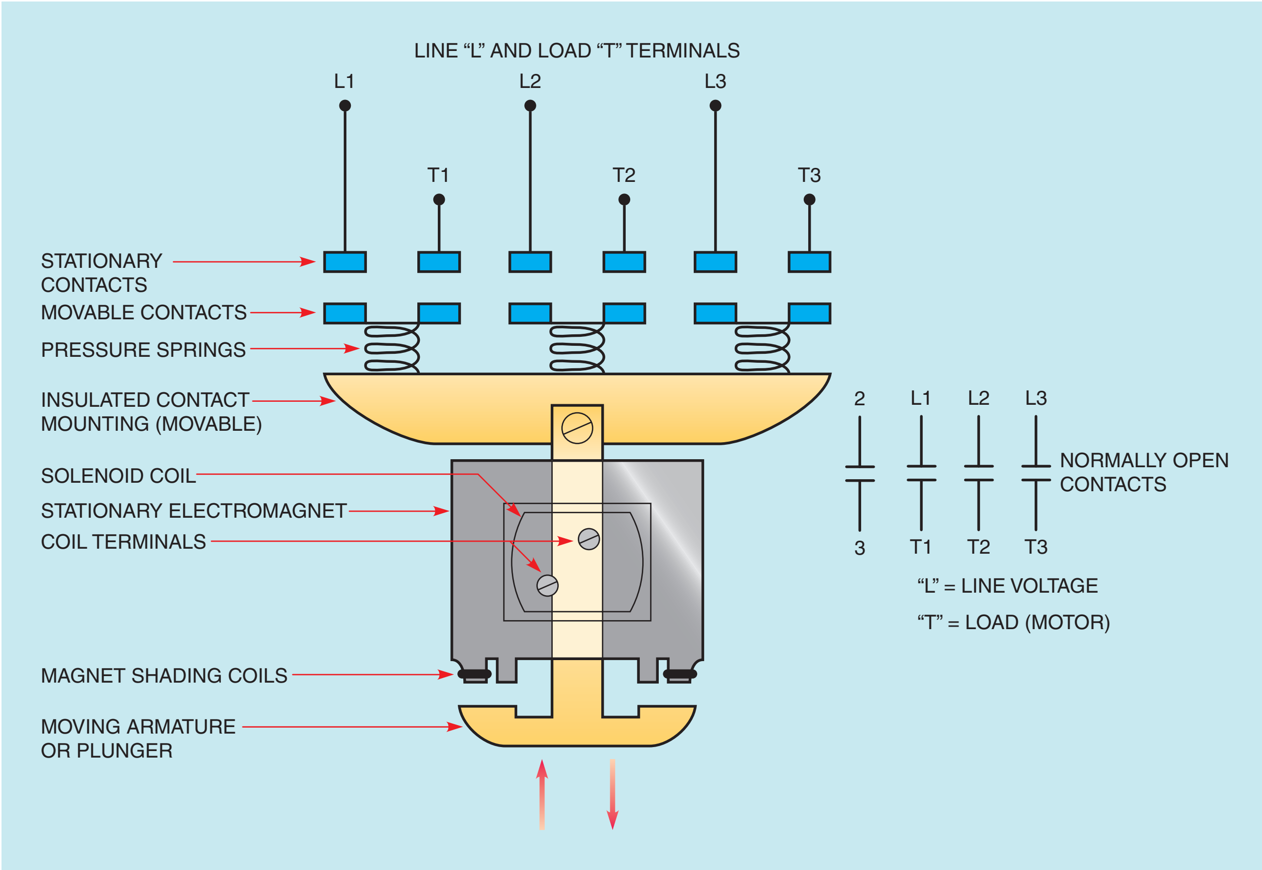


Figure 13–1 Three-pole, solenoid-operated magnetic switch (contactor) and electrical wiring symbols.

Operation

In the construction of a magnetic controller, the armature is mechanically connected to a set of contacts so that, when the armature moves to its closed position, the contacts also close. There are different variations and positions, but the operating principle is the same.

The simple up-and-down motion of a solenoid-operated, three-pole magnetic switch is shown in Figure 13–1. Not shown are the motor overload relays. Double break contacts are used on this type of starter to cut the voltage in half on each contact, thus providing high arc rupturing capacity and longer contact life.

Starter Electromagnets

The operating principle that makes a magnetic starter different from a manual starter is the use of an electromagnet. Electrical control equipment makes extensive use of a device called a solenoid. This electromechanical device is used to operate motor starters, contactors, relays, and valves. By placing a coil of many turns of wire around a soft iron core, the magnetic flux set up by the energized coil tends to be concentrated; therefore, the magnetic field effect is strengthened. Since the iron core is the path of least resistance to the magnetic lines of force, magnetic attraction concentrates according to the shape of the magnet core.

There are several different variations in design of the basic solenoid magnetic core and coil. Figure 13–2 shows a few examples. As shown in the solenoid design of Figure 13–2C, linkage to the movable contacts assembly is obtained through a hole in the movable plunger. The plunger is shown in the open de-energized position.

The center leg of each of the E-shaped magnet cores in Figures 13–2B and C is ground shorter than the outside legs to prevent the magnetic switch from accidentally staying closed (due to residual magnetism) when power is disconnected.

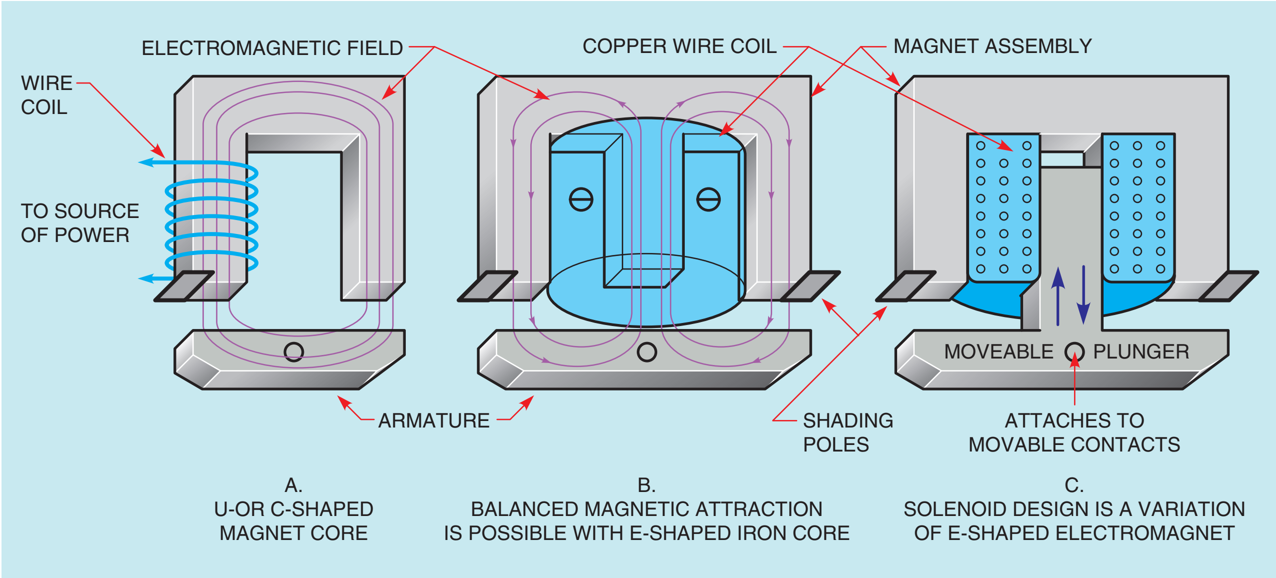


Figure 13–2 Some variations of basic magnet core and coil configurations of electromagnets.

Figure 13–3 shows a manufactured magnet structure and how the starter contacts are mounted on the armature.

When a magnetic motor starter coil is energized and the armature has sealed in, it is held tightly against the magnet assembly. A small air gap is always deliberately placed in the center leg, iron circuit. When the coil is de-energized, a small amount of magnetism remains. If it were not for this gap in the iron circuit, the residual magnetism might be enough to hold the moveable armature in the sealed-in position. This knowledge can be important to the electrician when troubleshooting a motor that will not stop.

The OFF or OPEN position is obtained by de-energizing the coil and allowing the force of gravity or spring tension to release the plunger from the magnet body, thereby opening the electrical contacts. The actual contact surfaces of the plunger and core body are machine ground to ensure a high degree of flatness on the contact surfaces so that operation on alternating current is quieter. Improper alignment of the contacting surfaces and foreign matter between the surfaces may cause a noisy hum on ac magnets.

Another source of noise is loose laminations. The magnet body and plunger (armature) are made up of thin sheets of iron laminated and riveted together to reduce *eddy currents* and hysteresis, iron losses showing up as heat (Figure 13–4). Eddy currents are shorted currents induced in the metal by the transformer action of an ac coil. Although these currents are small, they heat up the metal, create an iron loss, and contribute to inefficiency. At one time, laminations in magnets were insulated from each other by a thin, nonmagnetic coating; however, it was found that the normal oxidation of the metallic laminations reduces the effects of eddy currents to a satisfactory degree, thus eliminating the need for a coating.

Hysteresis losses are caused by molecular friction. When alternating current is connected to a coil, the magnetic field around the coil continually changes in intensity and direction. When the voltage is positive, the magnetic field will be either north or south. When

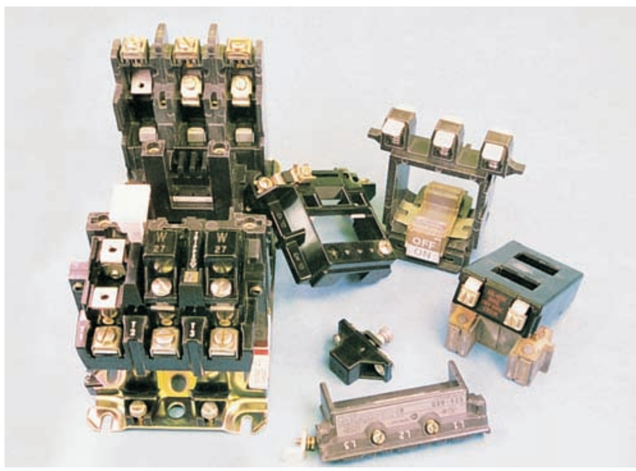


Figure 13–3 Structure of a three-phase motor starter.

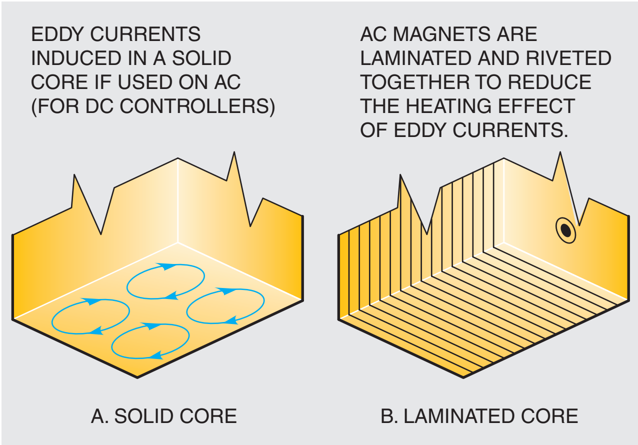


Figure 13–4 Types of magnet cores.

the voltage becomes negative, the polarity of the field also changes. This continuous changing of the magnetic field causes the molecules in the metal core to continually change directions. The friction of molecular motion produces heat. The amount of heat produced is proportional to magnetic field strength and frequency. The higher the frequency, the greater the amount of heat produced.

Shaded Pole Principle

The shaded pole principle is used to provide a time delay in the decay of flux in dc coils, and to prevent chatter and wear in the moving parts of ac magnets. Figure 13–5 shows a copper band or short-circuited coil (shading coil) of low resistance connected around

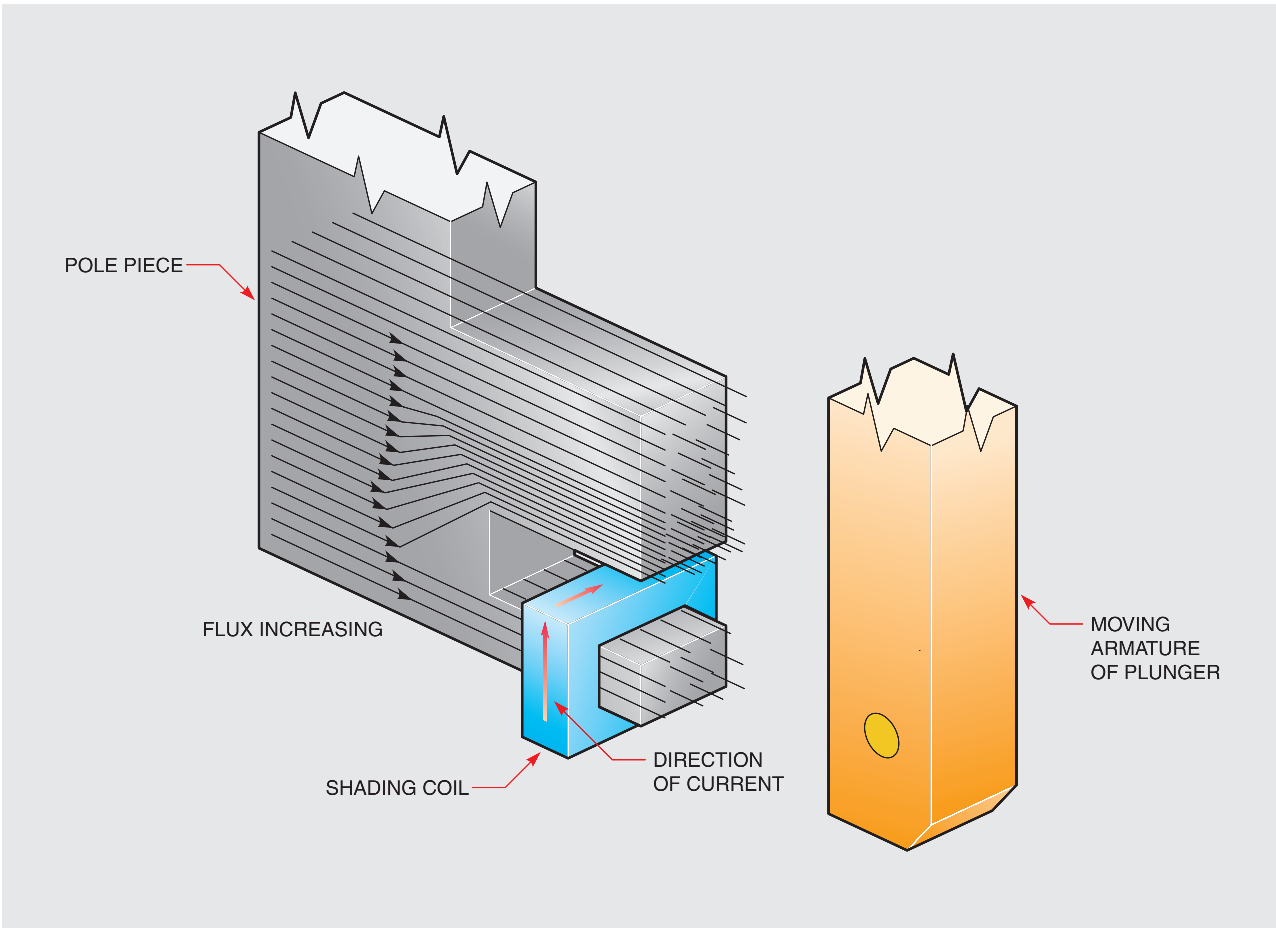


Figure 13–5 Pole face section with shading coil; current is in the clockwise direction for increasing flux.

a portion of a magnet pole piece. When the flux is increasing in the pole piece from left to right, the induced current in the shading coil is in a clockwise direction.

The magnetic flux produced by the shading coil opposes the direction of the flux of the main field. Therefore, with the shading coil in place, the flux density in the shaded portion of the magnet will be considerably less, and the flux density in the unshaded portion of the magnet will be more than if the shading coil were not in place.

Figure 13–6 shows the magnet pole with the flux direction still from left to right, but now the flux is decreasing in value. The current in the coil is in a counterclockwise direction. As a result, the magnetic flux produced by the coil is in the same direction as the main field flux. With the shading coil in place, the flux density in the shaded portion of the magnet will be larger and that in the unshaded portion will be less than if the shading coil were not used.

Thus, when the electric circuit of a coil is opened, the current decreases rapidly to zero, but the flux decreases much more slowly because of the action of the shading coil. This produces a more stable magnetic pull on the armature as the ac waveform alternates from maximum to minimum values and helps prevent chatter and ac hum.

Use of the Shading Pole to Prevent Wear and Noise

The attraction of an electromagnet operating on alternating current is pulsating and equals zero twice during each cycle. The pull of the magnet on its armature also drops to zero twice during each cycle. As a result, the sealing surfaces of the magnet tend to separate each time the flux is zero and then contact again as the flux builds up in the opposite direction. This continual making and breaking of contact will result in a noisy starter and wear on the moving parts of the

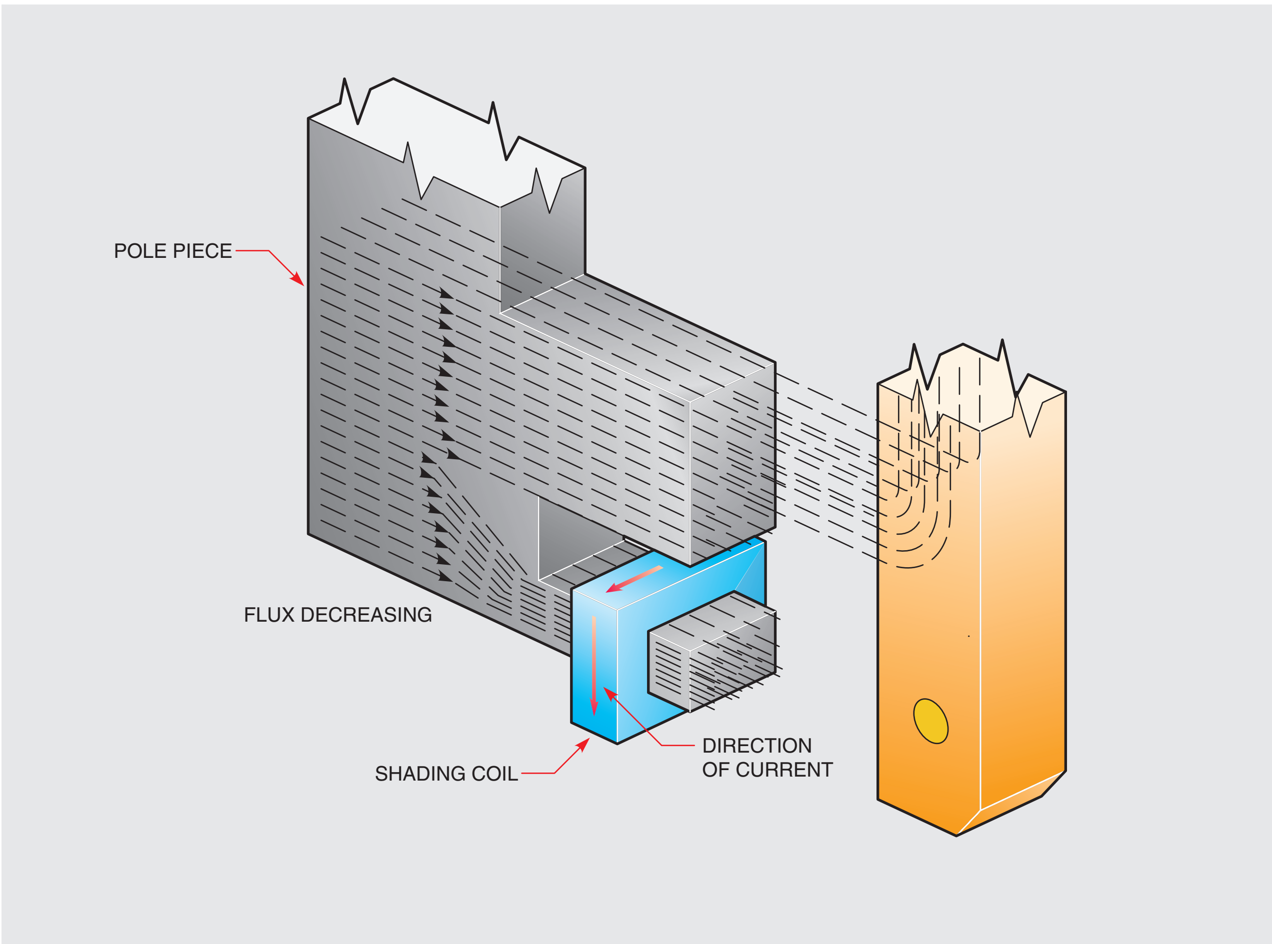


Figure 13–6 Pole face section; current is in the counterclockwise direction for decreasing flux.

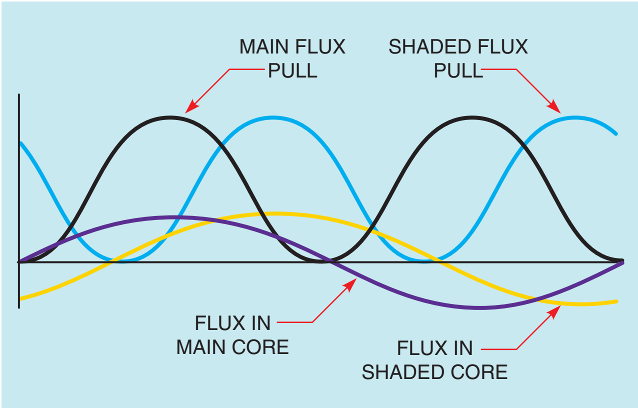


Figure 13–7 Relationship of main and shaded flux.

magnet. The noise and wear can be eliminated in ac magnets by the use of shaded poles. As shown previously, by shading a pole tip, the flux in the shaded portion lags behind the flux in the unshaded portion. Figure 13–7 shows the flux variations with time in both the shaded and unshaded portions of the magnet.

The two flux waves are made as near 90 degrees apart as possible. Pull produced by each flux is also shown. If flux waves are exactly 90° apart, the pulls will be 180° apart, and the resultant pull will be constant. However, with fluxes *nearly* 90° apart, the resulting pull varies only a small amount from its average value and never goes through zero. Voltage induced in the shading coil causes flux to exist in the electromagnet, even when the main coil current instantaneously passes through a zero point. As a result, contact between the sealing surfaces of the magnet is not broken and chattering and wear are prevented.

Magnet Coil

The magnet coil has many turns of insulated copper wire tightly wound on a spool. Most coils are protected by a tough epoxy molding that makes them very resistant to mechanical damage (Figure 13–8).

Above Normal Voltage Effects

The manufacturer makes available coils of practically any desired control voltage. Some starters are designed with dual-voltage coils.

NEMA standards require that the magnetic switch operate properly at varying control voltages from a high of 110% to a low of 85% of the rated coil voltage. This range of required operation is then designed by the

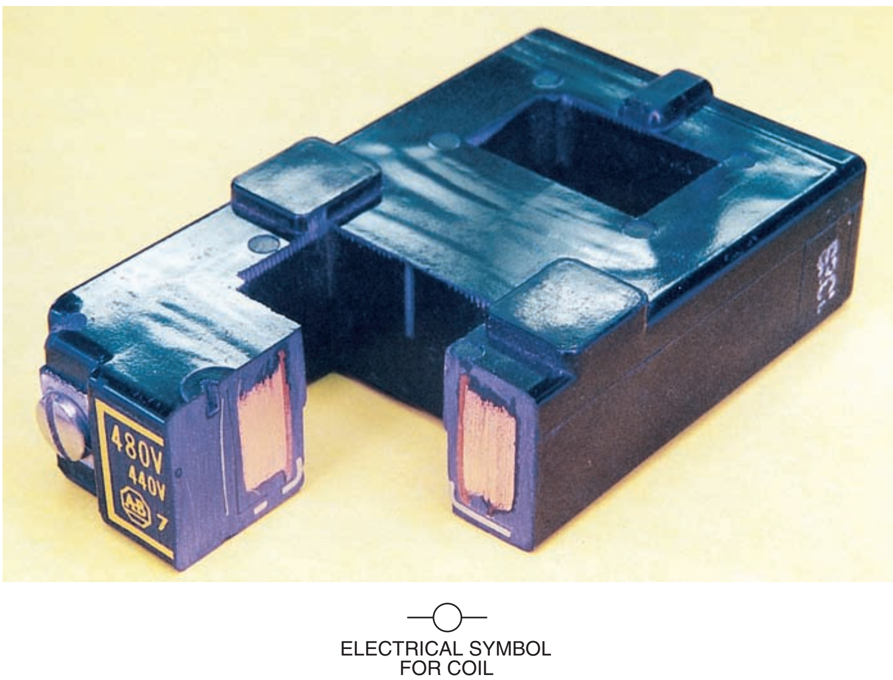


Figure 13–8 Magnet coil cut away to show insulated copper wire wound on a spool and protected by a molding.

manufacturer. It ensures that the coil will withstand elevated temperatures at voltages up to 10% over rated voltage and that the armature will pick up and seal in, even though the voltage may drop to 15% under the rating. Normally, power company service voltages are very reliable. Plant voltages may vary due to other loaded, operating machines, and other reasons affecting the electrical distribution system. If the voltage applied to the coil is too high, the coil will draw too much current. Excessive heat will be produced and may cause the coil insulation to break down and burn out. The magnetic pull will be too high and will cause the armature to slam in with too much force. The magnet pole faces will wear faster, leading to a shortened life for the controller. In addition, reduced contact life may result from excessive contact bounce.

Below Normal Voltage Effects

Undervoltage produces low coil currents thereby reducing the magnetic pull. On common starters the magnet may pick up (start to move) but not seal. The armature must sit against the pole faces of the magnet to operate satisfactorily. Without this condition, the coil current will not fall to the sealed value because the magnetic circuit is open, decreasing impedance (ac resistance). As the coil is not designed to continuously carry a current greater than its sealed current, it will quickly get very hot and burn out. The armature will also chatter. In addition to the noise, there is excessive wear on the magnet pole faces. If the armature does not seal, the contacts may touch but not close with enough pressure, creating another problem. Excessive heat, with arcing and possible welding of the contacts, will occur as the controller attempts to carry a motor-starting current with insufficient contact pressure.

Power (or Motor) Circuit of the Magnetic Starter

The number of poles refers to the number of power contacts, determined by the electrical supply service. For example, in a three-phase, three-wire system, a three-pole starter is required. The power circuit of a starter includes the main stationary and movable contacts and the thermal unit or heater unit of the overload relay assembly. This can be seen in Figure 13–9 (and in Figure 13–1, less the thermal overload relay assembly).

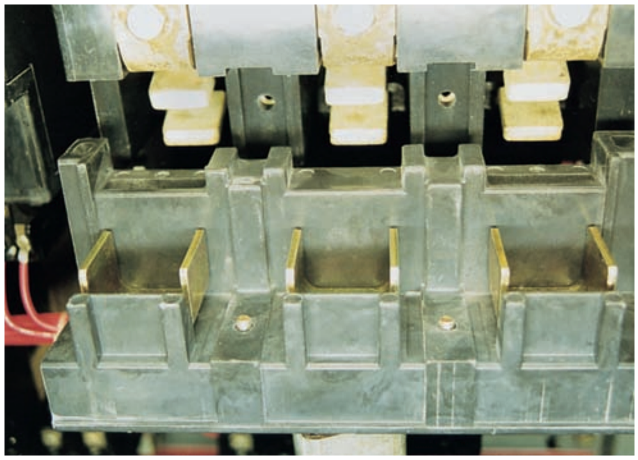


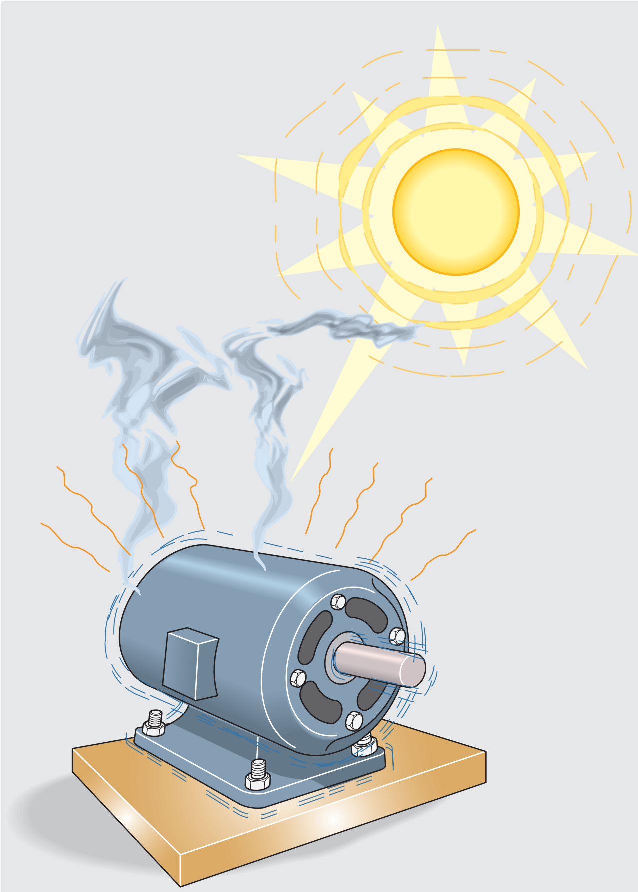
Figure 13–9 Ac magnetic starter showing the arcing chamber and load contacts.

Motor Overheat

An electric motor does not know enough to quit when the load gets too much for it. It keeps going until it burns out. If a motor is subjected, over a period of time, to internal or external heat levels that are high enough to destroy the insulation on the motor windings, it will fail—burn out.

A solution to this problem *might* be to install a larger motor whose capacity exceeds the normal horsepower required. This isn't too practical since there are other reasons for a motor to overheat besides excess loads. A motor will run cooler in winter snow country than in summer hot tropical weather. A high surrounding air temperature (*ambient temperature*) has the same effect as higher-than-normal current flow through a motor—it tends to deteriorate the insulation on the motor windings.

High ambient temperature is also created by *poor ventilation* of the motor. Motors must get rid of their heat so any obstructions to this must be avoided. High inrush currents of *excessive starting* create heat within the motor. The same is true with *starting heavy loads.* There are several other related causes that generate heat within a motor such as *voltage unbalance, low voltage,* and single phasing. In addition, when the rotating member of the motor will not turn (a condition called *locked rotor*), heat is generated. It must be impossible to design a motor that will adjust itself for all the various changes in total heat that can occur. Some device is needed to protect a motor against expected overheating.



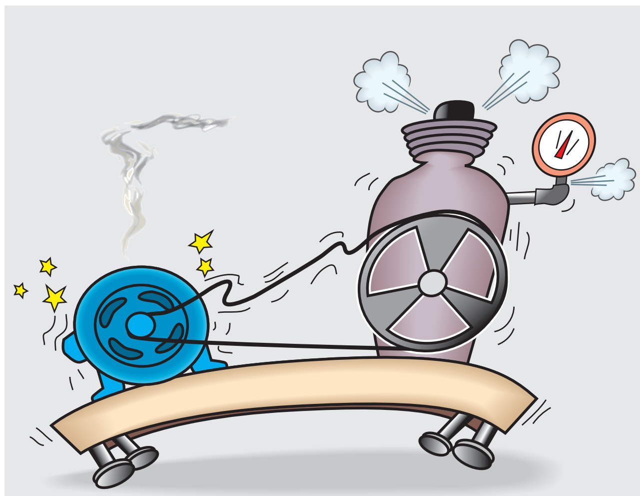
(EFFECTS OF HIGH AMBIENT TEMPERATURE)

Motor Overload Protection

The ideal overload protection for a motor is an element with current sensing properties very similar to the heating curve of the motor. This would act to open the motor circuit when full load is exceeded. The operation of the protective device is ideal if the motor is allowed to carry small, short, and harmless overloads, but is quickly disconnected from the line when an overload has persisted too long. Dual element, or time-delay, fuses may provide motor overload protection, but they have the disadvantage of being nonrenewable and must be replaced.

An overload relay is added to the magnetic switch shown in Figure 13–1. Now it is called a motor starter. The overload relay assembly is the heart of motor protection. A typical solid-state overload relay is shown in Figure 13–10. The motor can do no more work than the overload relay permits. Like the dual element fuse, the overload relay has characteristics permitting it to hold in during the motor accelerating period when the inrush current is drawn. Nevertheless, it still provides protection on small overloads above full-load current when the motor is running. Unlike the fuse, the overload relay can be reset. It can withstand repeated trip and reset cycles without need of replacement. It must be emphasized that the overload relay does *not* provide short circuit protection. This is the function of overcurrent protective equipment like fuses and circuit breakers, generally located in the disconnecting switch enclosure.

Figure 13–10 Three-phase solid-state overload relay. (Courtesy Square D Company.)



(MOTOR OVERLOAD)

Current drawn by a motor is a convenient and accurate measure of the motor load and motor heating. Therefore, the device used for overload protection, the overload relay, is usually connected with the motor current. It is provided as part of the starter or controller. As the relay carries the motor current, it is affected by that current. If a dangerous overcurrent condition occurs, it operates or trips the relay to open the control circuit of the magnetic starter and disconnect the motor from the line; this helps ensure the maximum operating life of the motor. In a manual starter, an overload trips a mechanical latch causing the starter contacts to open and disconnect the motor from the line.

To provide *overload* or *running protection* to keep a motor from overheating, overload relays are used on starters to limit the amount of current drawn to a predetermined value. The *NEC*® and local electrical codes determine the size of protective overload relays and heating elements that are properly sized to the motor.

The controller normally is installed in the same room or area as the motor. This makes it subject to the same ambient temperature as the motor. The tripping characteristic of the proper thermal overload relay will then be affected by room temperature exactly as the motor is affected. This is done by selecting a thermal relay element (from a chart provided by the manufacturer) that trips at the danger temperature for the motor windings. When excessive current is drawn, the relay de-energizes the starter and stops the motor.

Overload relays can be classified as being either *thermal* or *magnetic*. Magnetic overload relays react only to current excesses, and are not affected by temperature. As the name implies, *thermal overload relays* depend on the rising ambient temperature and temperatures caused by the overload current to trip the overload mechanism.

Thermal overload relays can be further subdivided into two types—melting alloy and bimetallic.

Melting Alloy Thermal Units

The melting alloy assembly consists of a heater element and solder pot (Figure 13–11A and Figure 13–11B). The solder pot holds the ratchet wheel in one position. Excessive motor current passes through the heater element and melts an alloy solder pot. Since the ratchet wheel is then free to turn in the molten pool, it trips a set of normally closed contacts in the starter control circuit; this stops the motor (Figure 13–12). A cooling-off period is required to allow the solder pot to become solid again before the overload relay can be reset and motor service restored.

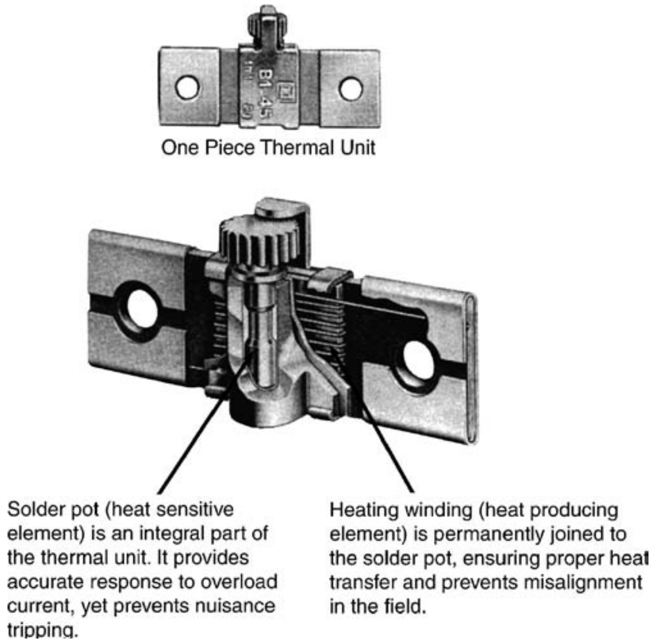


Figure 13–11A Melting alloy type overload heater. (Courtesy Square D Company.)

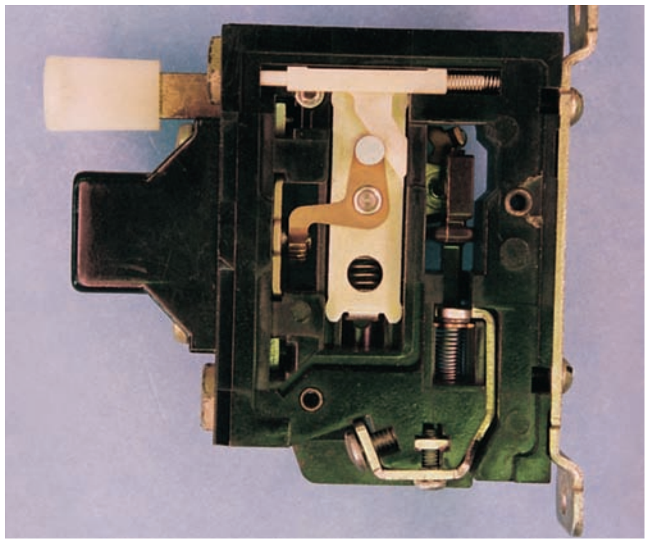


Figure 13–11B Cutaway view of a melting alloy type overload relay. The mechanism of overload relay is visible.

Melting alloy thermal units are interchangeable. They have a one-piece construction which ensures a constant relationship between the heater element and the solder pot. As a result, this unit can be factory calibrated, to make it virtually tamper-proof in the field. These important features are not possible with any other type of overload relay construction. To obtain appropriate tripping current for motors of different sizes, a wide selection of

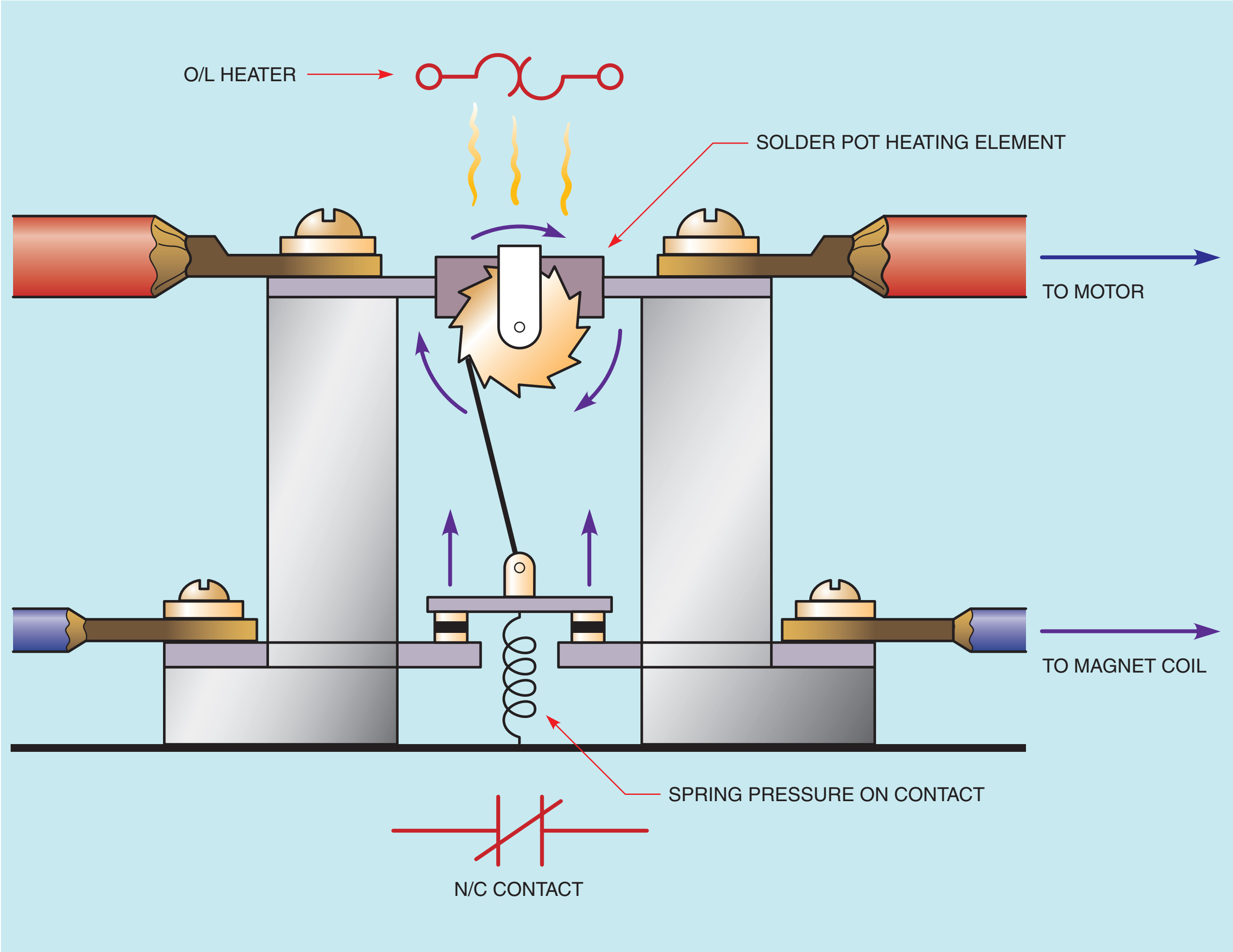


Figure 13–12 Melting alloy thermal overload relay. Spring pushes contact open as heat melts alloy allowing rachet wheel to turn freely. Note electrical symbols for overload heater and normally closed control contact.

interchangeable thermal units (heaters) is available. They give exact overload protection to motors of different full-load current ratings. Thermal units are rated in amperes and are selected on the basis of motor full-load current. For most accurate overload heater selection, the manufacturer publishes a number of rating tables keyed to the controller in which the overload relay is used. The units are easily mounted into the overload relay assembly and held in place with two screws. Being in series with the motor circuit, the motor will not operate without these heating elements installed in the starter.

Bimetallic Overload Relays

Bimetallic overload relays are designed specifically for two general types of application: the automatic reset and bimetallic relay. The automatic reset feature means that the devices can be mounted in locations that are not easily accessible for manual reset operation and may be set in the automatic position by the electrician.

In the automatic reset position, the relay contacts, after tripping, will automatically reclose after the relay has cooled down. This is an advantage when the reset button is hard to reach. Automatic reset overload relays are not normally recommended when used with automatic (two-wire) pilot control devices. With this control arrangement, when the overload relay contacts reclose after an overload trip, the motor will restart. Unless the cause of the overload has been removed, the overload relay will trip again. This event will repeat. Soon the motor will burn out because of the accumulated heat from the repeated high inrush and the overload current. (An overload-indicating light or alarm can be installed to call attention before this happens.)

Caution: The more important point to consider is the possible danger to personnel. This unexpected restarting of the machine may find the operator or electrician in a hazardous situation, as attempts are made to find out why this machine has stopped. *The NEC® prohibits this later installation.*

Most bimetallic relays can be adjusted to trip within a range of 85 to 115% of the nominal trip rating of the heater unit. This feature is useful when the recommended heater size may result in unnecessary tripping, while the next larger size will not give adequate protection. Ambient temperatures affect thermally-operated overload relays.

This ambient-compensated bimetallic overload relay is recommended for installations when the motor is located in a different ambient temperature from the motor starter. If the controller is located in a changing temperature, the overload relay can be adjusted to compensate for these temperature changes. This thermal overload relay is always affected by the surrounding temperature. If a standard thermal overload relay were used, it would not trip consistently at the same level of motor current whenever the controller temperature changed.

The tripping of the control circuit in the bimetallic relay results from the difference of expansion of two dissimilar metals fused together. Movement occurs if one of the metals expands more than the other when subjected to heat. A U-shaped bimetallic strip is used to calibrate this type of relay (Figure 13–13). The U-shaped strip and a heater element inserted in the center of the U compensate for possible uneven heating due to variations in the mounting location of the heater element. Since a motor starter is installed in series with the load, the starter must have the heating element (bimetallic and solder pot) installed in the overload relay before a motor will start.

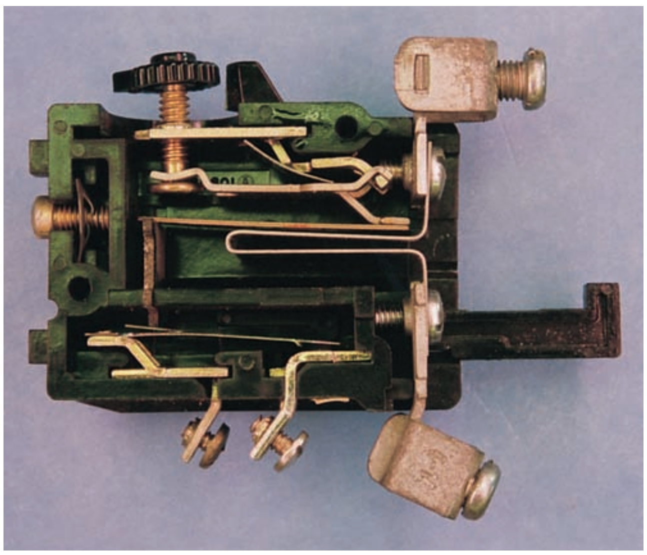


Figure 13–13 Cutaway view of a bimetallic type overload relay. The mechanism of overload relay is visible.

Magnetic Overload Relays

The magnetic overload relay coil is connected in series directly with the motor or is indirectly connected by current transformers (as in circuits with large motors). As a result, the coil of the magnetic relay must be wound with wire large enough to pass the motor current. These overload relays operate by current intensity and not heat.

Magnetic overload relays are used when an electrical contact must be opened or closed as the actuating current rises to a certain value. In some cases, the relay may also be used so that it is actuated when the current falls to a certain value. Magnetic overload relays are used to protect large motor windings against continued overcurrent. Typical applications are: to stop a material conveyor when conveyors ahead become overloaded, and to limit torque reflected by the motor current.

Time Limit Overload Relays

Time delay overload relays (Figure 13–14) make use of the oil dashpot principle. Motor current passing through the coil of the relay exerts a magnetic pull on a plunger. The magnetic flux set up inside the coil tends to raise the plunger which is attached to a piston immersed in oil. As the current increases in the relay coil, so does the magnetic flux. The force of gravity is overcome and the plunger and piston move upward. During this upward movement, oil is forced through bypass holes in the piston. As a result, the operation of the contacts is delayed. A valve disc is turned to open or close bypass holes of various sizes in the piston. This action changes the rate of oil flow and so adjusts the time delay factor. The rate of upward travel—of the core and piston—depends directly upon the degree of overload. The greater the current load, the faster the upward movement. As the rate of upward movement increases, the relay tripping time decreases.

This inverse time characteristic prevents the relay from tripping on the normal starting current or on harmless momentary overloads. In these cases, the line current drops to its normal value before the operating coil is able to lift the core and piston far enough to operate the

Figure 13–14 Dashpot type of overload relay. (Courtesy Square D Company.)

overload control contacts. However, if the overcurrent continues for a prolonged period, the core is pulled far enough to operate the contacts. As the line current increases, the relay tripping time decreases. Tripping current adjustment is achieved by adjusting the plunger core with respect to the overload relay coil. Quick tripping is obtained through the use of a light trade dashpot oil and by adjustment of the oil bypass holes.

A valve in the piston allows almost instantaneous resetting of the circuit to restart the motor. The current must then be reduced to a very low value before the relay will reset. This action is accomplished automatically when the tripping of the relay disconnects the motor from the line. Magnetic overload relays are available with either automatic reset contacts or hand reset contacts.

Reducing Overload Current for Large Motors

Large horsepower motors often have current draws of several hundred amperes, making the sizing of overload heaters difficult. When this is the case, it is common practice to use current transformers to reduce the amount of current to the overload heaters (Figure 13–15). The current transformers shown in Figure 13–15 have ratios of 150:5. This means that when 150 amperes of current flows through the primary, which is the line connected to the motor, the transformer secondary will produce a current of 5 amperes when the

Figure 13–15 Current transformers used to reduce overload current. Output of current transformers is connected to the overload heaters.

secondary terminals are shorted together. The secondaries of the current transformers are connected to the overload heaters to provide protection for the motor (Figure 13–16). Assume that the motor connected to the current transformers in Figure 13–15 has a full load current of 136 amperes. A simple calculation reveals that current transformers with a ratio of 150:5 would produce a secondary current of 4.533 amperes when 136 amperes flow through the primary.

$$\frac{150}{5} = \frac{136}{X}$$

$$150X = 680$$

$$X = 4.533$$

The overload heaters would actually be sized for a motor with a full load current of 4.533 amperes.

Caution: It should be noted that current transformers can produce very high voltages, if they are operated without a load connected to the output. The overload heater acts as the load. NEVER REMOVE THE HEATER WHEN POWER IS CONNECTED TO THE MOTOR.

Electronic Overloads

Electronic or solid state overload relays are becoming increasingly popular because they have many advantages over thermal overload relays and incorporate features that the others do not have. A starter with a solid state overload relay is shown in Figure 13–17. This relay senses motor current with small current transformers located inside the unit. It is much faster

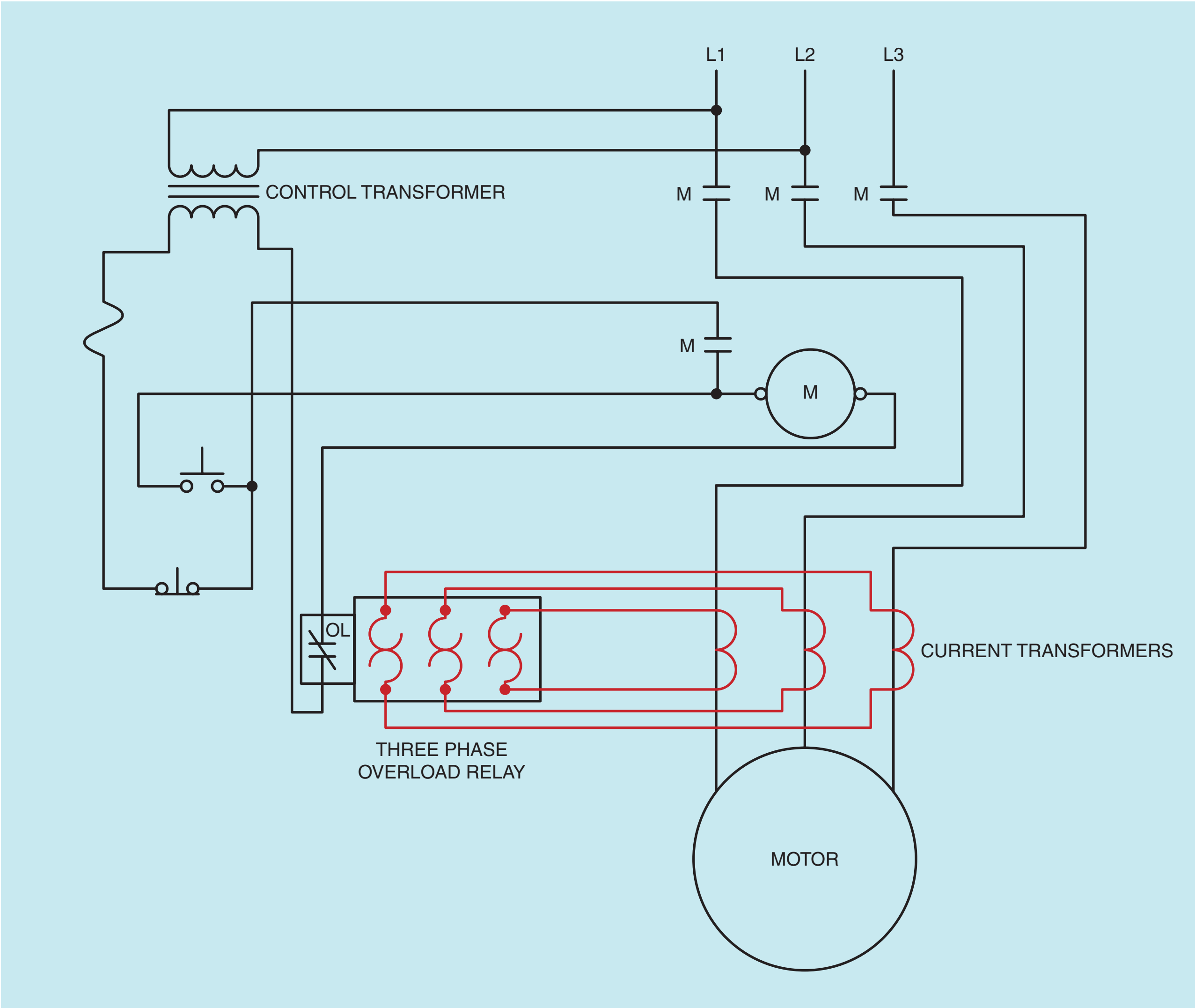


Figure 13–16 Current transformers reduce the current to the overload heaters.

acting than thermal units and provides the following features:

- Self powered
- Adjustment range up to 3.2 : 1
- Visible trip indicator
- Phase loss protection
- Low energy consumption
- Stall protection
- Ground fault protection
- Selectable trip class

Most electronic overload relays also offer both normally closed and normally open contacts. This permits the normally closed contact to be connected in series with the starter coil as usual, and the normally open contact can be used to light an indicator light to show the overload unit has tripped, or as in input to a programmable controller.

Solid State Starters

Solid state starters use electronic devices called Triacs to connect the motor to the line instead of load contacts. Solid state starters have the advantage of having no moving contacts to wear. They are resistant to dirt and vibration and generally contain solid state relay. A cabinet with solid state starters is shown in Figure 13–18.

Instantaneous Trip Current Relays

Instantaneous trip current relays are used to take a motor off the line as soon as a predetermined load

Figure 13–17 Starter with electronic overload relay. (Courtesy Square D Company.)

Figure 13–18 Cabinet with solid state starters. (Courtesy Toshiba International, Inc.)

condition is reached. For example, when a blockage of material on a woodworking machine causes a sudden high current, an instantaneous trip relay can cut off the motor quickly. After the cause of the blockage is removed, the motor can be restarted immediately because the relay resets itself as soon as the overload is removed. This type of relay is also used on conveyors to stop the motor before mechanical breakage results from a blockage.

The instantaneous trip current relay does not have the inverse time characteristic. Thus, it must not be used in ordinary applications requiring an overload relay. The instantaneous trip current relay should be considered as a special-purpose relay.

The operating mechanism of the trip relay in Figure 13–19 consists of a solenoid coil through which the motor current flows. There is a movable iron core within the coil. Mounted on top of the solenoid frame is a snap-action precision switch that has connections for either a normally open or normally closed contact. The motor current exerts a magnetic pull upward on the iron core. Normally, however, the pull is not sufficient to lift the core. If an overcurrent condition causes the core to be lifted, the snap-action precision switch is operated to trip the control contact of the relay.

The tripping value of the relay can be set over a wide range of current ratings by moving the plunger core up and down on the threaded stem. As a result, the position of the core in the solenoid is changed. By lowering the core, the magnetic flux is weakened and a higher current is required to lift the core and trip the relay.

Number of Overload Relays Needed to Protect a Motor

The *National Electrical Code*® requires three overload relays for three-phase starters on new installations. This helps maintain a balanced supply voltage for polyphase load installations.

Figure 13–19 Instantaneous trip current relay. (Courtesy Allen Bradley, a Rockwell International Company.)

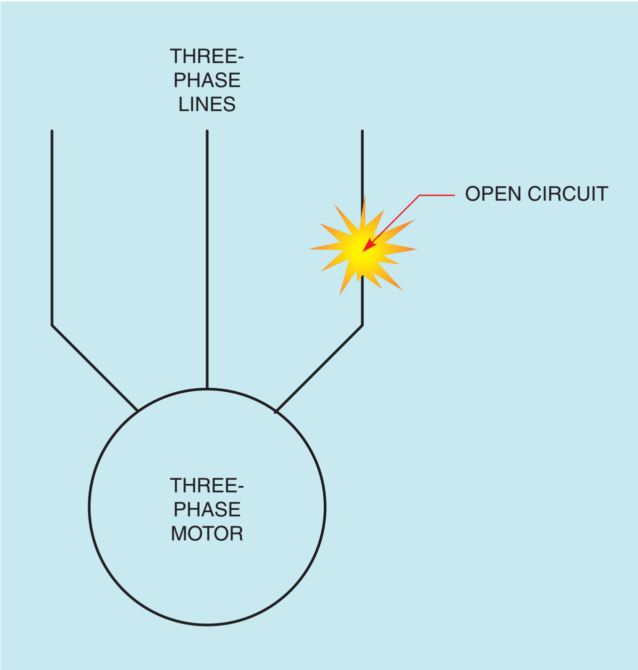


Figure 13–20 A single-phase condition: two high currents, one zero current.

A single-phase load on a three-phase circuit can produce serious unbalanced motor currents. A large three-phase motor on the same feeder with a small three-phase motor may not be protected if a single-phase condition occurs (Figure 13–20).

A defective line fuse, an open "leg" through a circuit breaker, a loose or broken wire anywhere in the conduit system or in a motor lead can result in single-phase operation. This will show up as a sluggish, hot-running motor. The motor will not start at all but will produce a distinct magnetic hum when it is energized. The three-phase motor may continue to operate (at reduced torque) when single phasing occurs. But once stopped, it will not restart. This is also a sign of a single-phase condition in a three-phase motor.

Unbalanced single-phase loads on three-phase panel boards must be avoided. Problems may occur on distribution systems where one or more large motors may feed back power to smaller motors under open-phase conditions.

The AC Magnetic Starter

An ac three-phase magnetic motor starter is shown in Figure 13–21. It is also called a *full-voltage* or *across-the-line* starter.

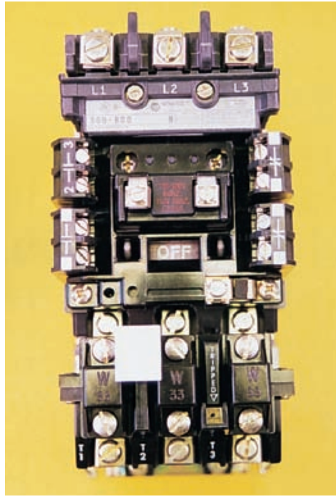


Figure 13–21 Three-phase motor starter with thermal overload relay.

The overload reset button can be seen on the bottom center of the figure. It is usual practice to build motor controllers with manual reset overload relays. This encourages the machine operator to remove the cause of the overload. It also enforces at least a little cooling off period after tripping.

Three overload heating elements for three-phase operation are installed in the relays above the reset button. The contacts are under the insulating arcing block cover, easily accessible for inspection with the removal of two screws. The starter must be mounted in an enclosure for installation.

Starter Sizes

Magnetic motor starters are available in different sizes. The size of the starter required is determined by the horsepower and voltage of the motor it is intended to control. There are two standards—NEMA and IEC—that are used to determine the size of the starter needed. Table 13–1 shows the NEMA size starters needed for normal starting duty. The capacity of the starter is determined by the size of its load or power contacts and the wire cross-sectional area that can be connected to the starter. The size of the load contacts is reduced when the voltage is doubled because the current is halved for the same power rating ($P = E \times I$).

The number of *poles* refers to the load contacts and does not include the number of control or auxiliary contacts. Three-pole starters are used to control three-phase motors, and two-pole starters are used for single-phase motors.

Table 13–1 Motor Starter Sizes and Ratings

NEMA Size	Load Volts	Maximum Horsepower Rating—Nonplugging and Nonjogging Duty: Single Phase	Poly Phase
	115	½	. . .
	200	. . .	1½
	230	1	1½
00	380	. . .	1½
	460	. . .	2
	575	. . .	2
	115	1	. . .
	200	. . .	3
	230	2	3
0	380	. . .	5
	460	. . .	5
	575	. . .	5
	115	2	. . .
	200	. . .	7½
	230	3	7½
1	380	. . .	10
	460	. . .	10
	575	. . .	10
	115	3	. . .
*1P	230	5	. . .
	115	3	. . .
	200	. . .	10
	230	7½	15
2	380	. . .	25
	460	. . .	25
	575	. . .	25

NEMA Size	Load Volts	Maximum Horsepower Rating—Nonplugging and Nonjogging Duty: Single Phase	Poly Phase
	115	7½	. . .
	200	. . .	25
	230	15	30
3	380	. . .	50
	460	. . .	50
	575	. . .	50
	200	. . .	40
	230	. . .	50
	380	. . .	75
4	460	. . .	100
	575	. . .	100
	200	. . .	75
	230	. . .	100
	380	. . .	150
5	460	. . .	200
	575	. . .	200
	200	. . .	150
	230	. . .	200
6	380	. . .	300
	460	. . .	400
	575	. . .	400
	230	. . .	300
7	460	. . .	600
	575	. . .	600
	230	. . .	450
8	460	. . .	900
	575	. . .	900

Tables are taken from NEMA Standards.

*1¾, 10 hp is available.

NEMA and IEC

NEMA is an acronym for the National Electrical Manufacturers Association. Likewise, IEC is an acronym for the International Electrotechnical Commission. Both organizations establish standards and ratings for different types of equipment. The IEC standards, however, are more widely used throughout Europe than in the United States. Many equipment manufacturers are now beginning to specify IEC standards for their products manufactured in the United States as well. The main reason is that much of the equipment produced in the United States is also marketed in Europe. Many European companies will not purchase equipment that is not designed using IEC standards.

Although the IEC uses some of the same ratings as similar NEMA-rated equipment, there is often a vast difference in the physical characteristics of the two. Two sets of load contacts are shown in Figure 13–22. The load contacts on the left are employed in a NEMA-rated 00 motor starter; the load contacts on the right are used in an IEC-rated 00 motor starter. Notice that the

surface area of the NEMA-rated contacts is much larger than that of the IEC-rated contacts. This permits the NEMA-rated starter to control a much higher current than the IEC starter. In fact, the IEC-rated 00 starter contacts are smaller than the contacts of a small eight-pin control relay (Figure 13–23). Due to the size difference in contacts between NEMA- and IEC-rated starters, many engineers and designers of control systems specify that IEC-rated equipment be one to two sizes larger than would be necessary for NEMA-rated equipment.

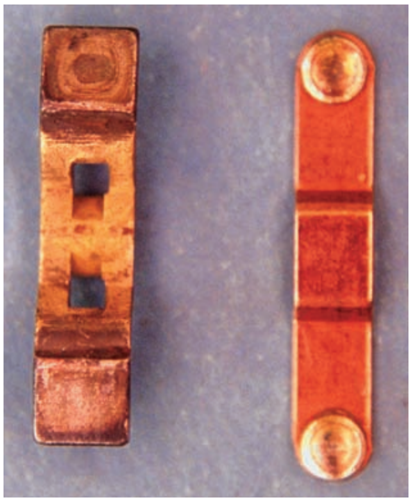


Figure 13–22 NEMA- and IEC-rated load contacts. NEMA size 00 contact is shown on the left and IEC size 00 contact is shown on the right.

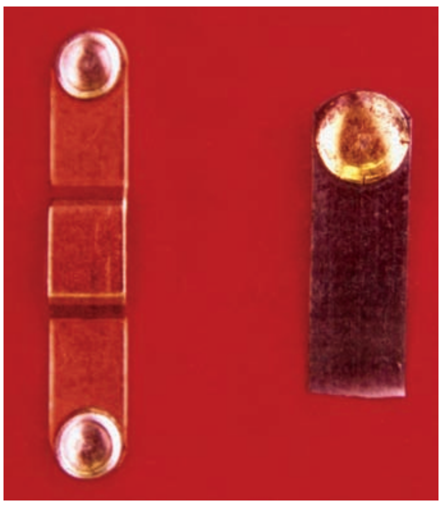


Figure 13–23 IEC size 00 load contacts (left) and 8-pin control relay contact (right).

AC Combination Starters

The circuit breakers and fuses of the motor feeders and branch circuits are normally selected for overcurrent, short-circuit or ground-fault protection.

With minor exceptions, the *NEC*® and some local codes also require that every motor has a disconnect means. This means may be an attachment cord and receptacle, a nonfusible isolation disconnect safety switch, a fusible disconnect motor switch or a combination starter. A combination starter (Figure 13–24) consists of an across-the-line starter and a disconnect means wired together in a common enclosure. Combination starters may have a blade-type disconnect switch, either fusible or nonfusible, or a thermal-magnetic trip circuit breaker. The starter may be controlled remotely with push buttons or selector switches, or these devices may be installed in the cover of the starter enclosure. The combination starter takes little mounting space and makes compact electrical installation possible.

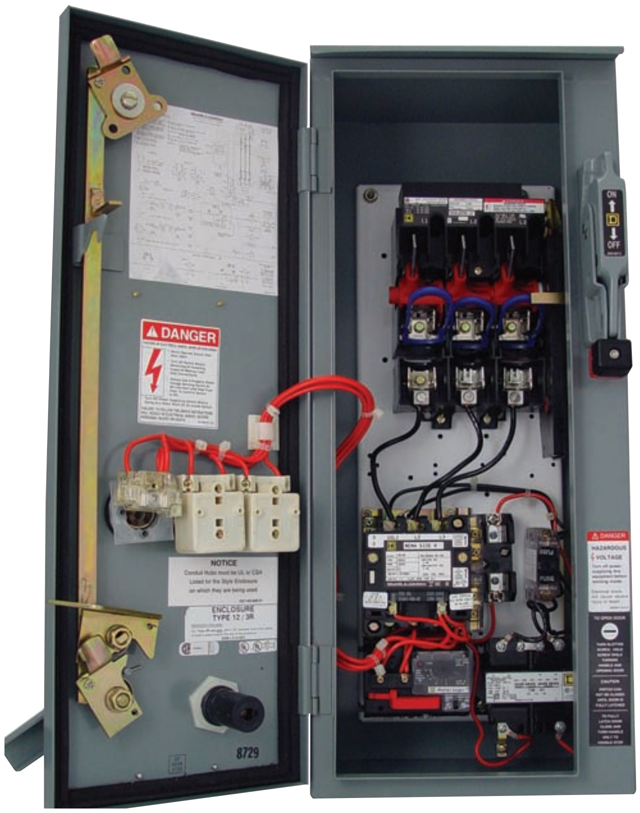


Figure 13–24 Combination starter with fused disconnect. (Courtesy Square D Company.)

A combination starter provides safety for the operator because the cover of the enclosure is interlocked with the external, operating handle of the disconnecting means. The door cannot be opened while the disconnecting means is closed. When the disconnecting means is open, all parts of the starter are accessible; however, the hazard is reduced since the readily accessible parts of the starter are not connected to the power line. This safety feature is not available on separately enclosed starters. In addition, the starter enclosure is provided with a means for padlocking the disconnect in the OFF position. Controller enclosures are available for every purpose and application.

The enclosure for a combination starter is often referred to as a module, cubicle, or can. They are designed to be inserted into a motor control center (MCC) (Figure 13–25). Connection to individual modules is generally made with terminal strips located inside the module. Most manufacturers provide some means of removing the entire terminal strip without having to remove each individual wire. If a starter fails, this permits rapid installation of a new starter. The defective starter can then be serviced at a later time.

Figure 13–25 Typical motor control center (MCC). (Courtesy Eaton Corp., Cutler-Hammer Products.)

Caution: By necessity, motor control centers have very low impedance and can produce extremely large fault currents. It is estimated that the typical MCC can deliver enough energy in an arc-fault condition to kill a person 30 ft away. For this reason, many industries now require electricians to wear full protection (flame retardant clothing, face shield, ear plugs, and hard hat) when opening the door on a combination starter or energizing the unit. When energizing the starter, they should always stand to the side of the unit and not directly in front of it. In a direct short condition, it is possible for the door to be blown off or open.

Oil Immersion Starters

Oil immersion starters have their load contacts immersed in dielectric oil. The starter shown in Figure 13–26 uses an oil container located below the main cabinet to house the load contacts and dielectric oil. This starter can be used in a class 1 division 2 area because the contacts are immersed in oil. It is designed to permit the oil reservoir to be lowered so load contacts can be serviced or the dielectric oil

Figure 13–26 2300 volt oil immersion type starter.

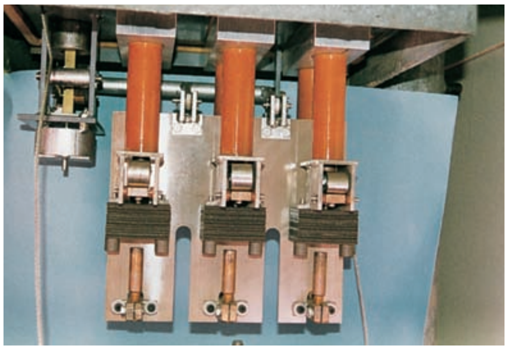


Figure 13–27 The oil reservoir can be lowered to permit the contacts to be serviced or the oil to be changed.

changed if it should become contaminated (Figure 13–27). This starter controls a 2300 volt motor and is a combination disconnect and starter (Figure 13–28). It should be noted that *this type of starter should never be operated without oil in the reservoir, and never open the disconnect when the motor is in operation.* The dielectric oil is used to suppress arcs that occur when the motor current is interrupted. If the circuit is opened without the dielectric oil, there is a possibility of explosion or flash over. The disconnect switch is used primarily to disconnect power from the starter when it is serviced or to prevent operation of the motor. The disconnect switch should not be opened until the oil immersed starter contacts have disconnected the motor from the line.

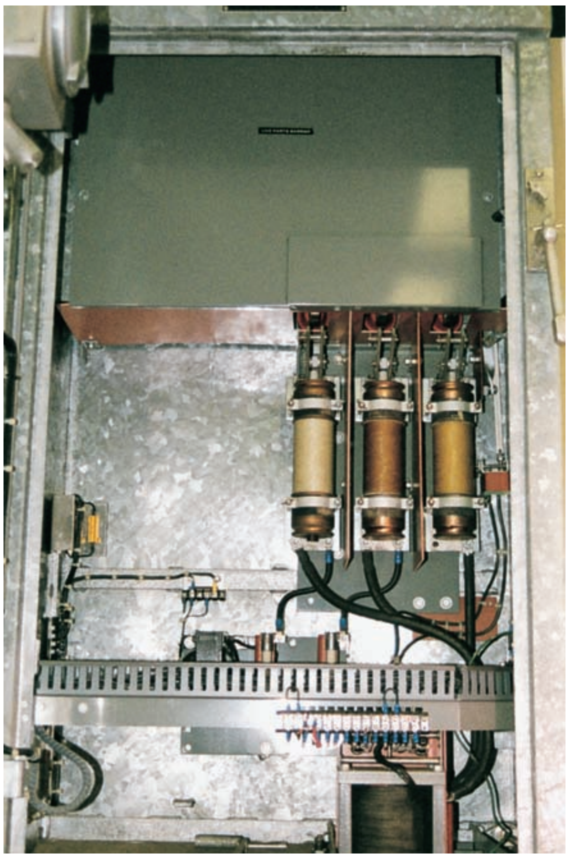


Figure 13–28 2300 volt disconnect and starter.

Protective Enclosures

The selection and installation of the correct enclosure can contribute to useful, safe service and freedom from trouble in operating electromagnetic control equipment.

An enclosure is the surrounding controller case, cabinet or box. Generally, this electrical equipment is enclosed for one or more of the following reasons:

A. To shield and protect workers and other personnel from accidental contact with electrically live parts, thereby preventing electrocution.
B. To prevent other conducting equipment from coming into contact with live electrical parts, thereby preventing unnecessary electrical outages and indirectly protecting personnel from electrical contact.
C. To protect the electrical controller from harmful atmospheric or environmental conditions, such as the presence of dust or moisture, to prevent corrosion and interference of operation.
D. To contain the electrical arc of switching within the enclosure, to prevent explosions and fires which may occur with flammable gases or vapors within the area.

You may readily understand why some form of enclosure is necessary and required. The most frequent requirement is usually met by a general-purpose, sheet steel cabinet. The conduit is installed with lock-nuts and bushings. The presence of dust, moisture, or explosive gases often makes it necessary to use a special enclosure to protect the controller from corrosion or the surrounding equipment from possible explosions. Conduit access is through threaded openings, hubs, or flanges. In selecting and installing control apparatus, it is necessary to carefully consider the conditions under which the

apparatus must operate. There are many applications where a general-purpose sheet steel enclosure does not give sufficient protection.

Watertight and dusttight enclosures are used for the protection of control apparatus. Dirt, oil, or excessive moisture are destructive to insulation and frequently form current-carrying paths that lead to short circuits or grounded circuits.

Special enclosures for hazardous locations are used for the protection of life and property. Explosive vapors or dusts exist in some departments of many industrial plants as well as in grain elevators, refineries, and chemical plants. The *NEC*® and local codes describe hazardous locations. UL has defined the requirements for protective enclosures according to the hazardous conditions. NEMA has standardized enclosures from these requirements. Some examples follow.

General-purpose enclosures (NEMA 1) General-purpose enclosures are constructed of sheet steel, and are designed primarily to prevent accidental contact with live parts. Covers have latches with provisions for padlocking (Figure 13–29). Enclosures are intended for use indoors, in areas where unusual service conditions do not exist. They do provide protection from light splash, dust, and falling debris such as dirt.

Watertight enclosures (NEMA 4) The *NEC*® defines a watertight enclosure as being so constructed that moisture will not enter the enclosure under specified test conditions. These enclosures are made of cast construction or of sheet metal of suitable rigidity and are designed to pass a hose test with no leakage of water. Watertight enclosures are suitable for outdoor applications on ship docks, in dairies, breweries, and other locations where the enclosure is subjected to dripping or splashing liquids (Figure 13–30). Enclosures that meet requirements for more than one NEMA type may be designated by a combination of type numbers such as: Type 3–4, dusttight and watertight.

Dusttight enclosures (NEMA 12) The *NEC*® defines dusttight enclosures as being constructed so that dust will not enter the case under specified test conditions. Dusttight enclosures are constructed of sheet metal and are provided with cover gaskets to exclude dust, lint, dirt, fibers, and flying particles. They are suitable for use in steel and knitting mills, and similar locations where nonhazardous dusts are present. Mounting is by means of outside flanges or mounting feet.

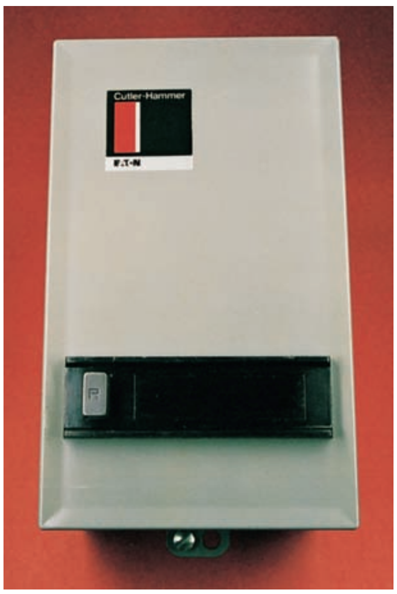


Figure 13–29 General-purpose enclosure (NEMA 1).

Figure 13–30 Watertight enclosure (NEMA 4).

Hazardous locations (NEMA 7) Class 1 enclosures are designed for use in hazardous locations where atmospheres containing gasoline, petroleum, naphtha, alcohol, acetone, or lacquer solvent vapors are present or may be encountered. Enclosures are heavy, gray iron castings, machined to provide a metal-to-metal seal (Figure 13–31).

NOTE: Applicable and enforced national, state, or local electrical codes and ordinances should be consulted to determine the safe way to make any installation.

Figure 13–31 Hazardous location enclosure (NEMA 7).

Review Questions

1. What is a magnetic line voltage motor starter?
2. How many poles are required on motor starters for the following motors: (a) 240-volt, single-phase induction motor, (b) 440-volt, three-phase induction motor?
3. If a motor starter is installed according to directions but will not start, what is a common cause for the failure to start?
4. Using the time limit overload or the dashpot overload relay, how are the following achieved: time delay characteristics; tripping current adjustments?
5. What is meant by chattering of an ac magnet?
6. What is the phase relationship between the flux in the main pole of a magnet and the flux in the shaded portion of the pole?
7. In what devices is the principle of the shaded pole used?
8. What does the electrician look for to remedy the following conditions: loud or noisy hum; chatter?
9. What type of protective enclosure is used most commonly?
10. Why is a disconnect fuse switch or circuit breaker installed with a motor starter?
11. What safety feature does the type of assembly given in question 10 provide that individual starter assemblies do not?
12. List the probable causes if the armature does not release after the magnetic starter is de-energized.
13. How is the size of the overload heaters selected for a particular installation?
14. What type of motor starter enclosure is recommended for an installation requiring safe operation around an outside flammable paint filling pump?

Select the *best* answer for each of the following.

15. The magnetic starter is held closed
    a. mechanically
    b. by 15% undervoltage
    c. by 15% overvoltage
    d. magnetically
16. When a motor starter coil is de-energized
    a. the contacts stay closed
    b. it is held closed mechanically
    c. gravity and spring tension open contacts
    d. it must cool for a restart

17. An ac magnet may hum excessively due to
    a. improper alignment
    b. foreign matter between contact surfaces
    c. loose laminations
    d. all of these

18. Ac magnets are made of *laminated* iron
    a. for better induction
    b. to reduce heating effect
    c. for ac and dc use
    d. to prevent chattering

19. The purpose of overload protection on a motor is to protect the
    a. motor from sustained overcurrents
    b. wire from high currents
    c. motor from sustained overvoltage
    d. motor from short circuits

20. When the reset button does not re-establish the control circuit after an overload, the probable cause is
    a. the overload heater is too small
    b. the overload trip has not cooled sufficiently
    c. the auxiliary contacts are defective
    d. the overload heater is burned out

21. If an operator pushes a start button on a three-phase induction motor and the motor starts to hum, but not run, the probable trouble is
    a. one fuse is blown and the motor is single phasing
    b. the overload trip needs resetting
    c. the auxiliary contact is shorted
    d. one phase is grounded

22. A combination starter provides
    a. disconnecting means
    b. overload protection
    c. short circuit protection
    d. all of these

UNIT 14

PUSH BUTTONS AND CONTROL STATIONS

OBJECTIVES

After studying this unit, the student will be able to:

- Describe the difference between closed and open push buttons.
- Draw the wiring diagram symbols for push buttons and pilot lights.
- Draw simple circuits using normally open and closed push buttons.
- Connect combination push buttons in simple circuits.
- Explain single and double break contacts.
- List type of control operators on control stations.
- Draw simple circuits using a selector switch.
- Wire simple circuits with a selector switch.

Push Buttons

A push-button station is a device that provides control of a motor through a motor starter by pressing a button that opens or closes contacts. It is possible to control a motor from as many places as there are stations—through the same magnetic controller. This can be done by using more than one push-button station. A single circuit push-button station is shown in Figure 14–1.

Two sets of momentary contacts are usually provided with push buttons so that when the button is pressed, one set of contacts is opened and the other set is closed. The use of this combination push button is simply illustrated in the wiring diagram of Figure 14–2. When the push button is in its normal position as shown in Figure 14–2A, current flows from L1 through the normally closed contacts, through the red pilot light (on top) to L2 to form a complete circuit; this lights the lamp. Since the lower push-button circuit is opened by the normally open contact, the green pilot lamp does not glow. Note that this situation is reversed when the button is pushed (Figure 14–2B). Current now flows from L1 through the pushed closed contact and lights the green pilot lamp when completing the circuit to L2.

Figure 14–1 Push-button control station with general purpose enclosure. Usually made of molded plastic or sheet metal. (Courtesy Square D Company.)

The red lamp is now out of the circuit and does not glow. However, because the push buttons are momentary contact (spring loaded), we return to the position shown in Figure 14–2A when pressure on the button is released. Thus, by connecting to the proper set of contacts, either a normally open or a normally closed situation is obtained. *Normally open* and *normally closed* mean that the contacts are in a rest position, held there by spring tension, and are not subject to either mechanical or electrical external forces.

Push-button stations are made for two types of service: *standard duty* stations for normal applications safely passing coil currents of motor starters up to size 4, and *heavy duty* stations, when the push buttons are to be used frequently and subjected to hard or rough usage. Heavy duty push-button stations have high contact ratings.

The push-button station enclosure contain the contacts is usually made of molded plastic or sheet metal. Some double-break contacts are made of copper. However, in most push buttons, silver-to-silver contact surfaces are provided for better electrical conductivity and longer life.

Figure 14–3 shows a combination, normally open and normally closed, push-button unit with a mushroom head for fast and easy access such as may be required in a safety circuit. This is also called a *palm-operated push button,* especially when it is used as a safety device for both operator and machine, such as a punch-press or emergency stop in a control station. The push-button terminals in Figure 14–2 represent one-half of

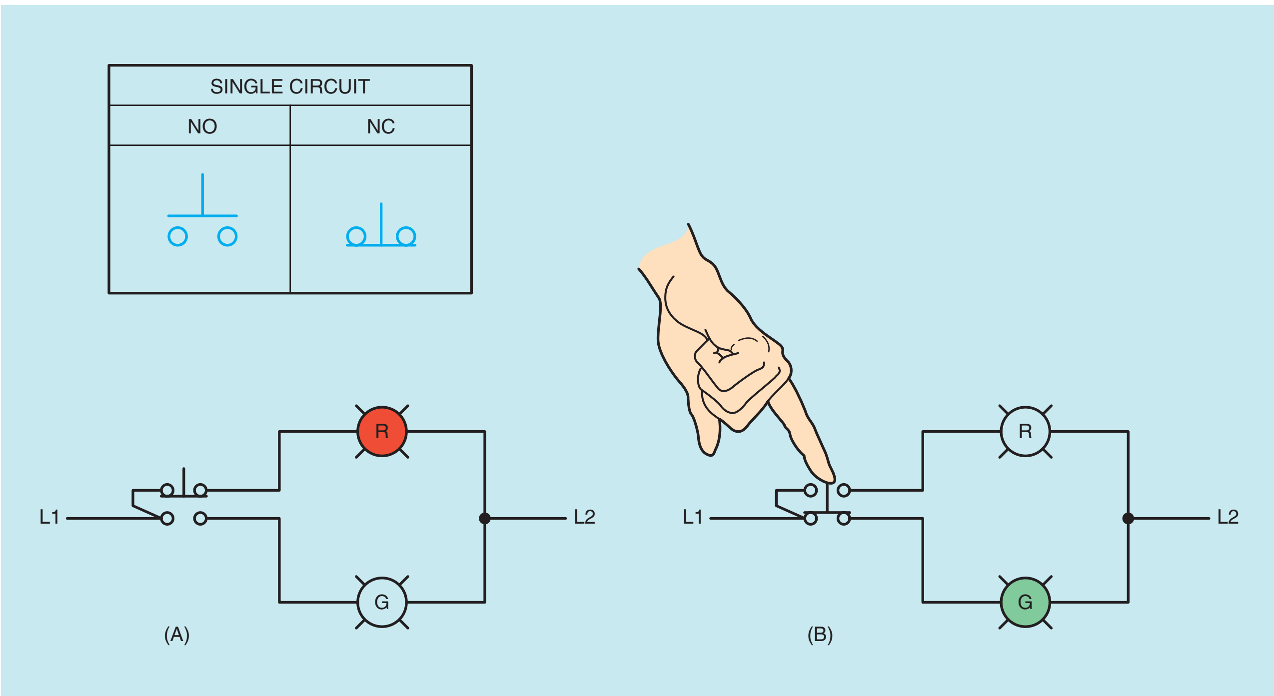


Figure 14–2 Combination push button: (A) Red pilot light is lit through normally closed push-button contact. (B) Green pilot light is lit when the momentary contact button is pushed.

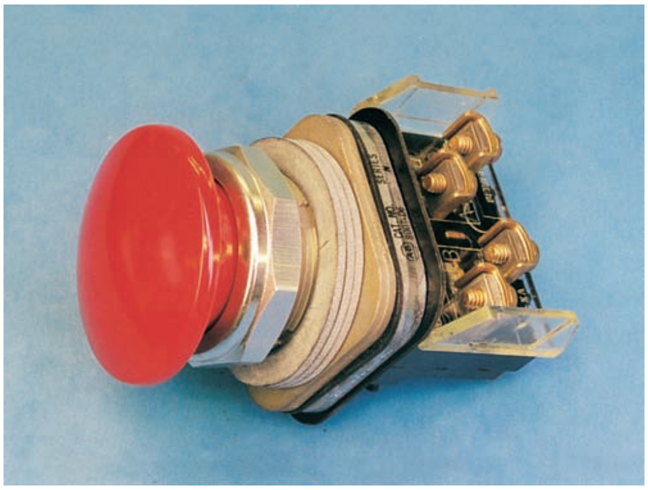


Figure 14–3 Open push-button unit with mushroom head.

the terminals shown in Figures 14–3 and 14–4, for a double-pole, double-throw push button.

Since control push buttons are subject to high momentary voltages caused by the inductive effect of the coils to which they are connected, good clearance between the contacts and insulation to ground and operator is provided.

The push-button station may be mounted adjacent to the controller or at a distance from it. The amount of current broken by a push button is usually small. As a result, operation of the controller is hardly affected by the length of the wires leading from the controller to a remote push-button station.

Push buttons can be used to control any or all of the many operating conditions of a motor, such as *start, stop, forward, reverse, fast,* and *slow.* Push buttons also may be used as remote stop buttons with manual controllers equipped with potential trip or low-voltage protection.

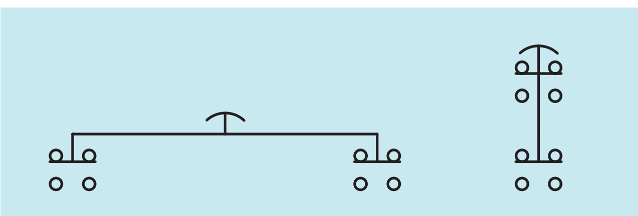


Figure 14–4 Terminal configurations used by different manufacturers of Figure 14–3 push-button. Both configurations represent the same push-button.

Selector Switches

Selector switches, as can be seen in Figure 14–5, are usually “maintained” contact positions, with three and sometimes two selector positions. Selector switch positions are made by turning the operator knob—not pushing it. Figure 14–5 is a double-break contact, disconnecting the control circuit at two points. Some switches may also have a spring return to give momentary contact operation.

Figure 14–6A shows a single break contact selector switch connected to two lights. The red light may be selected to glow by *turning* the switch to the red position. Current now flows from line 1 through the selected red position of the switch, through the red lamp to line 2, completing the circuit. Note this switch has an OFF position in the center. In Figure 14–6B, there are two position selector switches available, with no OFF position. Here, whichever light is selected would burn continuously.

Figure 14–7A is an elementary diagram of the heavy duty, double-break selector switch similarly shown in Figure 14–5. Note that the red light will glow (Figure 14–7A) with the two-position switch in this position, the green indicating lamp is de-energized, and there is no OFF position. Figure 14–7B illustrates a three-position selector switch containing an OFF position. Both lamps may be turned off using this switch, but not the switch illustrated in (A).

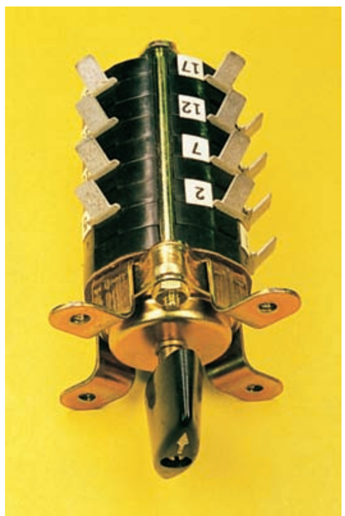


Figure 14–5 Open selector switch.

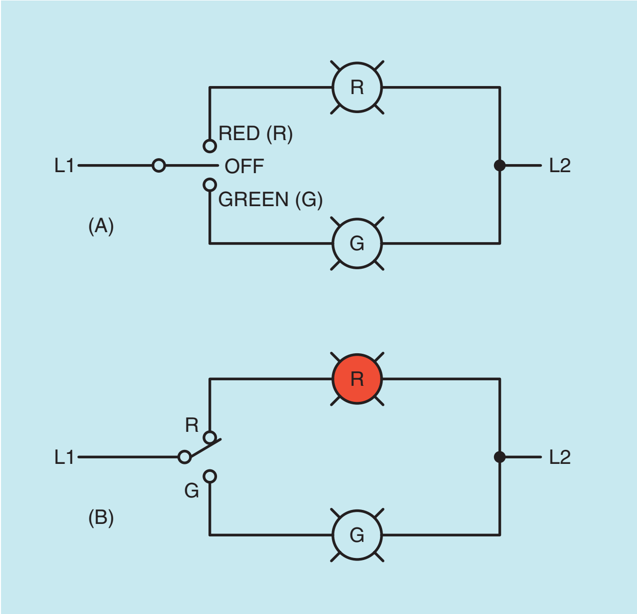


Figure 14–6 Elementary diagram using (A) a single-break, three-position selector switch and (B) a two-position, single-break switch.

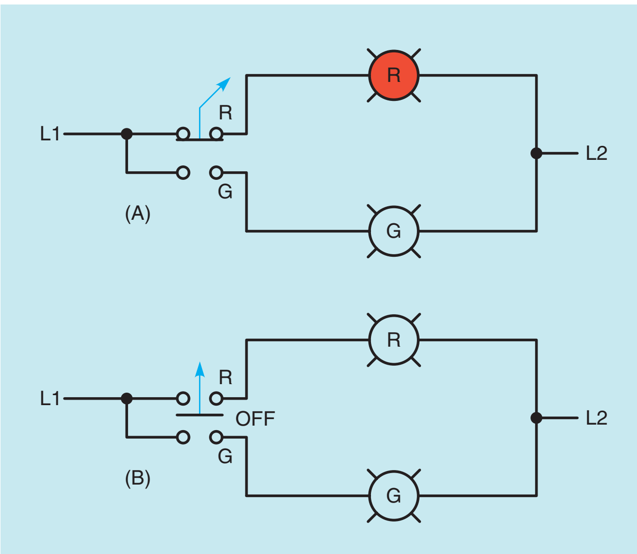


Figure 14–7 Heavy-duty, double-break selector switch for (A) two-position and (B) three-position switches.

Control Stations

A control station may contain push buttons alone (Figure 14–8A) or a combination of push buttons, selector switches and pilot lights (indicating lights) (Figure 14–8B). Indicating lights may be mounted in the enclosure. These lights are usually red or green and are used for communication and safety purposes. Other common colors available are amber, blue, white, and clear. They indicate when the line is energized, the motor is running, or any other condition is designated.

Control stations may also include switches that are key, coin, or hand operated wobble sticks. A wobble stick is a stem-operated push button, for operation from any direction. There are ball lever push button operators for a gloved hand or for frequent operations.

Name plates are installed to designate each control operation. These can be seen in Figures 14–1 and 14–8. These control operators are commonly used in control circuits of magnetic devices in factory production machinery.

Combination indicating light, nameplate, push-button units are available. These illuminated push buttons and indicating lights are designed to save space in a wide variety of applications such as control and instrument panels, laboratory instruments, and computers. Miniature buttons are also used for this purpose.

Standard control station enclosures are available for normal general-purpose conditions, while special enclosures are used in situations requiring watertight, dust-tight, oiltight, explosion-proof, or submersible protection. Provisions are often made for *padlocking* stop buttons in the open position (for safety purposes) (Figure 14–9). Relays, contactors, and starters cannot be energized while an electrician is working on them with the stop button in this position.

The Push-Pull Operator

Another type of push-button control is the push-pull operator. This control contains two sets of contacts in one unit. One set of contacts is operated by pulling outward on the button and the other set is operated by pushing the button. The head of the push-pull operator is made in such a manner as to permit a machine operator to pull outward on the button by placing two fingers behind it. Figure 14–10 shows a push-pull operator control. The head of the control can be pushed to operate the other set of contacts.

There are two types of push-pull operators. The type used is determined by the requirements of the circuit. One type of control contains two normally open momentary contacts. Figure 14–11 shows a schematic drawing of this control. In its normal position, neither

Figure 14–8A Push-button control station with pilot light and Hand-Off-Auto switch.

movable contact A or B connects with either of the stationary contacts. In Figure 14–12, the control has been pulled outward. This causes movable contact A to connect with two of the stationary contacts. Movable contact B does not connect with its stationary contacts.

If the push-pull operator is pressed, movable contact B connects with a set of stationary contacts as shown

Figure 14–9 Push button with provision for mechanical lockout. (Courtesy Square D Company.)

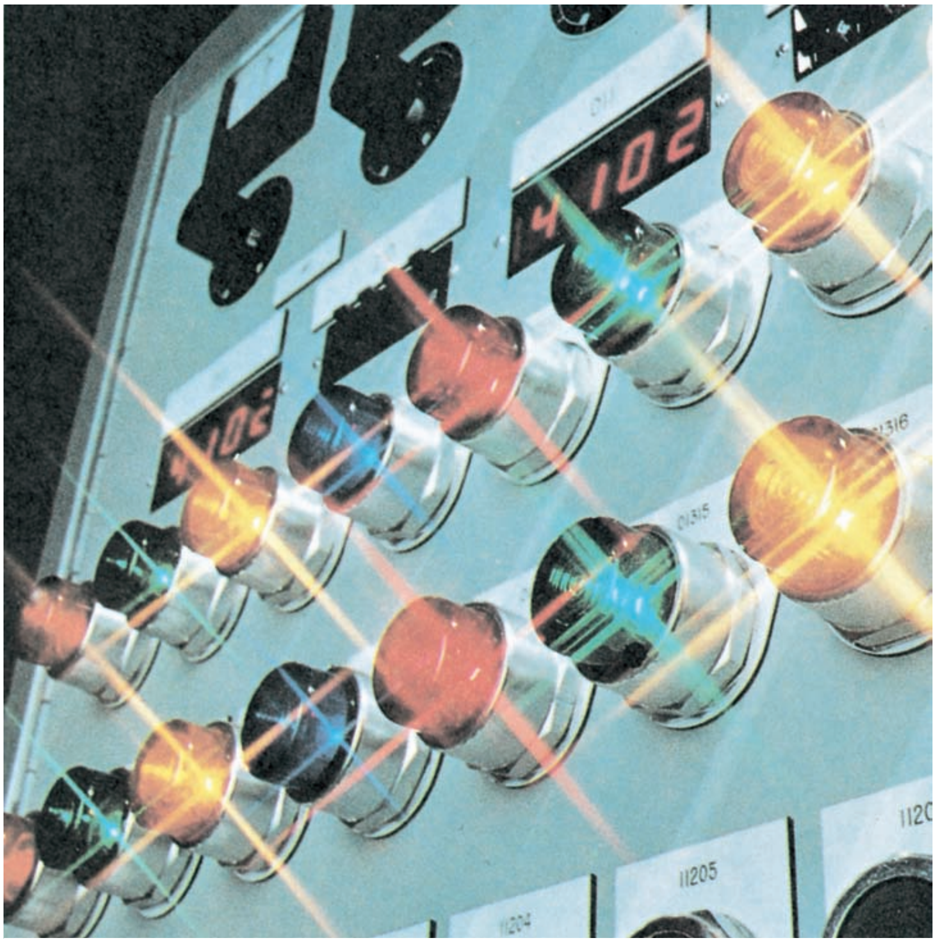


Figure 14–8B Control station with push-buttons, selector switches, and indicating lights. (Courtesy Allen-Bradley, a Rockwell International Company.)

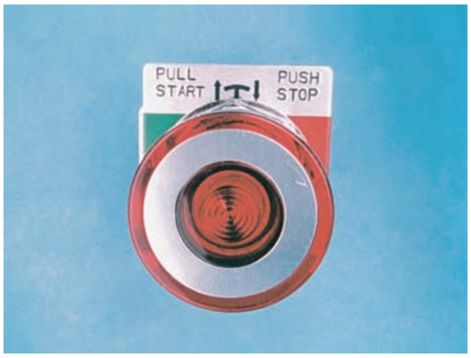


Figure 14–10 Push-pull operator with light unit.

in Figure 14–13. Movable contact A does not connect with its stationary contacts.

This type of push-pull operator control can used with run-jog controls. An example of this type of control is shown in Unit 41.

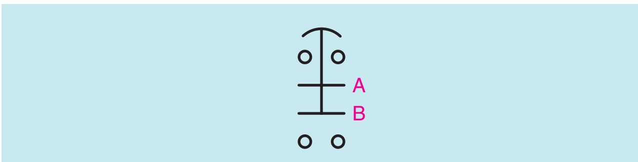


Figure 14–11 Push-pull operator with two normally open contacts.

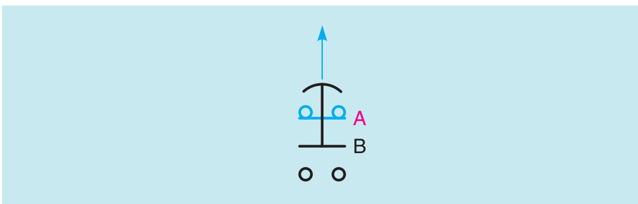


Figure 14–12 Movable contact A connects with the stationary contact.

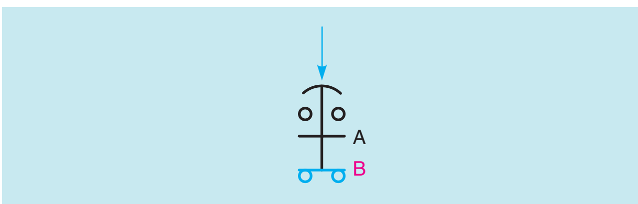


Figure 14–13 Movable contact B connects with the stationary contact.

The second type of push-pull operator has one normally open contact and one normally closed contact. Figure 14–14 shows a schematic drawing of this type of control. When this type of push-pull operator is in its normal position, movable contact A is open and movable contact B is closed.

When the button is pulled outward, contact A connects with its stationary contacts, and contact B maintains connection with its stationary contacts. Figure 14–15 illustrates this condition. When the button is released, the movable contacts return to their normal position.

When the push button is pressed, contact B breaks the connection with its stationary contact. Figure 14–16 shows this condition.

This type of push-pull operator control can be used as a start-stop motor control station. The advantage of this type of control is that it requires the space of only one push-button control element instead of two. Also,

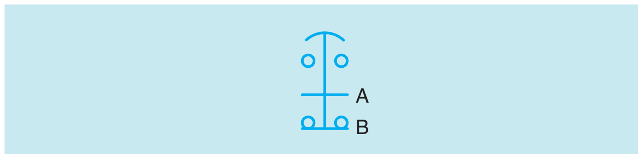


Figure 14–14 Movable contact A is normally open and movable contact B is normally closed.

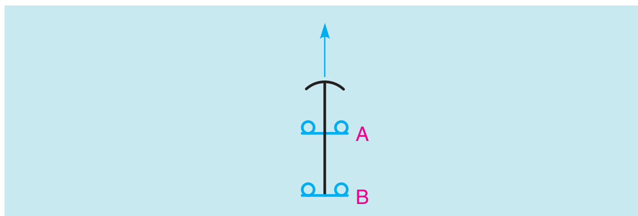


Figure 14–15 Both movable contacts connect with their stationary contacts.

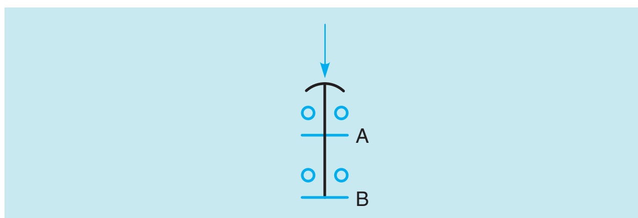


Figure 14–16 Both movable contacts break connection with their stationary contacts.

since the control must be pulled outward to start the motor and pressed inward to stop the motor, the possibility of accidentally pushing the wrong button is eliminated.

A start-stop control circuit using the push-pull operator is shown in Figure 14–17. When the push-pull operator is pulled outward, contact A completes a circuit to motor starter coil M. Normally open contact M, connected parallel to contact A, closes to maintain the circuit to coil M when the button is released. When the push-pull operator is pressed, movable contact B breaks the circuit to motor starter coil M and the circuit de-energizes.

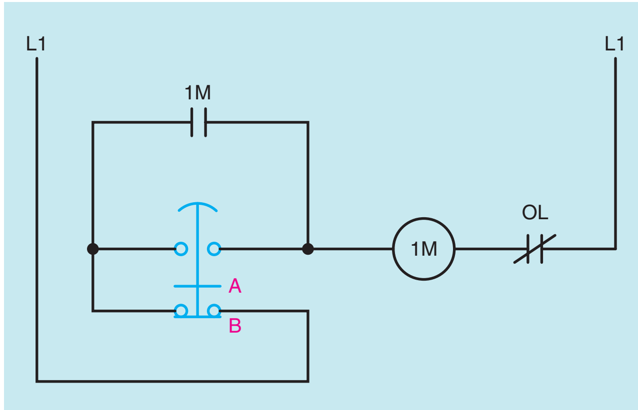


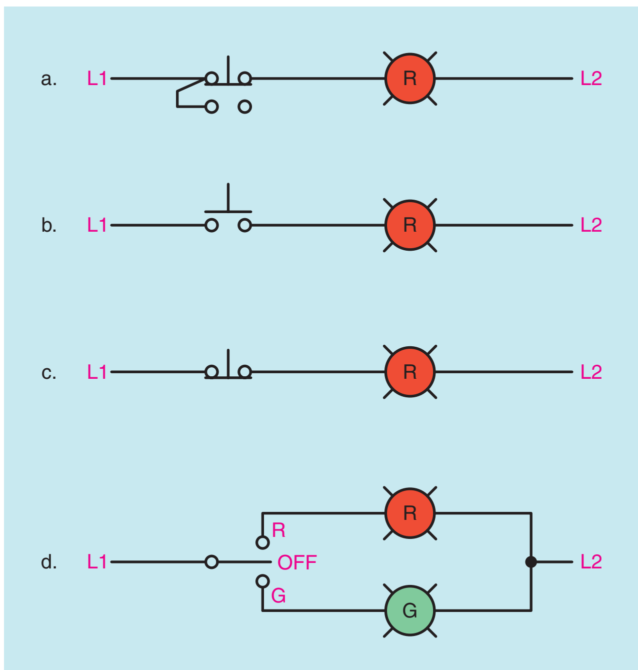
Figure 14–17 Push-pull operated used as a start-stop motor control.

Review Questions

1. What is meant by normally open contacts and normally closed contacts?
2. Why is it that normally open and normally closed contacts cannot be closed simultaneously?
3. How are colored pilot lights indicated in wiring diagrams?

Select the *best* answer for each of the following.

4. A single-break control is a
   a. heavy duty selector switch
   b. single-circuit push button
   c. standard duty selector switch
   d. double-circuit push button
5. Control stations may contain
   a. push buttons
   b. selector switches
   c. indicating lights
   d. all of these
6. A wobble stick is
   a. operated from any direction
   b. knob controlled
   c. palm controlled
   d. glove operated
7. Common selector switches are
   a. one position
   b. two positions
   c. three positions
   d. two and three positions
8. Most push buttons are
   a. momentary contact
   b. single contact
   c. double contact
   d. a combination
9. Control station enclosures are
   a. general purpose
   b. explosion proof
   c. watertight
   d. all of these
10. The diagram that illustrates a single circuit, normally closed push button is



11. One type of push-pull operator contains
    a. Two normally closed momentary contacts
    b. Two normally closed maintained contacts
    c. Two normally open momentary contacts
    d. Two normally open maintained contacts

12. Another type of push-pull operator contains
    a. Two momentary normally closed contacts
    b. One maintained normally open contact and one momentary normally closed contact
    c. Two maintained normally open contacts
    d. One maintained normally closed contact and one momentary normally open contact

UNIT 15
RELAYS AND CONTACTORS

OBJECTIVES

After studying this unit, the student will be able to:

- Tell how magnetic relays differ from contactors.
- List the principal uses of each magnetic relay and contactor.
- Describe the operation of magnetic blowout coils and how they provide arc suppression.
- Identify single and double throw contacts; single and double break contacts.
- Draw the wiring diagram symbols for contactors and relays.
- Describe the operation and use of mechanically held relays.
- Draw elementary diagrams of control and load for mechanically held relays and contactors.
- Connect wiring for mechanically held relays and contactors.

Control Relays

Control magnetic relays are used as auxiliary devices to switch control circuits and large motor starter and contactor coils, and to control small loads such as small motors, solenoids, electric heaters, pilot lights, audible signal devices, and other relays (Figure 15–1).

A magnetically held relay is operated by an electromagnet which opens or closes electrical contacts when the electromagnet is energized. The position of the contacts changes by spring and gravity action when the electromagnet is de-energized.

Relays are generally used to enlarge or amplify the contact capability, or multiply the switching functions of a pilot device by adding more contacts to the circuit (Figures 15–2 and 15–3).

Most relays are used in control circuits; therefore, their lower ratings (0–15 amperes maximum to 600 volts) show the reduced current levels at which they operate.

Magnetic relays do not provide motor overload protection. This type of relay ordinarily is used in a two-wire control system (any electrical contact-making device with two wires). Whenever it is desired to use momentary contact pilot devices, such as push buttons,

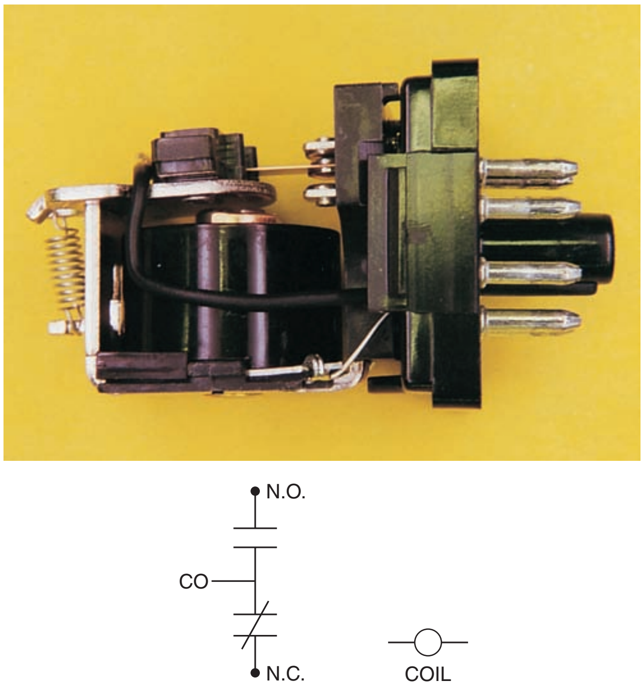


Figure 15–1 Single-pole, double-throw, single break AC control relay with wiring symbols.

any available normally open contact can be wired as a holding circuit in a three-wire system. The contact arrangement and the magnetic structure of relays is described in Unit 13. Starters, contactors, and relays are similar in construction and operation but are not identical.

Control relays are available in single- or double-throw arrangements with various combinations of normally open (NO) and normally closed (NC) contact circuits. While there are some single-break contacts used in industrial relays, most of the relays used in machine tool control have double-break contacts. Figures 15–1 and 15–2 illustrate the difference. Looking at the relay contacts in Figure 15–2, note the upper contact being open at two points, making it a double break. The lower contact is normally closed with a circuit from the left-hand terminal screw, through the double-break contact to the right-hand terminal screw. One set of normally closed and one of normally open contacts represents this description with the wiring symbols. This is also a single-throw contact because it has no common connection between the normally open and normally closed contacts, such as can be seen in Figure 15–1. The common terminal between the normally closed and

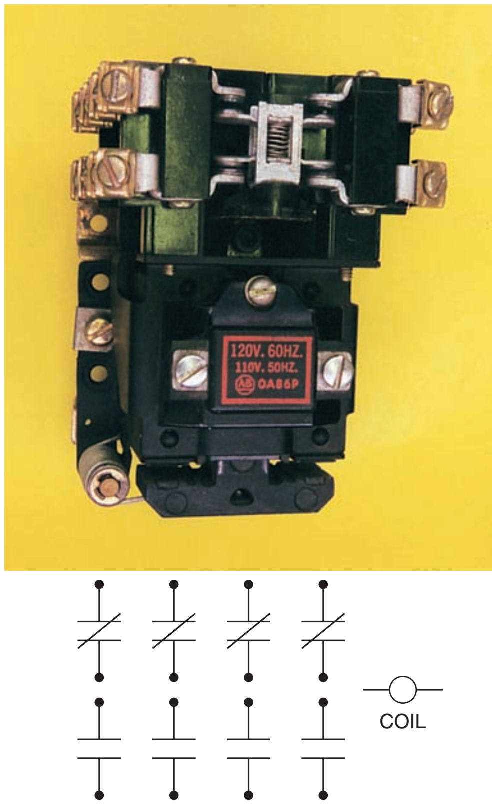


Figure 15–2 Eight-pole control relay with four normally open and four normally closed contacts.

normally open contacts makes this a "single-pole, double-throw" relay.

Some of the most popular control relays are the eight- and eleven-pin relays shown in Figure 15–3.

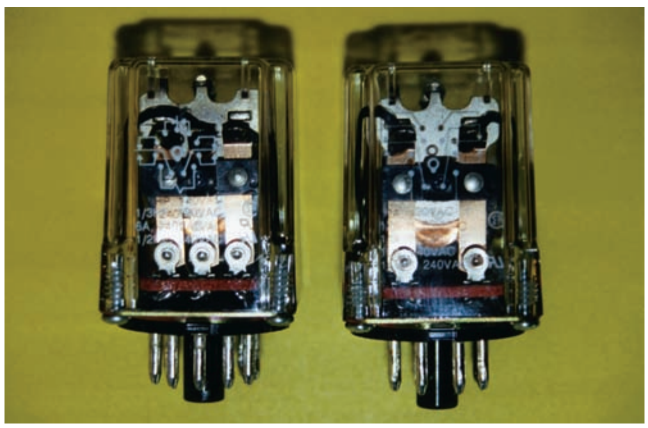


Figure 15–3 Eleven- and eight-pin relays.

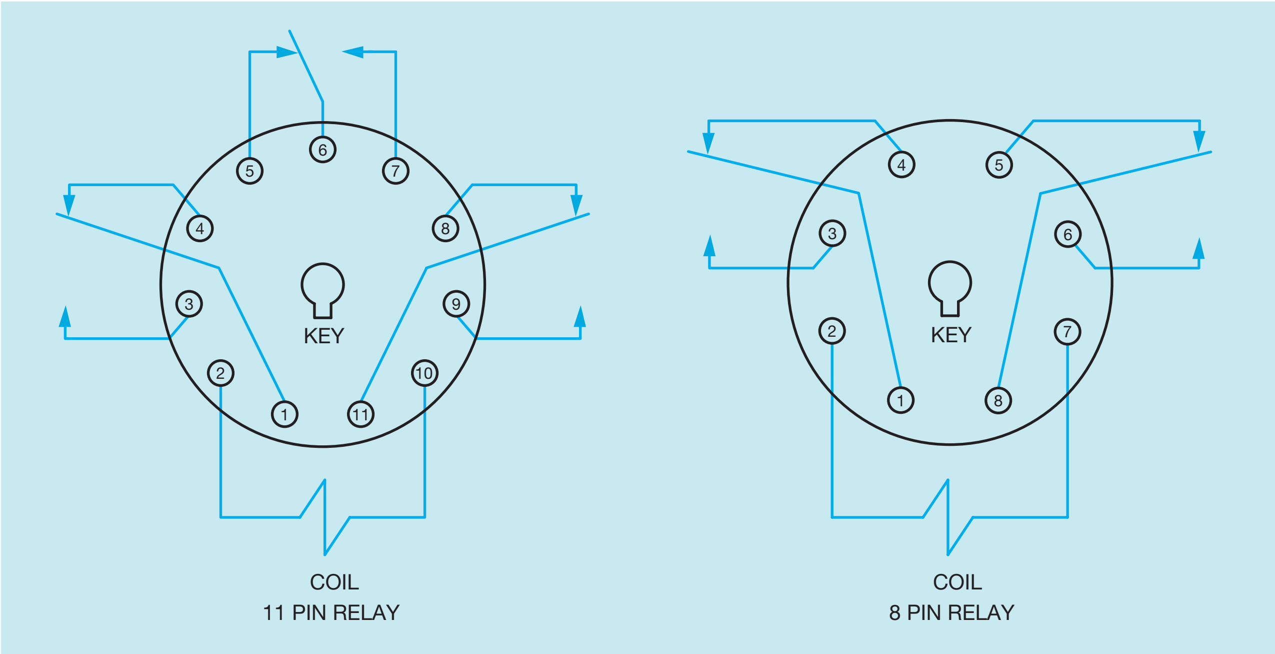


Figure 15–4 Connection diagrams for eleven- and eight-pin relays.

These relays are often called *ice cube* relays because of their appearance. They are inexpensive, reliable, and very easy to replace when necessary. These relays are designed to fit into common eight- and eleven-pin relay sockets. All wiring is connected to the socket, not the relay. When replacement is necessary, the relay is simply removed from the socket and a new one plugged in. The pin diagrams for both eight- and eleven-pin relays are shown in Figure 15–4.

It may be of particular interest to an electrician to know about changing contacts that are normally open to normally closed, or the other way around, NC to NO. Most machine tool relays have some means to make this change. It ranges from a simple flip-over contact to removing the contacts and relocating with spring location changes.

Also, by overlapping contacts in this case, one contact can be arranged to operate at a different time relative to another contact on the same relay. For example, the normally open contact closes before the normally closed contact opens.

Relays differ in voltage ratings, number of contacts, contact rearrangement, physical size, and in attachments to provide accessory functions such as mechanical latching and timing.

In using a relay for a particular application, one of the first steps should be to determine the control (coil) voltage at which the relay will operate. The necessary contact rating must be made, as well as the number of contacts and other characteristics needed. Because of the variety of styles of relays available, it is possible to select the correct relay for almost any application.

Relays are used more often to open and close control circuits than to operate power circuits. Typical applications include the control of motor starter and contactor coils, the switching of solenoids, and the control of other relays. A relay is a small but vital switching component of many complex control systems. Low-voltage relay systems are used extensively in switching residential and commercial lighting circuits and individual lighting fixtures.

While control relays from various manufacturers differ in appearance and construction, they are interchangeable in control wiring systems if their specifications are matched to the requirements of the system. Different types of relays are shown in Figure 15–5.

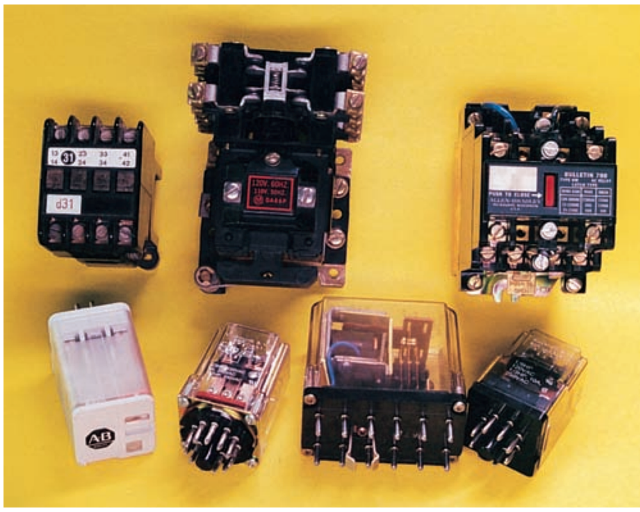


Figure 15–5 Different types of control relays found throughout industry.

Contactors

Magnetic contactors are electromagnetically operated switches that provide a safe and convenient means for connecting and interrupting branch circuits. The principal difference between a contactor and a motor starter is that the contactor does not contain overload relays. Contactors are used in combination with pilot control devices to switch lighting and heating loads and to control ac motors in those cases where overload protection is provided separately. The larger contactor sizes are used to provide remote control of relatively high-current circuits where it is too expensive to run the power leads to the remote controlling location (Figure 15–6). This flexibility is one of the main advantages of electromagnetic control over manual control. Pilot devices such as push buttons, float switches, pressure switches, limit switches, and thermostats are provided to operate the contactors.

Magnetic Blowout

The contactor shown in Figure 15–7 operates on direct current. The contacts are heavy-duty and intended to open on a large amount of current. The fact that the contactor is intended for use in a direct current circuit makes opening the circuit more difficult. Alternating current turns off at frequent intervals, but direct current does not (Figure 15–8). The problem of contact arcing is much less in an alternating current circuit due to the current turning off at periodic intervals. Since the current in a dc circuit remains relatively constant, once an arc has been established it tends to continue. This can cause extreme damage to the contacts. Heavy-duty contact arc-chutes are provided on most large contactors

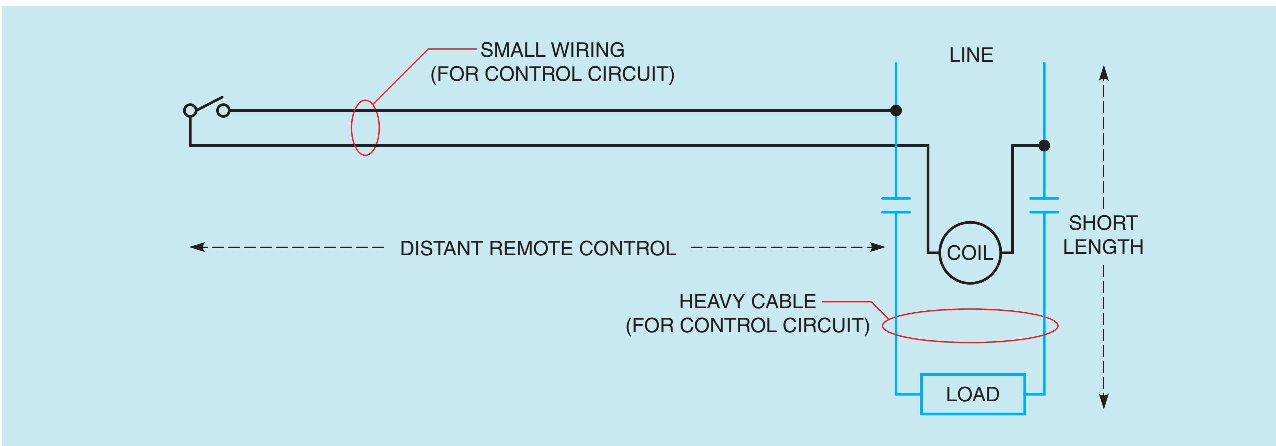


Figure 15–6 Contactor.

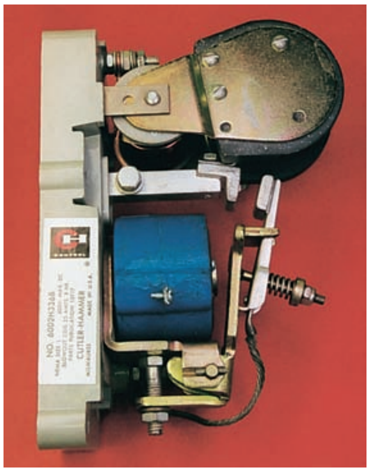


Figure 15–7 Open magnetic contactor with blow-out coil used primarily for control of direct-current devices. Contactor is of the “clapper” type.

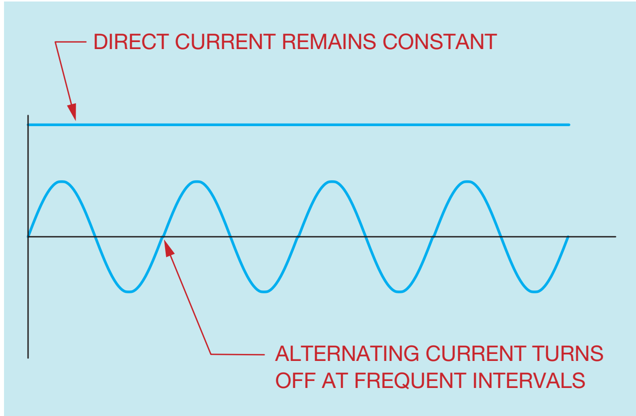


Figure 15–8 Direct current remains constant and alternating current turns off at periodic intervals.

like the one shown in Figure 15–7. The chutes contain heavy copper coils called blowout coils, mounted above the contacts in series with the load to provide better arc suppression. These magnetic blowout coils help to extinguish an electric arc at contacts opening under ac and dc loads. These arcs may be similar in intensity to the electric arc welding process. An arc-quenching device is used to ensure longer contact life. Since the hot arc is transferred from the contact tips very rapidly, the contacts remain cool and, thereby, last longer.

Contactor and motor starter contacts that frequently break heavy currents are subject to a destructive burning effect if the arc is not quickly extinguished. the arc that is formed when the contacts open can be lengthened, and extinguished by motor action if it is in a magnetic field. This magnetic field is provided by the magnetic blowout coil. Since the coil of the magnet is usually in

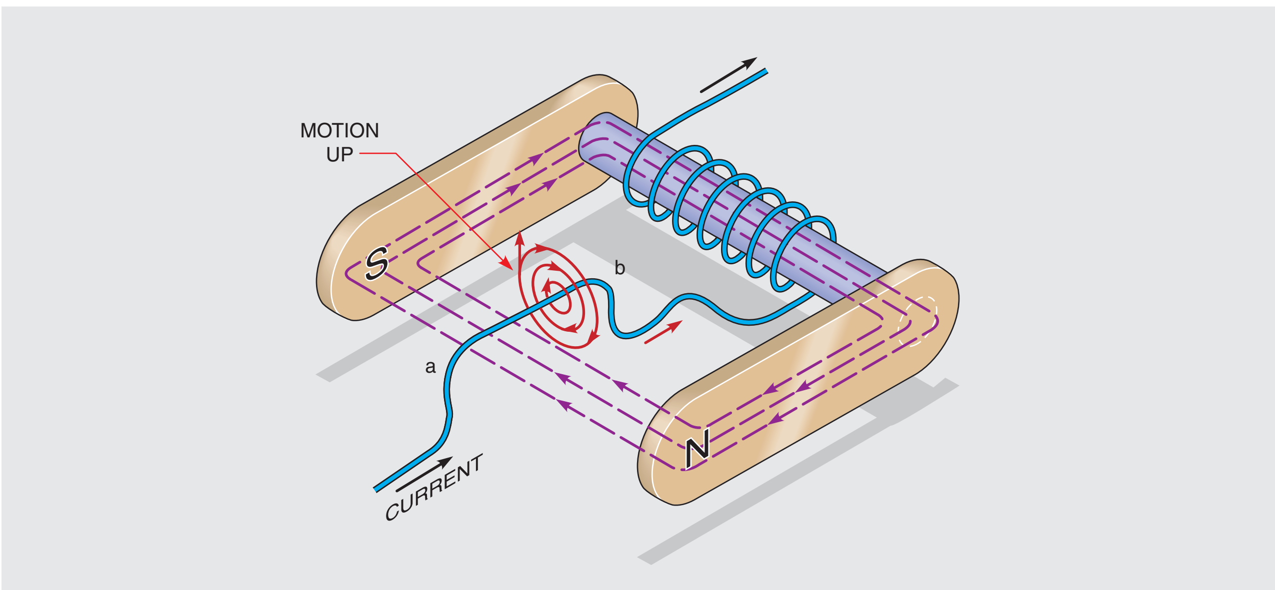


Figure 15–9 Illustration of the magnetic blowout principle. Straight conductor simulates arc.

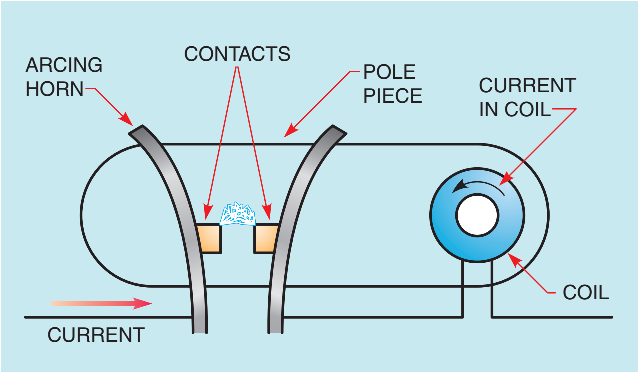


Figure 15–10 Section of blowout magnet with straight conductor replaced by a set of contacts. An arc is conducting between the contacts.

series with the line, the field strength and extinguishing action are in proportion to the size of the arc.

Figure 15–9 is a sketch of a blowout magnet with a straight conductor (ab) located in the field and in series with the magnet. This figure can represent either dc polarity or instantaneous alternating current. With alternating current, the blowout coil magnetic field and the conductor (arc) magnetic field will reverse simultaneously. According to Fleming's left-hand rule, motor action will tend to force the conductor in an upward direction. The application of the right-hand rule for a single conductor shows that the magnetic field around the conductor aids the main field on the bottom and opposes it on the top, thus producing an upward force on the conductor.

Figure 15–10 shows a section of Figure 15–9 with the wire (ab) replaced by a set of contacts. The contacts have started to open and there is an arc between them.

Figure 15–11 shows what happens because of the magnetic action. Part A shows the beginning deflection of the arc because of the effect of the motor action. Part B shows that the contacts are separated more than in A and the arc is beginning to climb up the horns because of the motor action and the effect of increased temperature. Part C of Figure 15–11 shows the arc near the tips of the horns. At this point, the arc is so lengthened that it will be extinguished.

The function of the blowout magnet is to move the arc upward at the same time that the contacts are opening. As a result, the arc is lengthened at a faster rate than would normally occur because of the opening of the contacts alone. It is evident that the shorter the time the arc is allowed to exist, the less damage it will do to the contacts. Most arc quenching action is based upon this principle.

AC Mechanically Held Contactors and Relays

Mechanically held contactors and relays are often referred to as *latching* contactors or relays. They employ two electromagnets to operate. One coil is generally called the *latch* coil and the other is called the *unlatch* coil. The latch coil causes the contacts to change position and mechanically hold in position after power is removed from the latch coil. To return the contacts to their normal de-energized position, the unlatch coil must be energized. Power to both coils is momentary. The coils of most mechanically held contactors and relays are intended for momentary use and continuous power will often cause burnout.

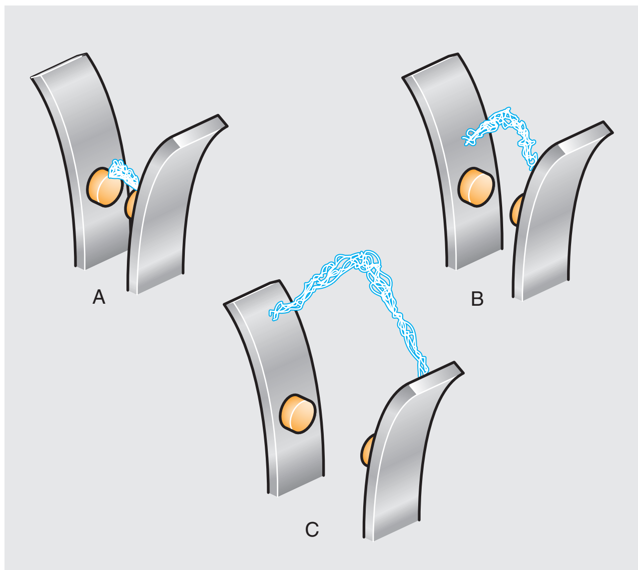


Figure 15–11 Arc deflection between contacts.

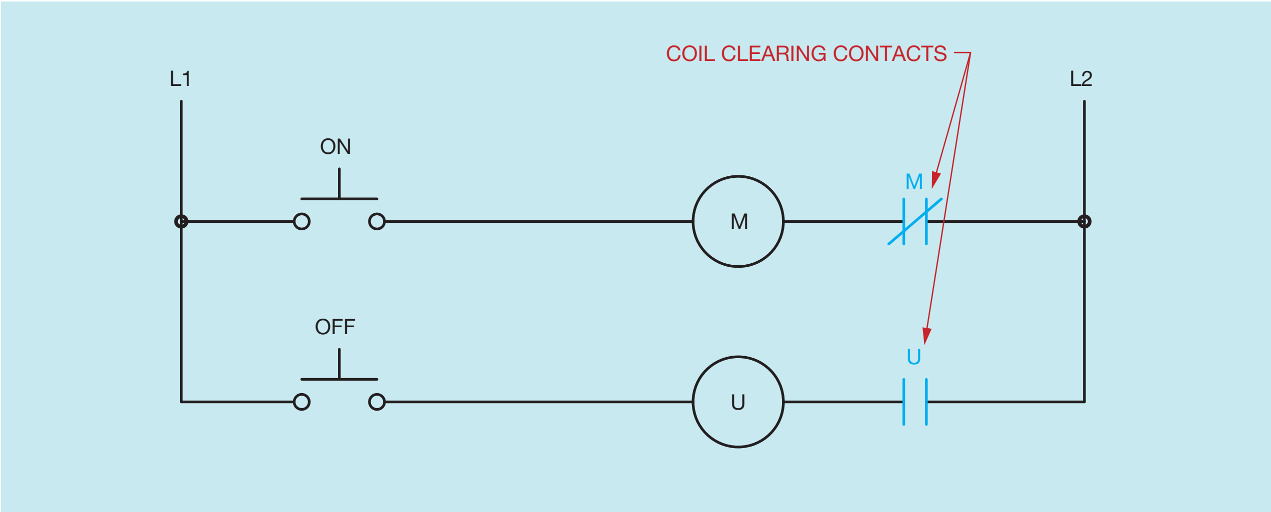


Figure 15–12A Mechanically held relay control circuit.

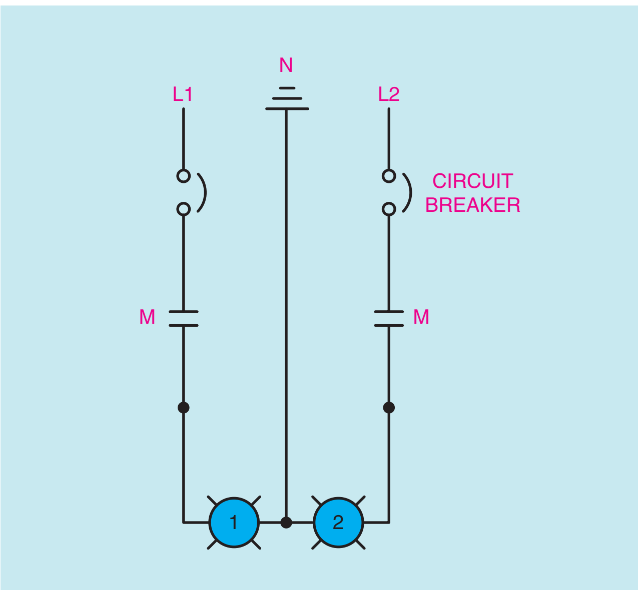


Figure 15–12B Load connections for a 115/230–volt, three-wire load.

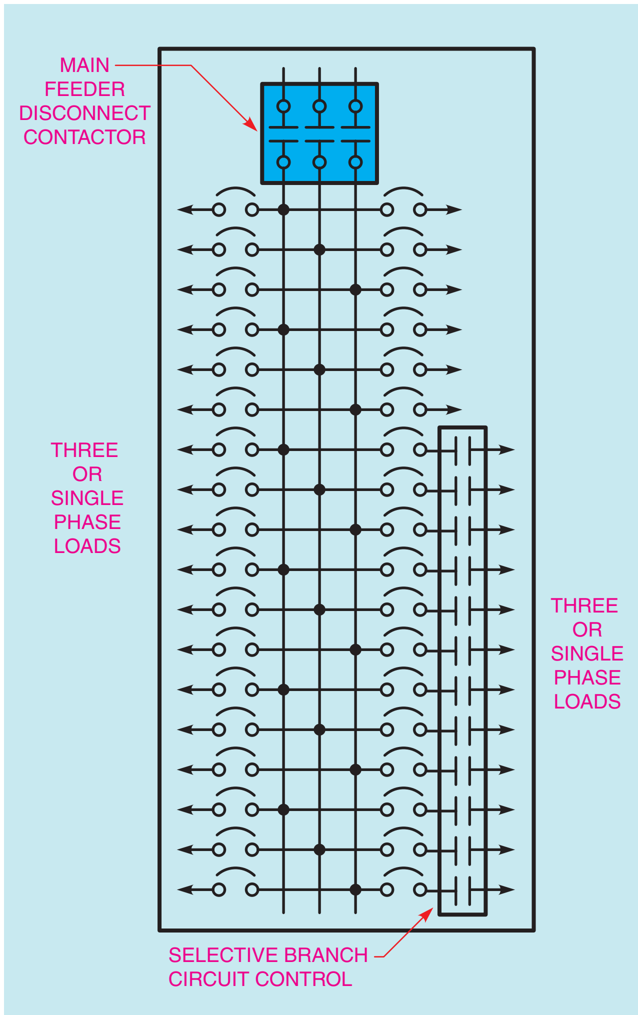


Figure 15–13 Mechanically held contactor loads for three-phase power.

Unlike common magnetic contactors or relays, the contacts of latching relays and contacts do not return to a normal position if power is interrupted. They should be used only where there is no danger of harming any person or equipment if power is suddenly restored after a power failure.

Sequence of Operation

Many latching type relays and contactors contain contacts that are used to prevent continuous power being supplied to the coil after it has been energized. These contacts are generally called *coil clearing contacts.* In Figure 15–12A, coil M is the latching coil and coil U is the unlatch coil. When the ON push button is pressed, current can flow to coil M, through normally closed contact M to L2. When the relay changes to the latch position, the normally closed M contact connected in series with coil M opens and disconnects power to coil M. This prevents further power from being supplied to coil M. At the same time, the open contact U connected in series with coil U closes to permit operation of coil U when the OFF push button is pressed. When coil M is energized, it also closes the M load contacts shown in Figure 15–12B, energizing a bank of lamps when the circuit breaker is closed. The lamps can be turned off by pressing the OFF push button and energizing coil U. This causes the relay to return to the normal position shown in Figure 15–12A. Notice that the coil clearing contacts prevent power from being supplied continuously to the coils of the mechanically held relay.

Figure 15–13 shows a three-phase power load application using one main contactor to disconnect the distribution panel. Selective single, or three-phase, branch circuits may be switched independently by other mechanically held contactors or relays.

These mechanically held contactors and relays are electromechanical devices (Figure 15–14). They

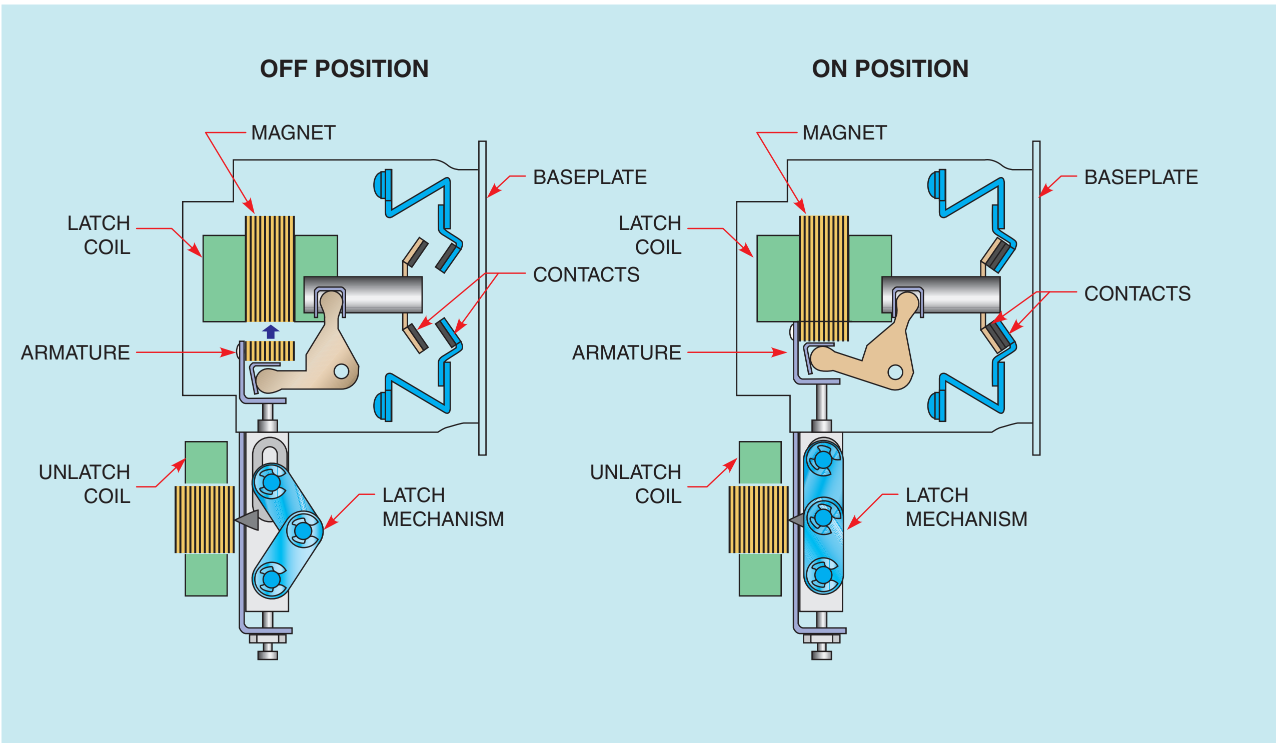


Figure 15–14 Two types of latched-in or mechanically-held relays in service. The upper coil is energized momentarily to close contacts, and the lower coil is energized to momentarily open the contact circuit. The momentary energizing of the coil is an energy-saving feature.

provide a safe and convenient means of switching circuits where *quiet operation, energy efficiency,* and *continuity of circuit connection* are requirements of the installation. For example, circuit continuity during power failures is often important in automatic processing equipment, where a sequence of operations must continue from the point of interruption after power is resumed—rather than return to the beginning of the sequence. Quiet operation of contactors and relays is required in many control systems used in hospitals, schools, and office buildings. Mechanically held contactors and relays are generally used in locations where the slight hum, characteristic of alternating-current magnetic devices, is objectionable.

In addition, mechanically held relays are often used in machine tool control circuits. These relays can be latched and unlatched through the operation of limit switches, timing relays, starter interlocks, timeclocks, photoelectric cells, other control relays, or push buttons. Generally, mechanically held relays are available in 10- and 15-ampere sizes; mechanically held contactors are also available in sizes ranging from 30 amperes to 1200 amperes.

Vacuum Contactors

Vacuum contactors enclose their load contacts in a sealed vacuum chamber. A metal bellows connected to the movable contact permits it to move without breaking a seal (Figure 15–15). Sealing contacts inside a vacuum chamber permits them to switch higher voltages with a relative narrow space between the contacts without establishing an arc. The contacts shown in Figure 15–15 are rated 7.2 KV and 400 amperes.

An electric arc is established when the voltage is high enough to ionize the air molecules between stationary and movable contacts. Medium voltage contactors are generally large because they must provide enough distance between the contacts to break the arc path. Some medium voltage contactors use arc suppressers, arc shields, and oil immersion to quench or prevent an arc. Vacuum contactors operate on the principle that if there is no air surrounding the contact, there is no ionization path for the establishment of an arc. Vacuum contactors are generally much smaller in size than other types of medium voltage contactors. A three phase vacuum contactor rated at 7.2 KV and 400 amperes is shown in Figure 15–16. A three phase vacuum contactor rated at 12 KV and 400 amperes is shown in Figure 15–17.

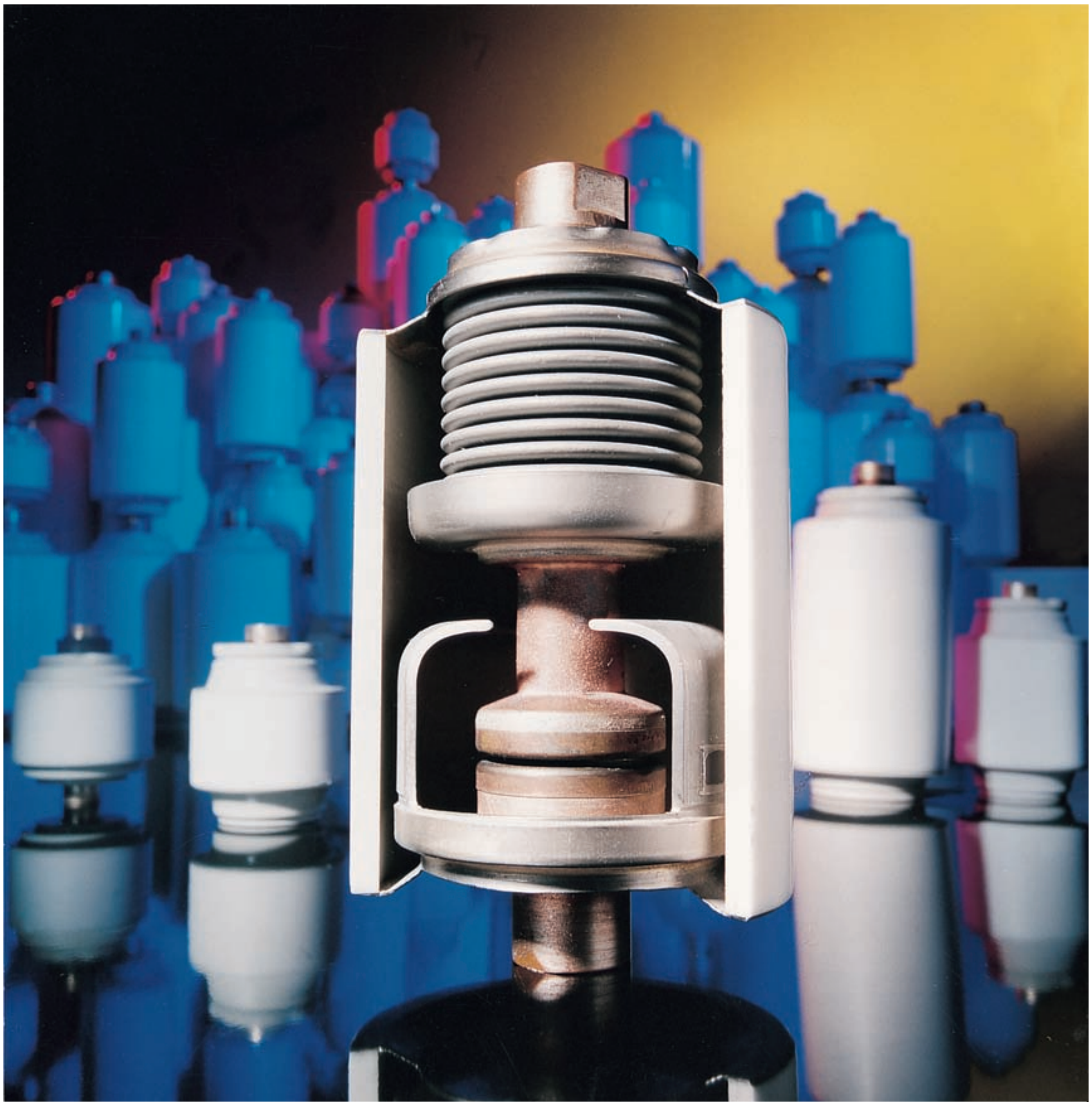


Figure 15–15 Vacuum contacts are sealed inside a vacuum chamber. (Courtesy GEC Alsthom.)

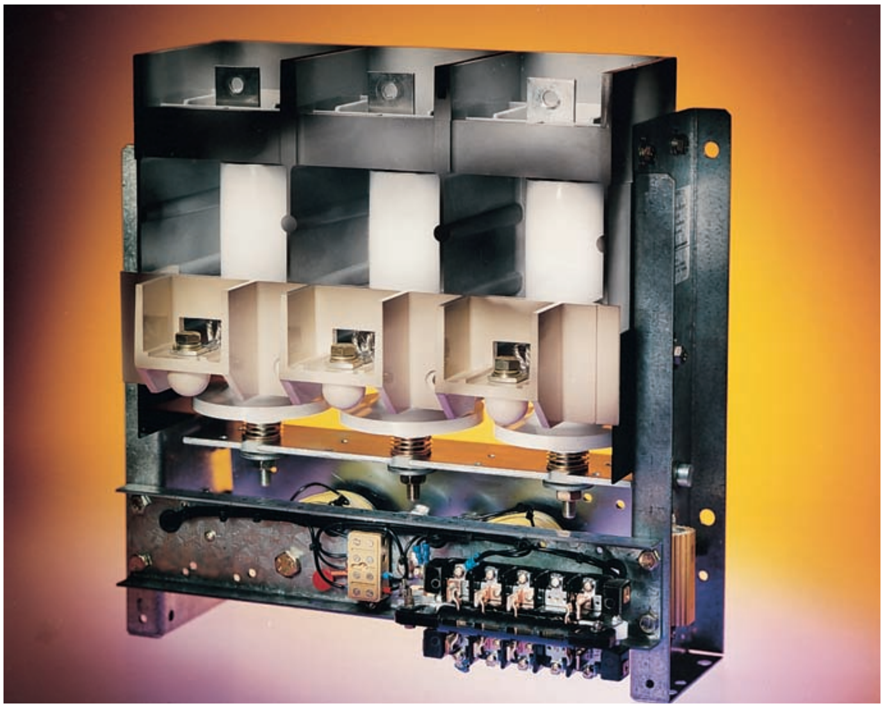


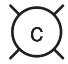
Figure 15–16 Three phase vacuum contactor rated at 7.2kV and 400 amperes. (Courtesy GEC Alsthom.)

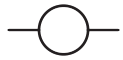
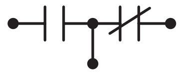
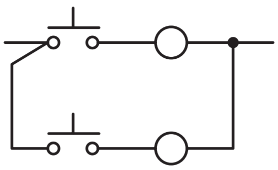
Figure 15–17 Three phase vacuum contactor rated at 12kV and 400 amperes. (Courtesy GEC Alsthom.)

Review Questions

1. What are control relays?
2 What are typical uses for control relays?
3. Why are contactors described as both control pilot devices and large magnetic switches controlled by pilot devices?
4. What is the principal difference between a contactor and a motor starter?
5. What causes the arc to move upward in a blowout magnet?
6. Why is it desirable to extinguish the arc as quickly as possible?
7. What will happen if the terminals of the blowout coil are reversed?
8. Why will the blowout coil also operate on alternating current?
9. What are the advantages of a mechanically held relay?
10. Why are mechanically held relays energy-saving devices?
11. Match each item in the left-hand column with the appropriate item in the right-hand column.

a. Double-break contact
b. Relay
c. Magnetic blowout coil
d. Single pole, double throw
e. Normally closed contact
f. Latched-in relay control
g. Single-break contact
h. Relay coil
i. Normally open contact
j. Contactor

1. 

2. 
3. 
4. 
5. Arc suppression
6. 
7. 0–15 amperes
8. Three-phase power
9. 
10. 1200 amperes
11. 
12. 

UNIT 16
THE SOLID-STATE RELAY

OBJECTIVES

After studying this unit, the student will be able to:

- Discuss the differences between dc solid-state relays and ac solid-state relays.
- Discuss opto-isolation.
- Discuss magnetic isolation.
- Connect a solid-state relay in a circuit.

The Solid-State Relay

The solid-state relay is a device that has become increasingly popular for switching applications. The solid-state relay has no moving parts, it is resistant to shock and vibration, and it is sealed against dirt and moisture. The greatest advantage of the solid-state relay, however, is the fact that the control input voltage is isolated from the line device the relay is intended to control (Figure 16–1).

Solid-state relays can be used to control dc and ac loads. If the relay is designed to control a dc load, a power transistor is used to connect the load to the line as shown in Figure 16–2. The relay shown in Figure 16–2 has a *light-emitting diode* (LED) connected to the input or control voltage. When the input voltage turns the LED on, a photodetector connected to the base of the transistor turns the transistor on and connects the load to the line. This optical coupling is a very common method used with solid-state relays. The relays that use this method of coupling are said to be *opto-isolated,* which means the load side of the relay is optically isolated from the control side of the relay. Since a light beam is used as the control medium, no voltage spikes or electrical noise produced on the load side of the relay can be transmitted to the control side of the relay.

Solid-state relays intended for use as ac controllers have a triac, rather than a power transistor, connected to the load circuit (Figure 16–3). As in Figure 16–2, an LED is used as the control device in this example. When the photodetector “sees” the LED, it triggers the gate of the triac and connects the load to the line.

Although opto-isolation is probably the most commonly used method for the control of a solid-state relay, it is not the only method used. Some relays use a small reed relay to control the output (Figure 16–4). A small set of reed contacts are connected to the gate of the triac. The control circuit is connected to the coil of the reed relay. When the control voltage causes a current to flow through the coil, a magnetic field is produced around the coil of the relay. This magnetic field closes the reed contacts, causing the triac to turn on. In this type of solid-state relay a magnetic field, rather than

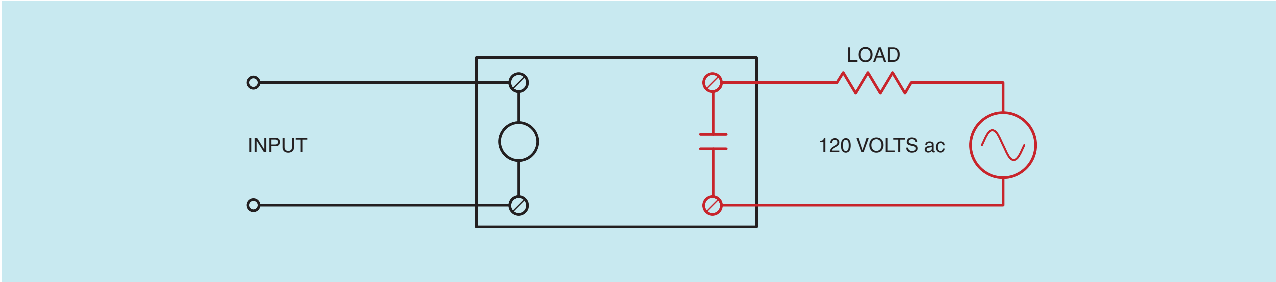


Figure 16–1 Solid-state relay.

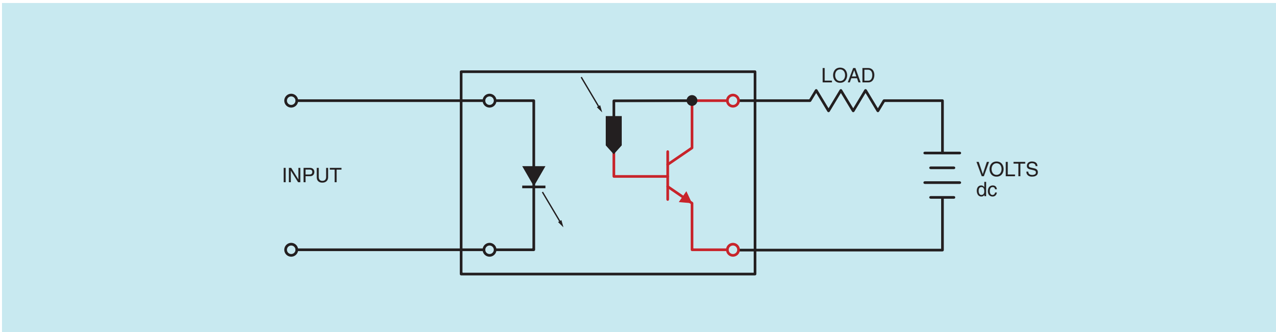


Figure 16–2 Power transistor used to control a dc load.

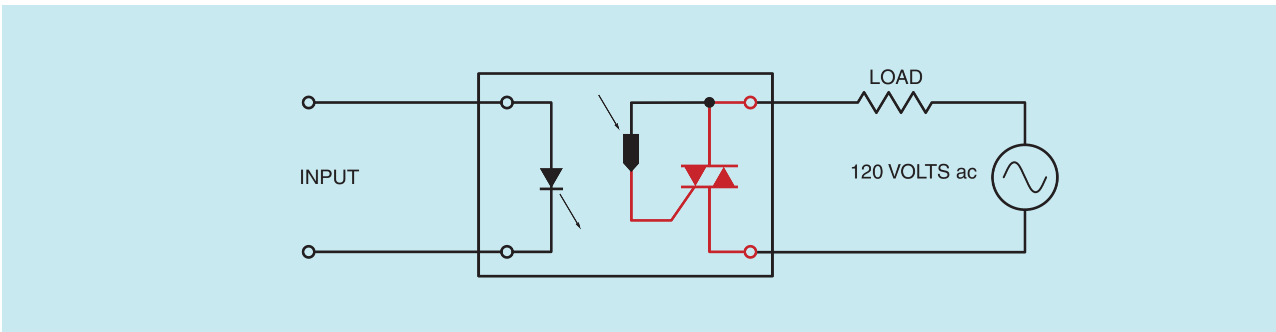


Figure 16–3 Triac used to control an ac load.

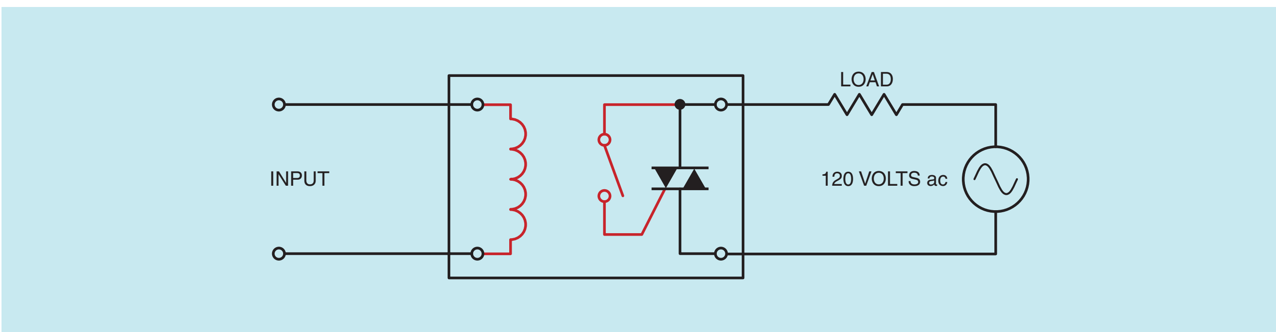


Figure 16–4 Reed relay controls the output of a solid-state relay.

a light beam, is used to isolate the control circuit from the load circuit.

The control voltage for most solid-state relays ranges from about 3 to 32 volts and can be dc or ac. If a triac is used as the control device, load voltage ratings of 120 to 240 volts ac are common and current ratings can range from 5 to 25 amps. Many solid-state relays have a feature known as *zero switching*. Zero switching means that if the relay is told to turn off when the ac voltage is in the middle of a cycle, it will continue to conduct until the ac voltage drops to a zero level, and will then turn off. For example, assume that the ac voltage is at its positive peak value when the gate tells the triac to turn off. The triac will continue to conduct until the ac voltage drops to a zero level before it actually turns off. Zero switching can be a great advantage when used with some inductive loads such as transformers. The core material of a transformer can be left saturated on one end of the flux swing if power is removed from the primary winding when the ac voltage is at its positive or negative peak. This can cause inrush currents of up to 600% of the normal operating current when power is restored to the primary winding.

Solid-state relays are available in different case styles and power ratings. Figure 16–5 shows a typical solid-state relay. Some solid-state relays are designed to be used as time delay relays. One of the most common uses for the solid-state relay is the I/O (eye-oh) track of a programmable controller, which will be covered in a later unit.

Figure 16–5 Solid-state relay. (Courtesy International Rectifier.)

Review Questions

1. What electronic component is used to control the output of a solid-state relay used to control a dc voltage?
2. What electronic component is used to control the output of a solid-state relay used to control an ac voltage?
3. Explain opto-isolation.
4. Explain magnetic isolation.
5. What is meant by zero switching?

UNIT 17
TIMING RELAYS

OBJECTIVES

After studying this unit, the student will be able to:

- Identify the primary types of timing relays.
- Explain the basic steps in the operation of the common timing relays.
- List the factors that affect the selection of a timing relay for a particular use.
- List applications of several types of timing relays.
- Draw simple circuit diagrams using timing relays.
- Identify *on*- and *off*-delay timing wiring symbols.

Time delay relays can be divided into two general classifications: the on-delay relay, and the off-delay relay. The on-delay relay is often referred to as DOE which stands for "Delay On Energize." The off-delay relay is often referred to as DODE which stands for "Delay On De-Energize."

Timer relays are similar to other control relays in that they use a coil to control the operation of some number of contacts. The difference between a control relay and a timer relay is that the contacts of the timer relay delay changing their position when the coil is energized or de-energized. When power is connected to the coil of an on-delay timer, the contacts delay changing position for some period of time. For this example assume that the timer has been set for a delay of 10 seconds. Also assume that the contact is normally open. When voltage is connected to the coil of the on-delay timer, the contacts will remain in the open position for 10 seconds and then close. When voltage is removed and the coil is de-energized, the contact will immediately change back to its normally open position. The contact symbols for an on-delay relay are shown in Figure 17–1.

The operation of the off-delay timer is the opposite of the operation of the on-delay timer. For this example, again assume that the timer has been set for a delay of 10 seconds, and also assume that the contact is normally open. When voltage is applied to the coil of the off-delay timer, the contact will change immediately from open to closed. When the coil is de-energized, however, the contact will remain in the closed position for 10 seconds before it reopens. The contact symbols for an off-delay relay are shown in Figure 17–2. Time-delay relays can have normally open, normally closed, or a combination of normally open and normally closed contacts.

Although the contact symbols shown in Figures 17–1 and 17–2 are standard NEMA symbols for on-delay and off-delay contacts, some control schematics may use a different method of indicating timed contacts. The abbreviations TO and TC are used with some control schematics to indicate a time-operated contact. *TO stands for time opening, and TC stands for time closing*. If these abbreviations are used with standard contact symbols, their meaning can be confusing. Figure 17–3 shows a standard normally open contact symbol with the abbreviation TC written beneath it. This contact must be connected to an on-delay relay if it is to be time delayed when closing. Figure 17–4 shows the same contact with the abbreviation TO beneath it. If this contact is to be time delayed when opening, it must be operated by an off-delay timer. These abbreviations can also be used with standard NEMA symbols as shown in Figure 17–5.

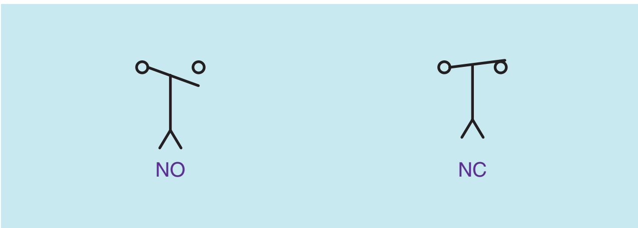


Figure 17–1 On-delay normally open and normally closed contacts.

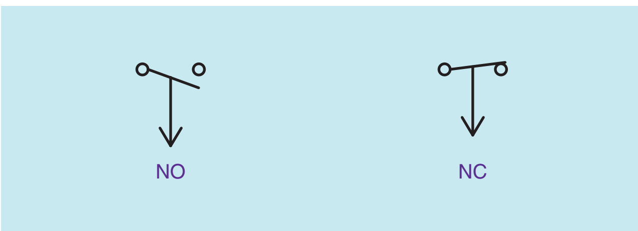


Figure 17–2 Off-delay normally open and normally closed contacts.

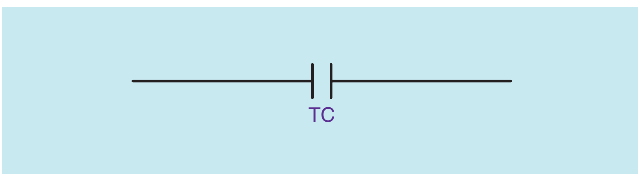


Figure 17–3 Time closing contact.

Pneumatic Timers

Pneumatic, or air timers, operate by restricting the flow of air through an orifice to a rubber bellows or diaphragm. Figure 17–6 illustrates the principle of operation of a simple bellows timer. If rod "A" pushes against the end of the bellows, air is forced out of the bellows through the check valve as the bellows contracts. When the bellows is moved back, contact TR changes from an open to a closed contact. When rod "A" is pulled away from the bellows, the spring tries to return the bellows to its original position. Before the bellows can be returned to its original position, however, air must enter the bellows through the air inlet port. The rate at which the air is permitted to enter the bellows is controlled by the needle valve. When the bellows returns to its original position, contact TR returns to its normally open position.

Pneumatic timers are popular throughout industry because they have the following characteristics:

A. They are unaffected by variations in ambient temperature or atmospheric pressure.

B. They are adjustable over a wide range of time periods.

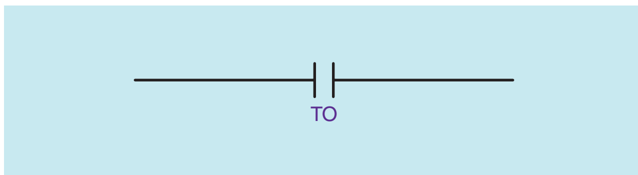


Figure 17–4 Time opening contact.

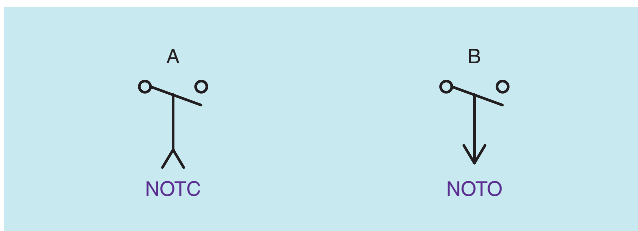


Figure 17–5 Contact A is an on-delay contact with the abbreviation NOTC (normally open time closing). Contact B is an off-delay contact with the abbreviation NOTO (normally open time opening).

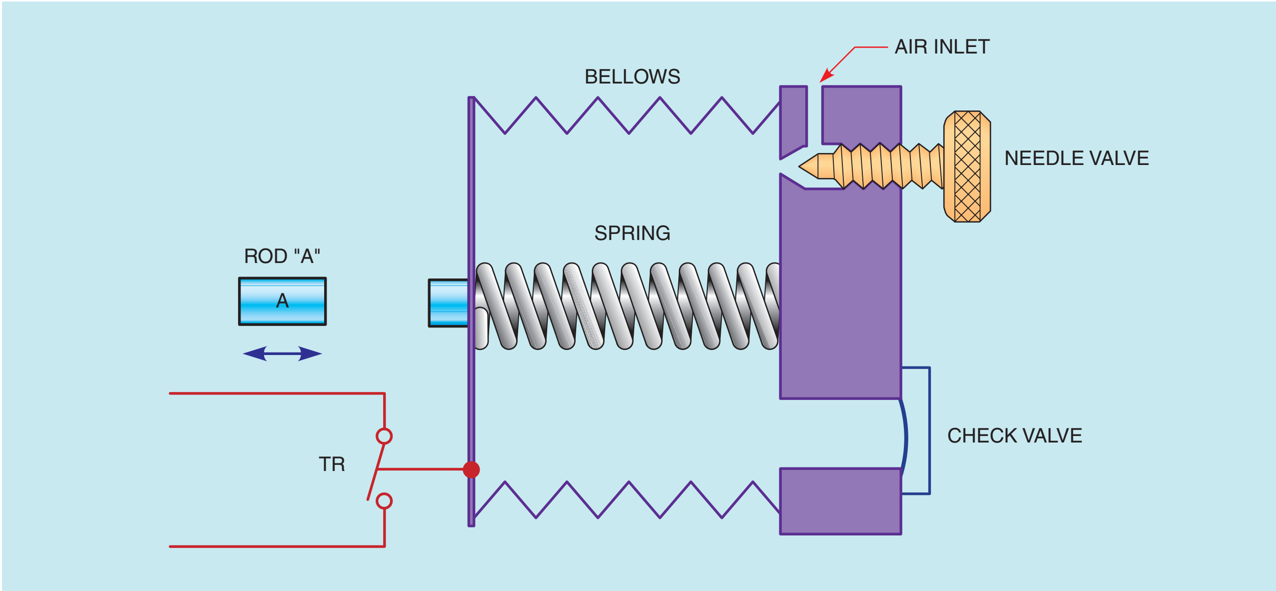


Figure 17–6 Bellows-operated pneumatic timer.

C. They have good repeat accuracy.

D. They are available with a variety of contact and timing arrangements.

Some pneumatic timers are designed to permit the timer to be changed from on-delay to off-delay, and the contact arrangement to be changed to normally opened or normally closed (Figure 17–7). This type of flexibility is another reason for the popularity of pneumatic timers.

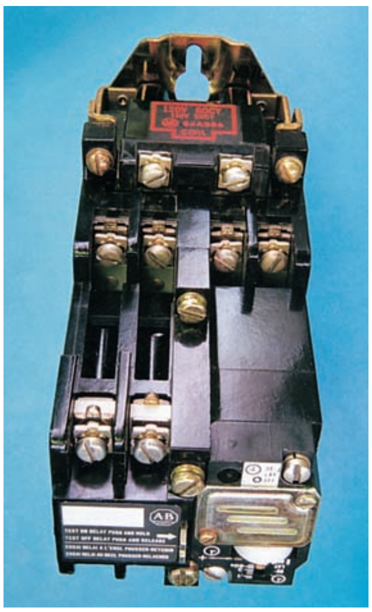


Figure 17–7 Pneumatic timer. (Courtesy Allen-Bradley, a Rockwell International company)

Many timers are made with contacts that operate with the coil as well as time delayed contacts. When these contacts are used, they are generally referred to as *instantaneous contacts* and indicated on a schematic diagram by the abbreviation, inst., printed below the contact (Figure 17–8). These instantaneous contacts change their positions immediately when the coil is energized and change back to their normal positions immediately when the coil is de-energized.

Clock Timers

Another timer frequently used is the clock timer (Figure 17–9). Clock timers use a small ac synchronous motor similar to the motor found in a wall clock to provide the time measurement for the timer. The

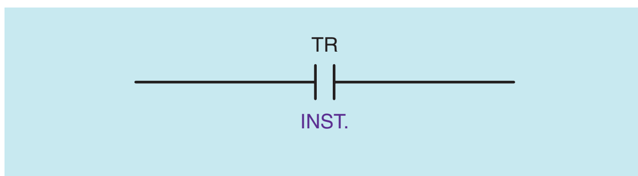


Figure 17–8 Normally open instantaneous contact of a timer relay.

Figure 17–9 Clock driven timer.

length of time of one clock timer may vary greatly from the length of time of another. For example, one timer may have a full range of 0 to 5 seconds and another timer may have a full range of 0 to 5 hours. The same type of timer motor could be used with both timers. The gear ratio connected to the motor would determine the full range of time for the timer. Some advantages of clock timers are:

A. They have extremely high repeat accuracy.

B. Readjustment of the time setting is simple and can be done quickly. Clock timers are generally used when the machine operator must make adjustments of the time length.

Motor-Driven Timers

When a process has a definite on and off operation, or a sequence of successive operations, a motor-driven timer is generally used (Figures 17–10 and 17–11). A typical application of a motor-driven timer is to control laundry washers where the loaded motor is run for a given period in one direction, reversed, and then run in the opposite direction.

Generally, this type of timer consists of a small, synchronous motor driving a cam-dial assembly on a common shaft. A motor-driven timer successively closes and opens switch contacts which are wired in circuits to energize control relays or contactors to achieve desired operations.

Min. Time Delay: 0.05 second

Max. Time Delay: 3 minutes

Minimum Reset Time: 0.75 second

Accuracy: 610 percent of setting

Contact Ratings:

Ac
6.0 A, 115 V
3.0 A, 230 V
1.5 A, 460 V
1.2 A, 550 V

Dc
1.0 A, 115 V
0.25 A, 230 V

Operating Coils: Coils can be supplied for voltages and frequencies up to 600 volts, 60 hertz ac and 250 volts dc

Types of Contact: One normally open and one normally closed. Cadmium silver alloy contacts.

Figure 17–10 Typical specifications.

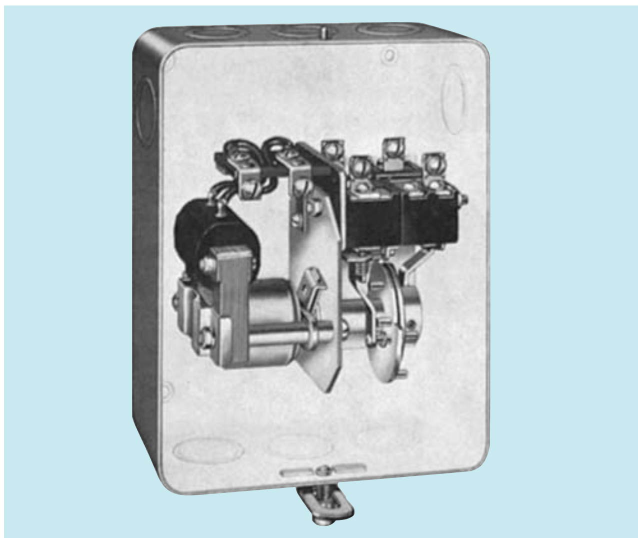


Figure 17–11 Motor-driven process timer. Often referred to as a cam timer. (Courtesy Allen-Bradley, a Rockwell International company)

Capacitor Time Limit Relay

Assume that a capacitor is charged by connecting it momentarily across a dc line and then the capacitor direct current is discharged through a relay coil. The current induced in the coil will decay slowly, depending on

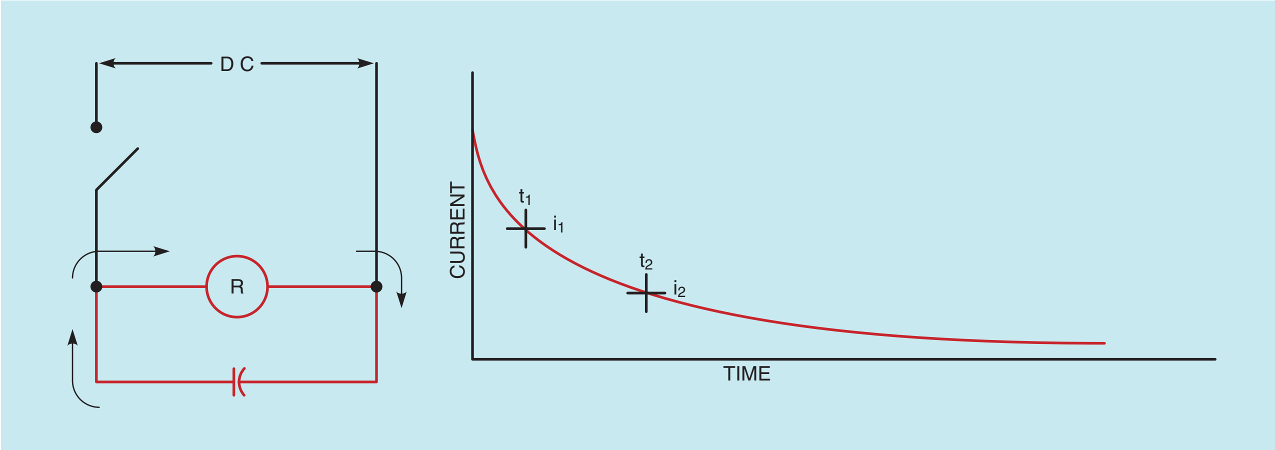


Figure 17–12 Charged capacitor discharging through a relay coil. The graph at the right illustrates the current decrease in the coil.

the relative values of capacitance, inductance, and resistance in the discharge circuit.

If a relay coil and a capacitor are connected parallel to a dc line (Figure 17–12), the capacitor is charged to the value of the line voltage and a current appears in the coil. If the coil and capacitor combination is now removed from the line, the current in the coil will start to decrease along the curve shown in Figure 17–12.

If the relay is adjusted so that the armature is released at current i_1, a time delay of t_1 is obtained. The time delay can be increased to a value of t_2 by adjusting the relay so that the armature will not be released until the current is reduced to a value of i_2. Figure 17–13 shows a relay used for this type of time control.

A potentiometer is used as an adjustable resistor to vary the time. This resistance-capacitance (RC) theory is used in industrial electronic and solid-state controls also. This timer is highly accurate and is used in motor acceleration control and in many industrial processes.

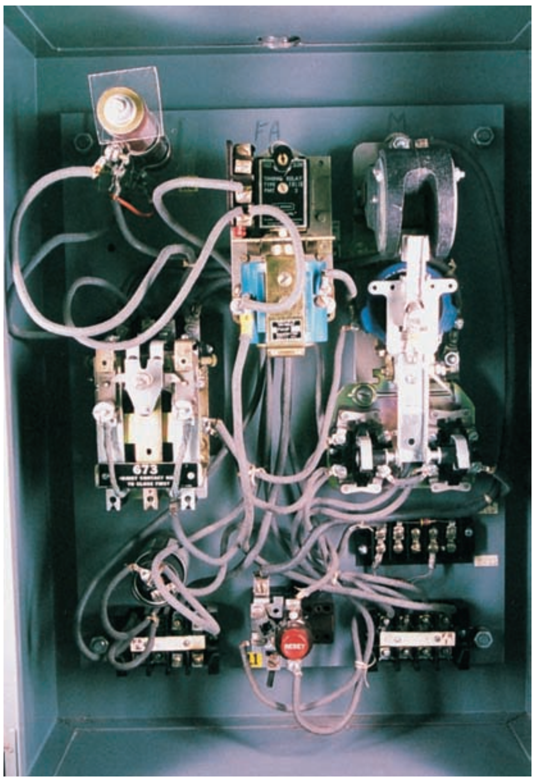


Figure 17–13 Capacitor timer limit controller. (Generally used with direct current control systems.)

Electronic Timers

Electronic timers use solid-state components to provide the time delay desired. Some of these timers use an RC time constant to obtain the time base and others use quartz clocks as the time base (Figure 17–14). RC time constants are inexpensive and have good repeat times. The quartz timers, however, are extremely accurate and can often be set for .1 second times. These timers are generally housed in a plastic case and are designed to be plugged into some type of socket. An electronic timer that is designed to be plugged into a standard eight-pin tube socket is shown in Figure 17–15. The length of the time delay can be set by adjusting the control knob shown on top of the timer.

Eight-pin electron timers similar to the one shown in Figure 17–15 are intended to be used as on-delay timers only. Many electronic timers are designed to

Figure 17–14 Digital clock timer.

Figure 17–15 Electronic timer.

plug into an eleven-pin tube socket (Figure 17–16) and are more flexible. Two such timers are shown in Figure 17–17A and Figure 17–17B. Either of these timers can be used as an on-delay timer, an off-delay timer, a pulse timer, or as a one-shot timer. Pulse timers

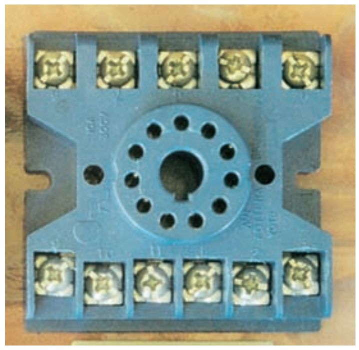


Figure 17–16 Eleven pin tube sockets.

continually turn on and off at regular intervals. A timing period chart for a pulse timer set for a delay of 1 second is shown in Figure 17–18. A one-shot timer will operate for one time period only. A timing period chart for a one shot timer set for 2 seconds is shown in Figure 17–19.

Most electronic timers can be set for a wide range of times. The timer shown in Figure 17–17A uses a thumb-wheel switch to enter the timer setting. The top selector switch can be used to set the full range value from 9.99 seconds to 999 minutes. This timer has a range from 0.01 second to 999 minutes (16 hrs. 39 min.). The timer shown in Figure 17–17B can be set for a range of 0.01 second to 100 hours by adjusting the range and units settings on the front of the timer. Most electronic timers have similar capabilities.

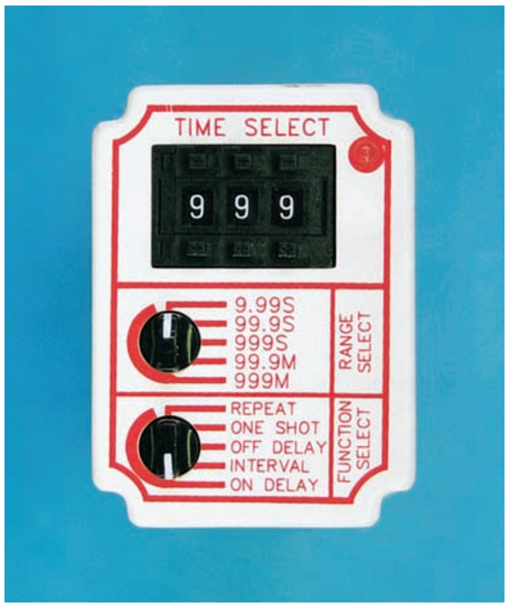


Figure 17–17A Dayton electronic timer.

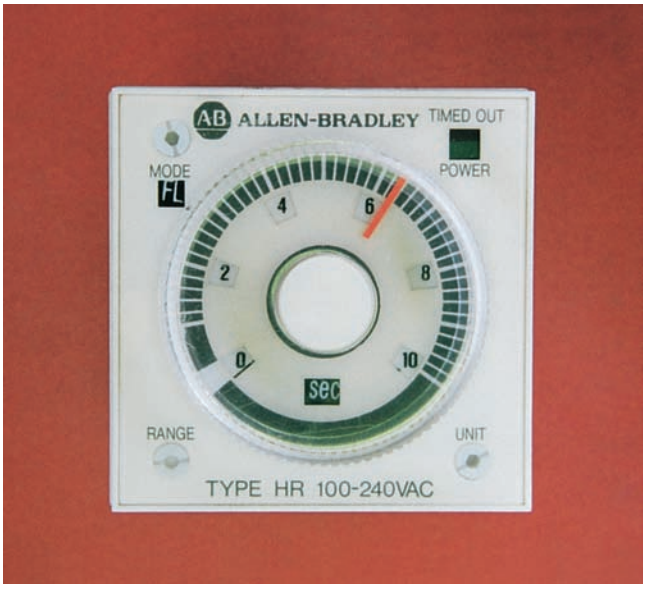


Figure 17–17B Allen-Bradley electronic timer.

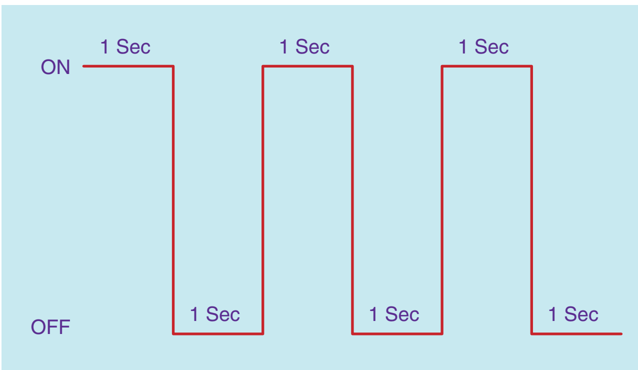


Figure 17–18 Timing chart for a pulse timer.

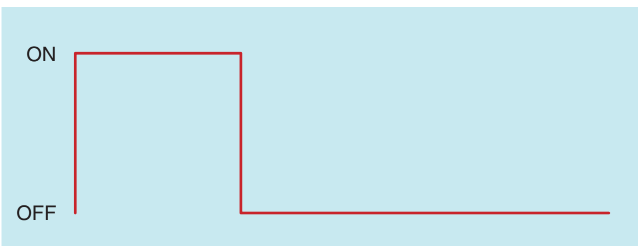


Figure 17–19 Timing chart for a one shot timer.

Connecting Eleven-Pin Timers

Connecting eleven-pin timers into a circuit is generally a little more involved than simply connecting the coil to power. The manufacturer's instructions should always be consulted before trying to connect one of these timers. Although most electronic timers are similar in how they are connected, there are differences. The pin connection diagram for the timer shown in Figure 17–17A is shown in Figure 17–20. Notice that a normally open push-button switch is shown across terminals 5 and 6. This switch is used to start the action of the timer when it is set to function as an off-delay timer or as a one-shot timer. The reason for this is that when the timer is to function as an off-delay timer, power must be applied to the timer at all times to permit the internal timing circuit to operate. If power is removed, the internal timer cannot function. The start switch is actually used to initiate the operation of the timer when it is set to function in the off-delay mode. Recall the logic of an off-delay timer: *When the coil is*

Figure 17–20 Pin connection diagram for Dayton timer.

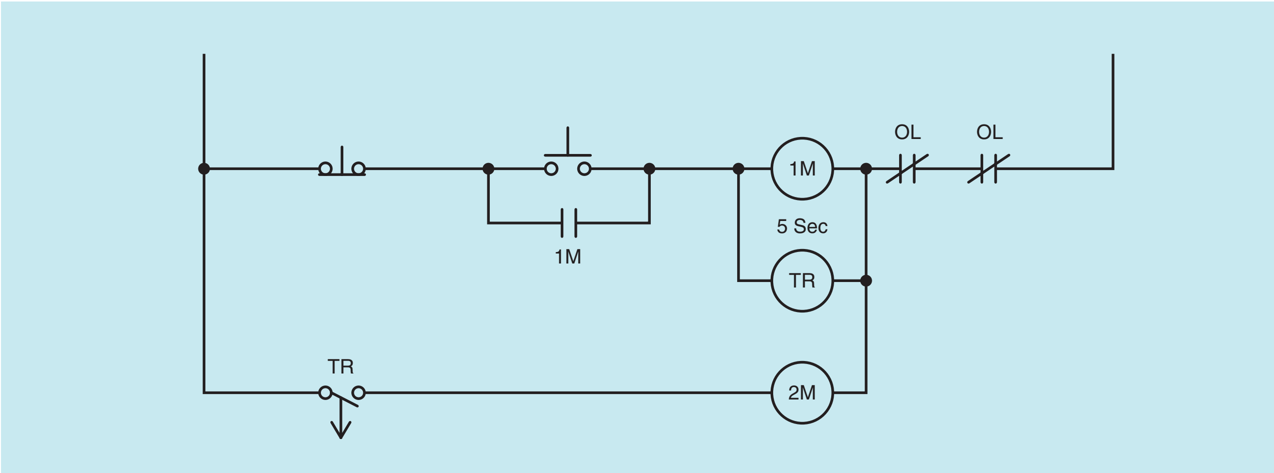


Figure 17–21 Off delay timer circuit using a pneumatic timer.

energized, the contacts change position immediately. When the coil is de-energized, the contacts delay returning to their normal position. According to the pin chart shown in Figure 17–20, pins 2 and 10 connect to the coil of the timer. To use this timer in the off-delay mode, power must be connected to pins 2 and 10 at all times. Shorting pins 5 and 6 together causes the timed contacts to change position immediately. When the short circuit between pins 5 and 6 is removed, the time sequence begins. At the end of the preset time period, the contacts will return to their normal position.

If electronic off-delay timers are to replace pneumatic off-delay timers in a control circuit, it is generally necessary to modify the circuit. For example, in the circuit shown in Figure 17–21, it is assumed that starters 1M and 2M control the operation of two motors and timer TR is a pneumatic off-delay timer. When the start-button is pressed two motors start at the same time. The motors will continue to operate until the stop-button is pressed, which causes motor #1 to stop running immediately. Motor #2, however, will continue to run for a period of 5 seconds before stopping.

Now assume that the pneumatic off-delay timer is to be replaced with an electronic off-delay timer (Figure 17–22). In this circuit, notice that the coil of the timer is connected directly across the incoming power, which permits it to remain energized at all times. In the circuit shown in Figure 17–21, the timer actually operates with starter 1M. When coil 1M energizes, timer TR energizes at the same time. When coil 1M de-energizes, timer TR de-energizes also. For this reason, a normally open auxiliary contact on starter 1M will be used to control the operation of the electronic off-delay timer. In the circuit shown in Figure 17–22 a set of normally open 1M contacts is connected to pins 5 and 6 of the timer. When coil 1M energizes, contact 1M closes and shorts pins 5 and 6, causing the normally open TR contacts to close and energize starter coil 2M. When coil 1M is de-energized, the contacts reopen and timer TR begins timing. After 5 seconds contacts TR reopen and de-energize starter coil 2M.

All electronic timers are similar, but there are generally differences in how they are to be connected. The connection diagram for the timer shown in Figure 17–17B is shown in Figure 17–23. Notice that this timer contains RESET, START, and GATE pins. Connecting pin 2 to pin 5 activates the GATE function, which interrupts or suspends the operation of the internal clock. Connecting pin 2 to pin 6 activates the START function, which operates in the same manner as the timer shown in Figure 17–17A. Connecting pin 2 to pin 5 activates the RESET function, which resets the internal clock to zero. If this timer were to be used in the circuit shown in Figure 17–22, it would have to be modified as shown in Figure 17–24 by connecting the 1M normally open contact to pins 2 and 6 instead of pins 5 and 6.

Construction of a Simple Electronic Timer

The schematic for a simple on-delay timer is shown in Figure 17–25. The timer operates as follows: When

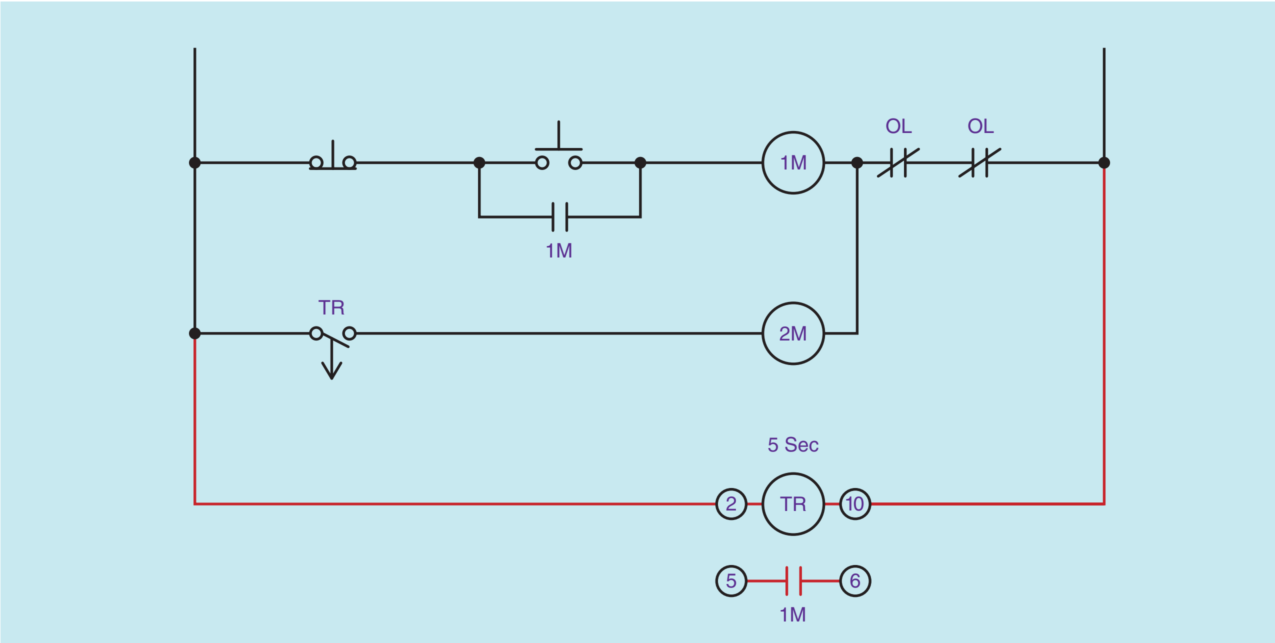


Figure 17–22 Modifying the circuit for an electronic off delay timer.

switch S1 is closed, current flows through resistor RT and begins charging capacitor C1. When capacitor C1 has been charged to the trigger value of the unijunction transistor, the UJT turns on and discharges capacitor C1 through resistor R2 to ground. The sudden discharge of capacitor C1 causes a spike voltage to appear across resistor R2. This voltage spike travels through capacitor C2 and fires the gate of the SCR. When the SCR turns on, current is provided to the coil of relay K1.

Resistor R1 limits the current flow through the UJT. Resistor R3 is used to keep the SCR turned off until the UJT provides the pulse to fire the gate. Diode D1 is used to protect the circuit from the spike voltage produced by the collapsing magnetic field around coil K1 when the current is turned off.

By adjusting resistor RT, capacitor C1 can be charged at different rates. In this manner, the relay can be adjusted for time. Once the SCR has turned on, it will remain on until switch S1 is opened.

Programmable controllers, which will be discussed in Unit 65, contain "internal" electronic timers. Most programmable controllers (PCs) use a quartz-operated clock as the time base. When the controller is programmed, the timers can be set in time increments of .1 second. This, of course, provides very accurate time delays for the controller.

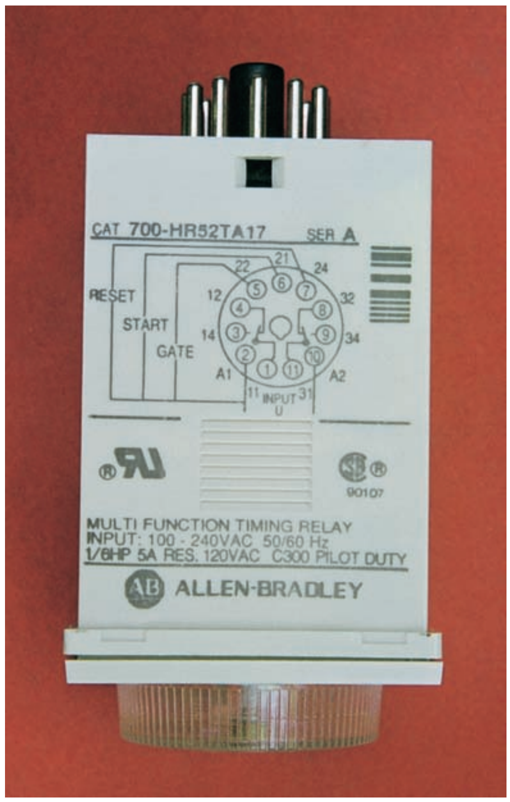


Figure 17–23 Pin connection diagram for Allen-Bradley timer.

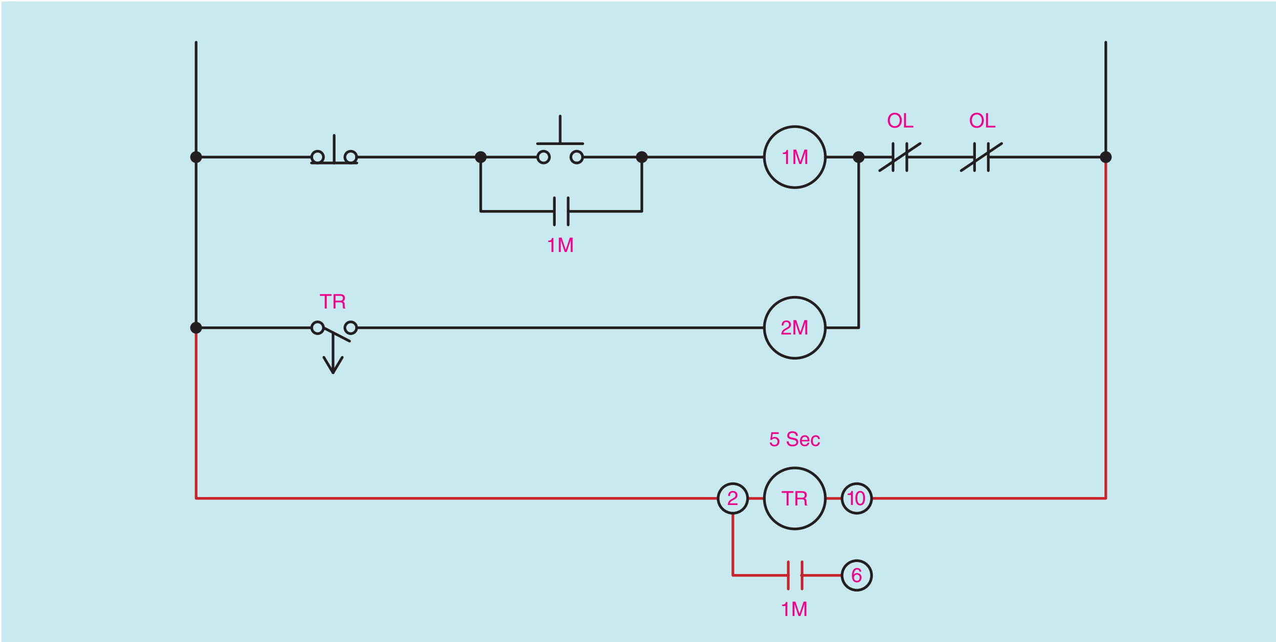


Figure 17–24 Replacing the Dayton timer with the Allen-Bradley timer.

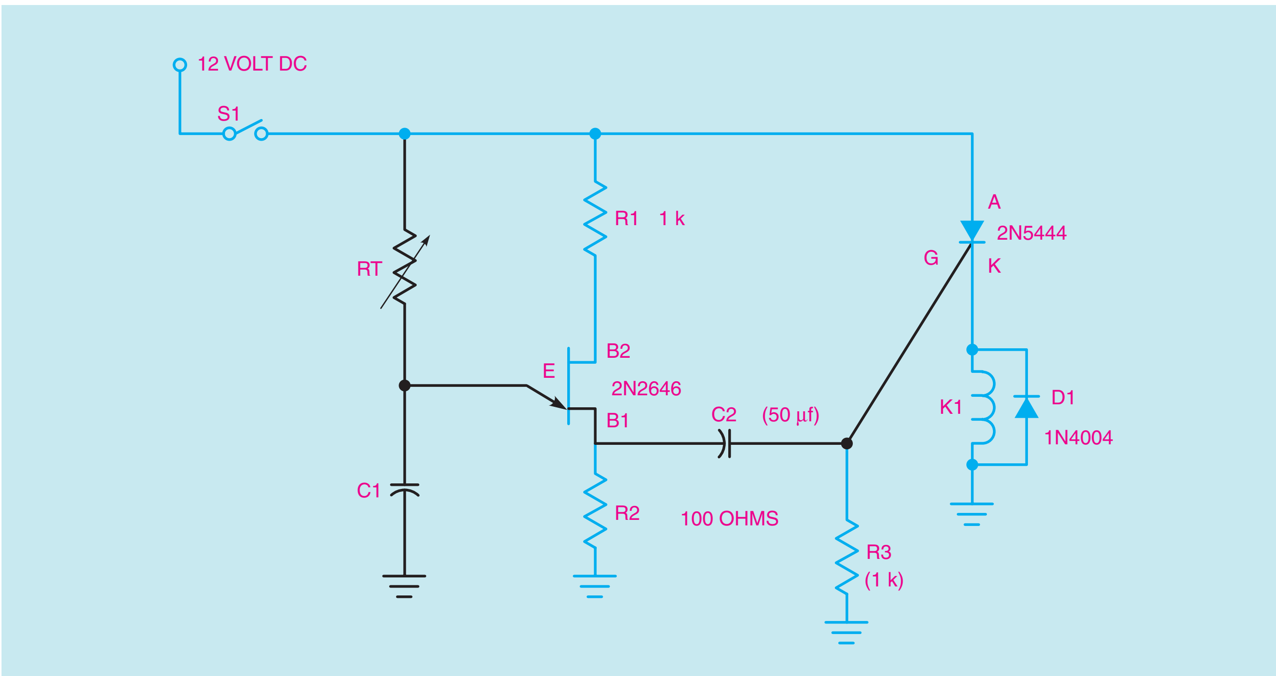


Figure 17–25 Schematic of electronic on-delay timer.

Review Questions

1. What are the two basic classifications of timers?
2. Explain the operation of an on-delay relay.
3. Explain the operation of an off-delay relay.
4. What are instantaneous contacts?
5. How are pneumatic timers adjusted?
6. Name two methods used by electronic timers to obtain their time base.

UNIT 18

PRESSURE SWITCHES AND REGULATORS

OBJECTIVES

After studying this unit, the student will be able to:

- Describe how pressure switches, vacuum switches, and pressure regulators may control motors.
- List the adjustments that can be made to pressure switches.
- Identify wiring symbols used for pressure switches.

Any industrial application that has a pressure sending requirement can use a pressure switch (Figure 18–1). A large variety of pressure switches are available to cover the wide range of control requirements for pneumatic or hydraulic machines such as welding equipment, machine tools, high pressure lubricating systems, and motor-driven pumps and air compressors.

The pressure ranges over which pressure switches can maintain control also vary widely. For example, a diaphragm-actuated switch can be used when a sensitive response is required to small pressure changes at low-pressure ranges. A metal bellows-actuated control is used for pressures up to 2000 pounds per square inch. Piston-operated hydraulic switches are suitable for pressures up to 15,000 psi. In all of these pressure controlled devices, a set of contacts is operated.

The most commonly used pressure switches are single-pole switches. Two-pole switches are also used for some applications. Field adjustments of the range and the differential pressure (or the difference between the cut-in and cut-out pressures) can be made for most pressure switches. The spring pressure determines the pressures at which the switch closes and opens its contacts.

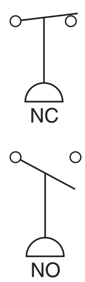


Figure 18–1 Industrial pressure switch with cover removed.

Pressure regulators provide accurate control of pressure or vacuum conditions for systems. When they are used as pilot control devices with magnetic starters, pressure regulators are able to control the operation of liquid pump or air compressor motors in a manner similar to that of pressure switches. Reverse action regulators can be used on pressure system interlocks to prevent the start of an operation until the pressure in the system has reached the desired level.

Pressure regulators consist of a Bourdon-type pressure gauge and a control relay. Delicate contacts on the gauge energize the relay and cause it to open or close. The relay contacts are used to control a large motor starter in order to avoid damage or burning of the gauge contacts. Standard regulators will open a circuit at high pressure and close it at low pressure. Special reverse operation regulators will close the circuit at high pressure and open the circuit at low pressure.

Pressure Sensors

Pressure sensors are designed to produce an output voltage or current that is dependent on the amount of pressure being sensed. Piezoresistive sensors are very popular because of their small size, reliability, and accuracy (Figure 18–2). These sensors are available in ranges from 0–1 psi (pounds per square inch) and 0–30 psi. The sensing element is a silicon diaphragm integrated with an integrated circuit chip. The chip contains four implanted piezoresistors connected to form a bridge circuit (Figure 18–3). When pressure is applied to the diaphragm, the resistance of piezoresistors changes proportionally to the applied pressure, which changes the balance of the bridge. The voltage across V0 changes in proportion to the applied pressure (V0 = V4 − V2 [when referenced to V3]). Typical millivolt outputs and pressures are shown below:

1 psi = 44 mV
5 psi = 115 mV
15 psi = 225 mV
30 psi = 315 mV

Another type of piezoresistive sensor is shown in Figure 18–4. This particular sensor can be used to sense

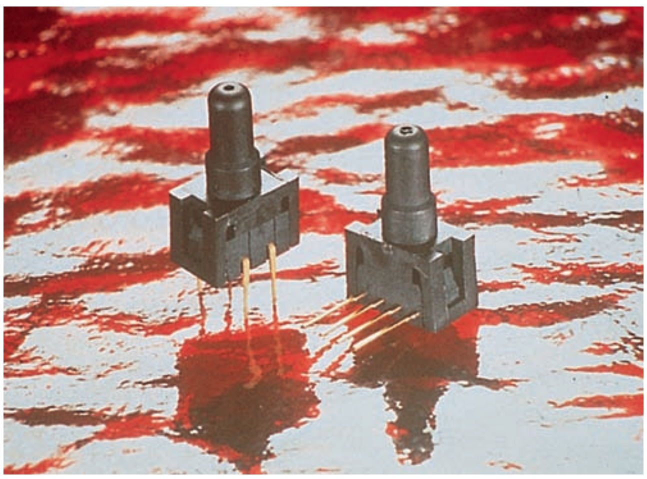


Figure 18–2 Piezoresistive pressure sensor. (Courtesy Honeywell's Micro Switch Division.)

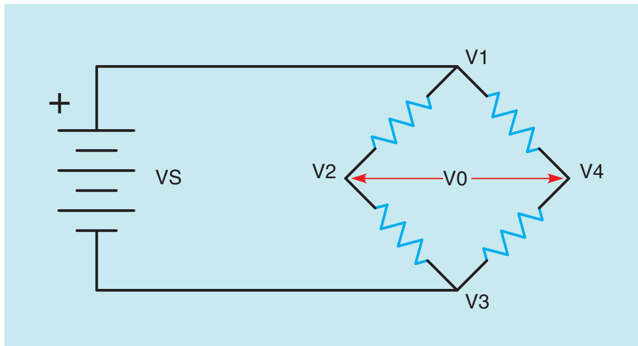


Figure 18–3 Piezoresistive bridge.

Figure 18–4 Differential pressure sensor. (Courtesy Honeywell's Micro Switch Division.)

absolute, gage, or differential pressure. Units are available which can be used to sense vacuum. Sensors of this type can be obtained to sense pressure ranges of 0–1, 0–2, 0–5, 0–15, 0–30, and 0–(−15[vacuum]). The sensor contains an internal operational amplifier and can provide an output voltage proportional to the pressure. Typical supply voltage for this unit is 8 VDC. The *regulated* voltage output for this unit is 1–6 volts. Assume for example that the sensor is intended to sense a pressure range of 0–5 psi. At 0 psi the sensor would produce an output voltage of 1 volt. At 15 psi the sensor would produce an output voltage of 6 volts.

Sensors can also be obtained that have a ratiometric output. The term ratiometric means that the output voltage will be proportional to the supply voltage. Assume that the supply voltage increases by 50% to 12 VDC. The output voltage would increase by 50% also. The sensor would now produce a voltage of 1.5 volts at 0 psi and 9 volts at 15 psi.

Other sensors can be obtained that produce a current output of 4 to 20 mA, instead of a reguated voltage output (Figure 18–5). One type of pressure to current sensor, which can be used to sense pressures as high as 250 psi, is shown in Figure 18–6. This sensor can also be used as a set point detector to provide a normally open or normally closed output. Sensors that produce a proportional output current instead of voltage have fewer problems with induced noise from surrounding magnetic fields, and with voltage drops due to long wire runs.

A flow-through pressure sensor is shown in Figure 18–7. This type of sensor can be placed in line with an existing system. In-line pressure sensors make it easy to add a pressure sensor to an existing system.

Figure 18–6 Pressure to current sensor for high pressure. (Courtesy Square D Company.)

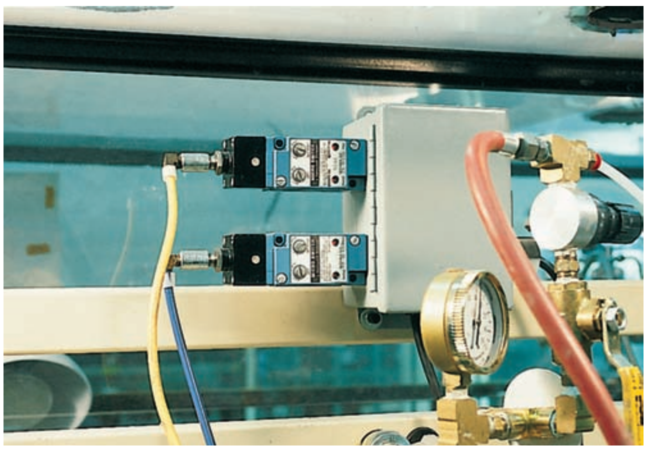


Figure 18–5 Pressure to current sensor for low pressures. (Courtesy Honeywell's Micro Switch Division.)

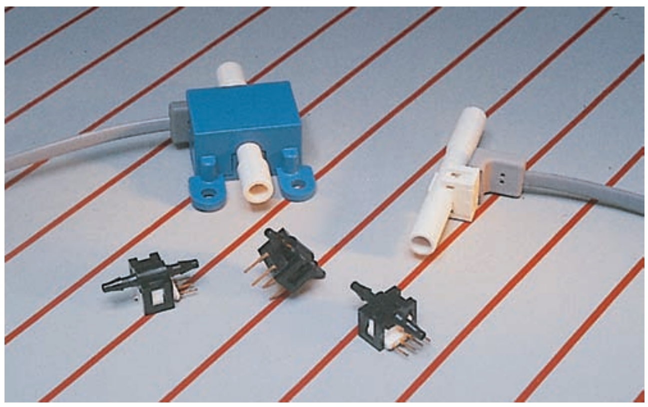


Figure 18–7 Flow-through pressure sensor. (Courtesy Honeywell's Micro Switch Division.)

Another device that is basically a pressure sensor is the force sensor (Figure 18–8). This sensor uses silicon piezoresistive elements to determine the amount of pressure to the sensing element.

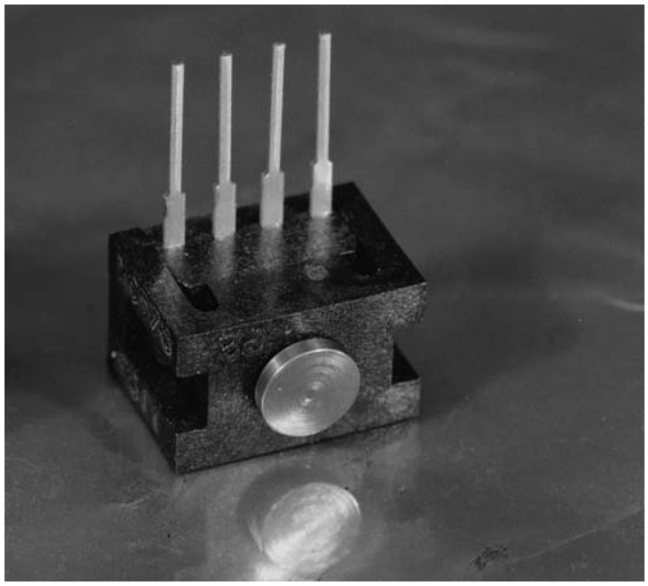


Figure 18–8 Force sensor. (Courtesy Honeywell's Micro Switch Division.)

Review Questions

1. Describe how pressure switches are connected to start and stop (a) small motors and (b) large motors.
2. Draw the schematic symbol for a pressure switch. Draw both the normally open and the normally closed contact.

UNIT 19
FLOAT SWITCHES

OBJECTIVES

After studying this unit, the student will be able to:

- Describe the operation of float switches.
- List the sequence of operation for sump pumping or tank filling.
- Draw wiring symbols for float switches.

A float switch is used when a pump motor must be started and stopped according to changes in the water (or other liquid) level in a tank or sump. Float switches are designed to provide automatic control of ac and dc pump motor magnetic starters and automatic direct control of light motor loads.

The operation of a float switch is controlled by the upward or downward movement of a float placed in a water tank. The float movement causes a rod-operated (Figure 19–1) or chain and counterweight (Figure 19–2) assembly to open or close electrical contacts. The float switch contacts may be either normally open or normally closed and may not be submerged. Float switches may be connected to a pump motor for tank or sump pumping operations or tank filling, depending on the contact arrangement.

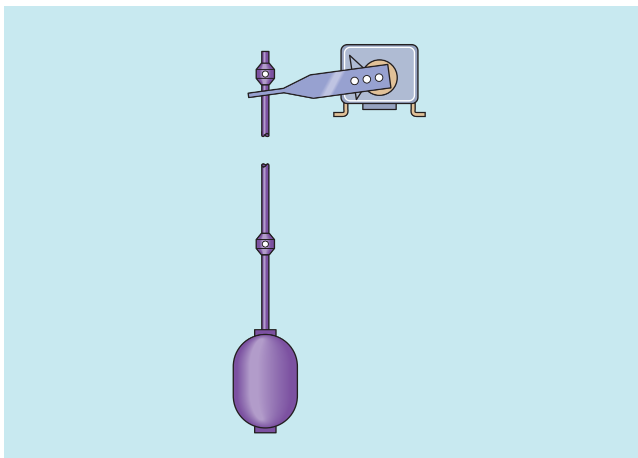


Figure 19–1 Rod-operated float switch.

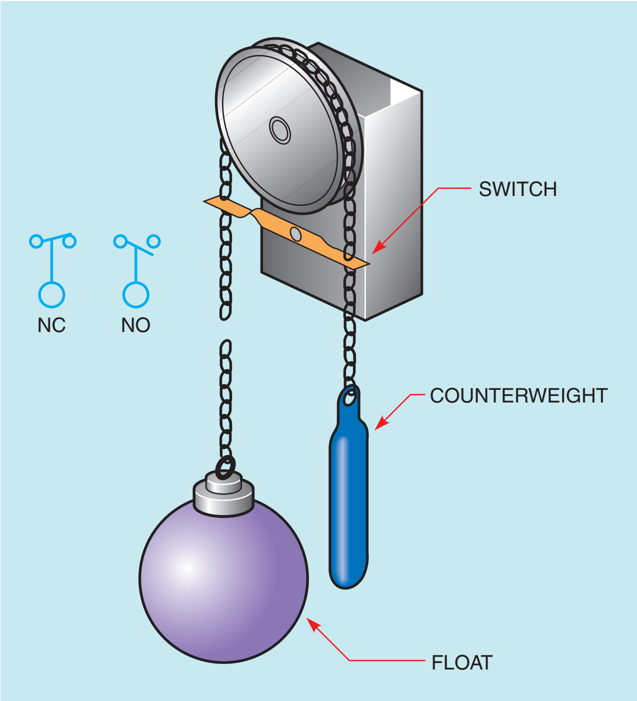


Figure 19–2 Chain-operated float switch with normally closed (NC) and normally open (NO) wiring symbols.

Mercury Bulb Float Switch

Another float switch that has become increasingly popular is the mercury bulb type of float switch. This type of float switch does not depend on a float rod or chain to operate. The mercury bulb switch appears to be a rubber bulb connected to a conductor. A set of mercury contacts are located inside the bulb. When the liquid level is below the position of the bulb, it is suspended in a vertical position (Figure 19–3A). When the liquid level rises to the position of the bulb, it changes to a horizontal position (Figure 19–3B). This change of position changes the state of the contacts in the mercury switch.

Since the mercury bulb float switch does not have a differential setting as does the rod or chain type of float switch, it is necessary to use more than one mercury bulb float switch to control a pump motor. The differential level of the liquid is determined by suspending mercury bulb switches at different heights in the tank. Figure 19–4 illustrates the use of four mercury bulb

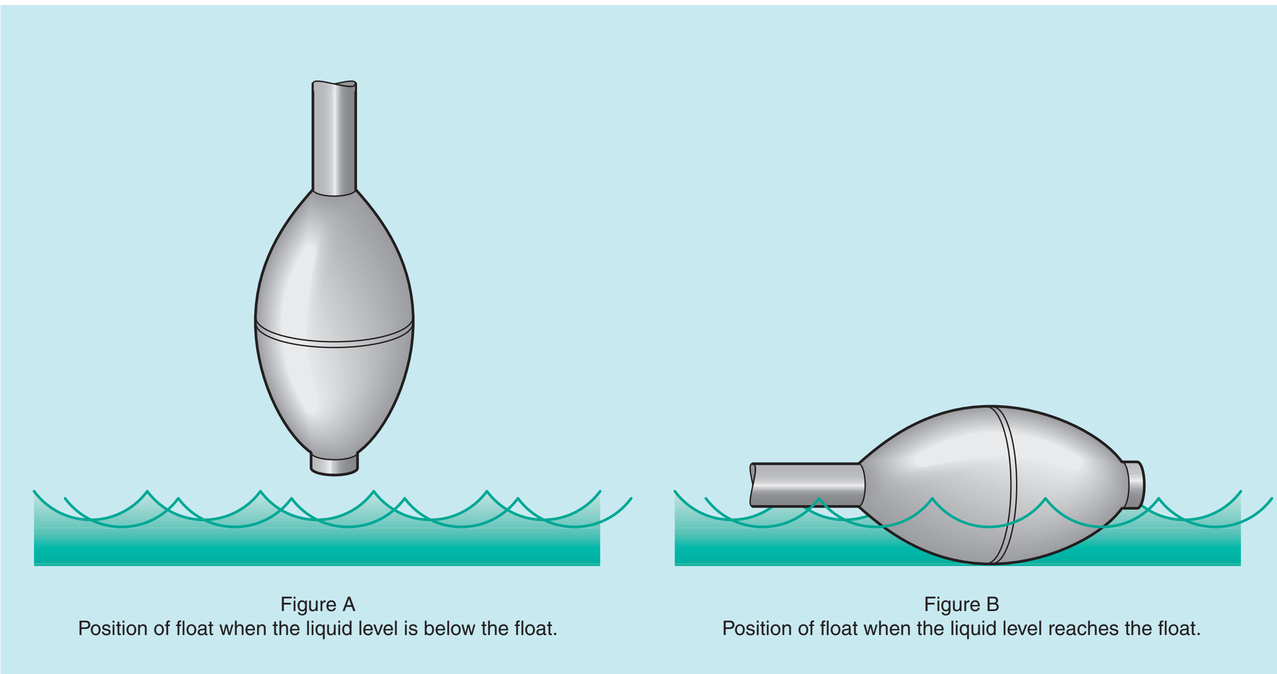


Figure 19–3 Mercury bulb type float switch.

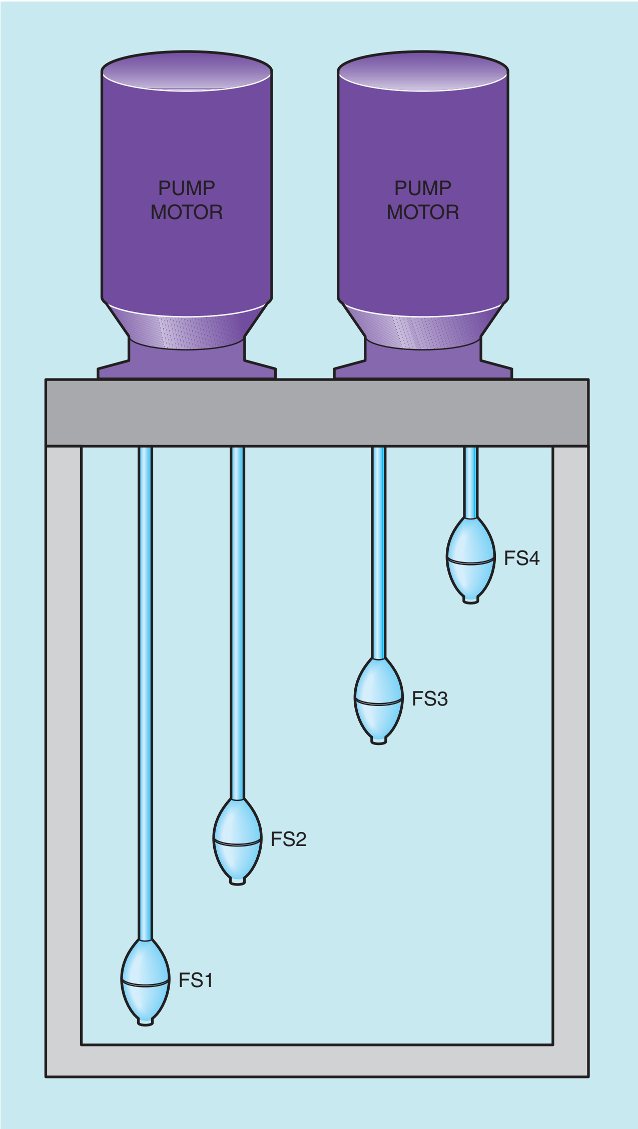


Figure 19–4 Float level is set by the length of the conductor.

type switches used to operate two pump motors and provide a high liquid level alarm. The control circuit is shown in Figure 19–5. Float switch FS1 detects the lowest point of liquid level in the tank and is used to turn both pump motors off. Float switch FS2 starts the first pump when the liquid level reaches that height. If pump #1 is unable to control the level of the tank, float switch FS3 will start pump motor #2 if the liquid level should rise to that height. Float switch FS4 operates a warning light and buzzer to warn that the tank is about to overflow. A reset button can be used to turn off the buzzer, but the warning light will remain on until the water level drops below the level of float switch FS4.

The Bubbler System

Another method often used to sense liquid level is the bubbler system. This method does not employ the use of float switches. The liquid level is sensed by pressure switches (Figure 19–6). A great advantage of this system is that the pressure switches are located outside the tank, which makes it unnecessary to open the tank to service the system.

The bubbler system is connected to an air line, which is teed to a manifold and another line which extends down into the tank. A hand valve is used to adjust the maximum air flow. The bubbler system operates on the principle that as the liquid level increases in the tank, it requires more air pressure to blow air through the line in the tank. For example, a 1-square-inch column of water 26.7 inches in height weighs 1 pound. Now assume a pipe with an inside area of 1 square inch is 10 feet in length. It would require a pressure of 4.494 psi to blow air through the pipe.

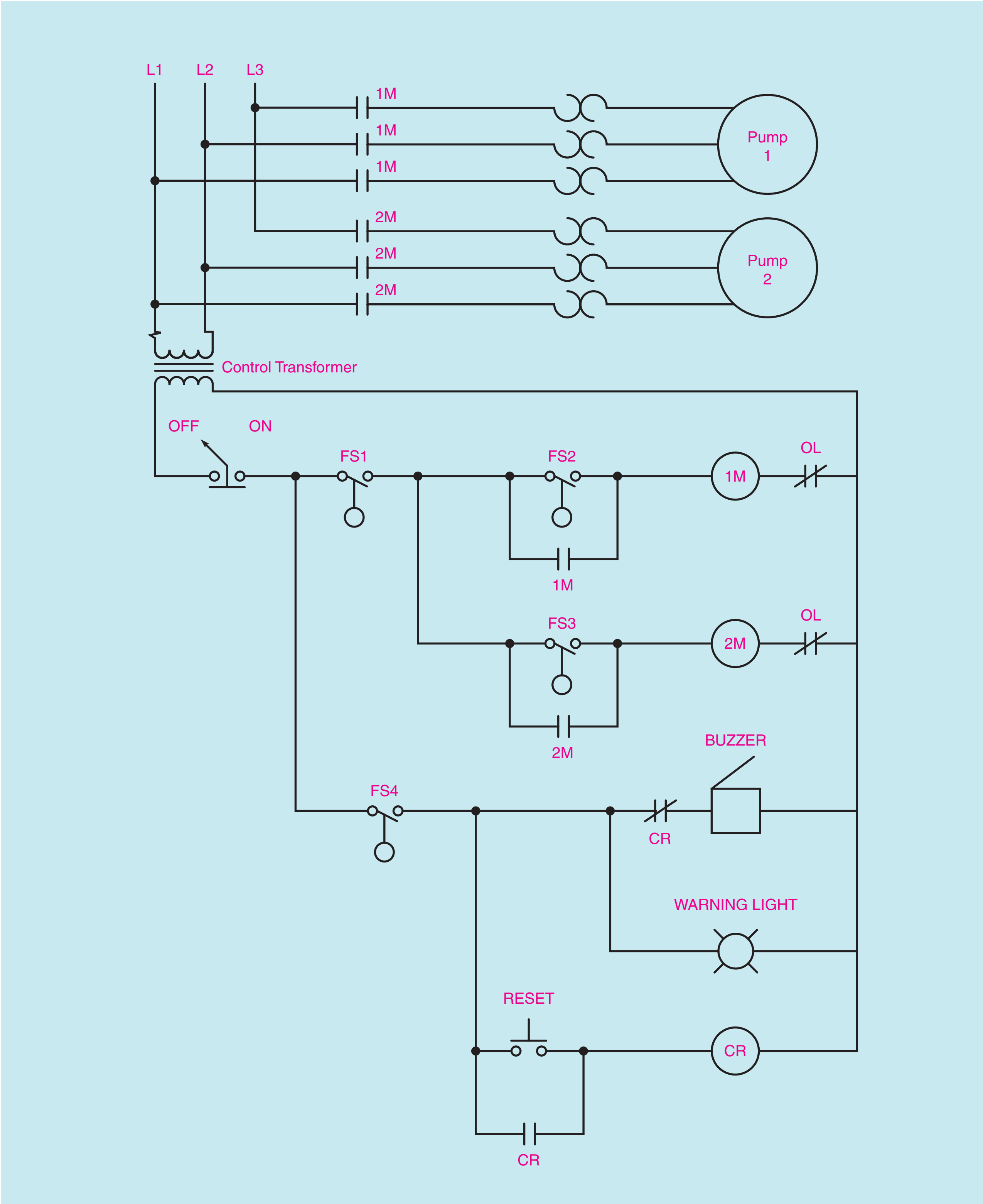


Figure 19–5 Two pump control with high liquid level warning.

$$\frac{120\ \textit{inches}}{26.7\ \textit{pounds per sq. in.}} = 4.494\ \textit{pounds}$$

If the water level was 7 feet in height it would require a pressure of only 3.146 psi.

Since the pressure required to bubble air through the pipe is directly proportional to the height of the liquid, the pressure switches provide an accurate measure of the liquid level. The pressure switches shown in Figure 19–6 could be used to control the two pump circuit previously discussed by replacing the float switches with pressure switches in the circuit shown in Figure 19–5.

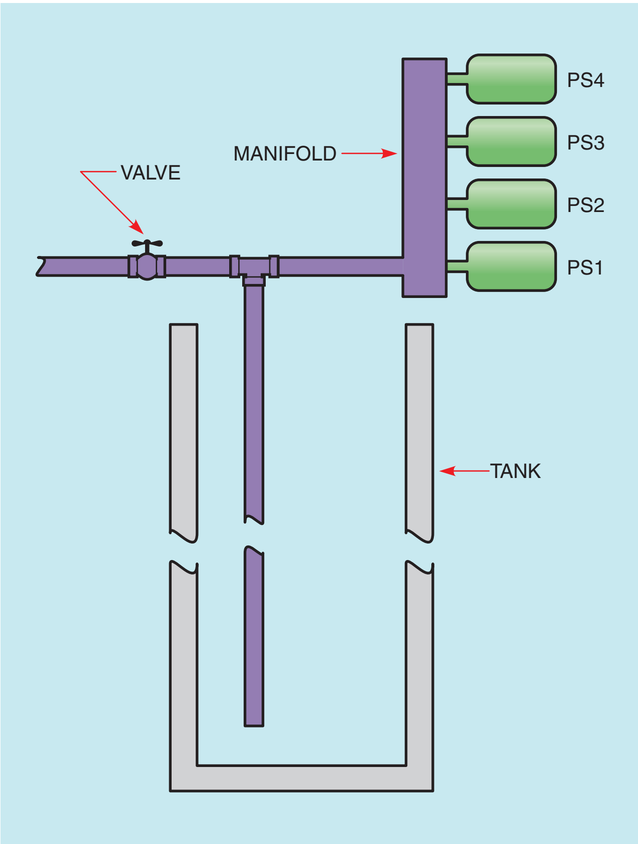


Figure 19–6 Bubbler system for detecting liquid level.

Microwave Level Gauge

The microwave level gauge operates by emitting a high frequency signal of approximately 24 GHz. into a tank and then measuring the frequency difference of the return signal that bounces off the product (Figure 19–7). A great adantage of the microwave level gauge is that no mechanical object touches or is inserted into the product. The gauge is ideal for measuring the level of turbulent, aerated, solids-laden, viscous, corrosive fluids. It also works well with pastes and slurries. A cut-away view of a microwave level gauge is shown in Figure 19–8.

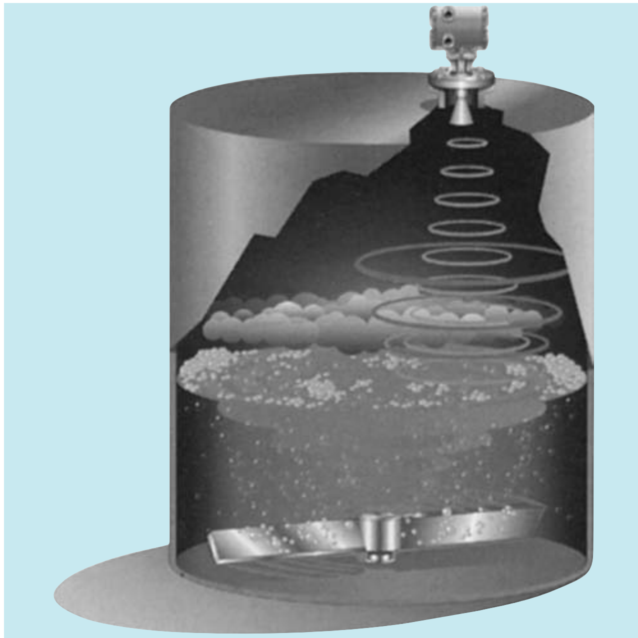


Figure 19–7 Operation of the radar gauge. (Courtesy ©1998 Rosemount, Inc., used by permission.)

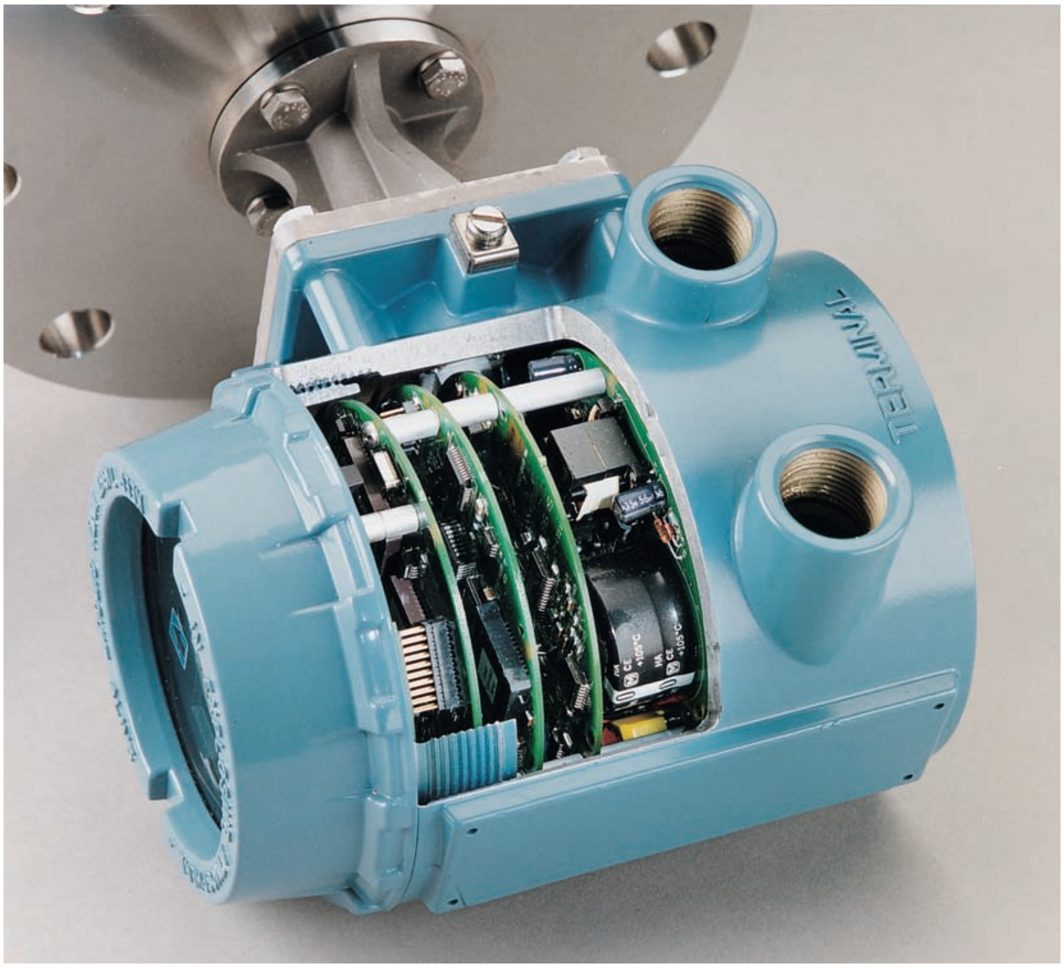


Figure 19–8 Cut-away view of a microwave level gauge. (Courtesy © 1998 Rosemount, Inc., used by permission.)

Figure 19–9 Microwave level gauge with meter. (Courtesy ©1998 Rosemount, Inc., used by permission.)

The gauge shown in Figure 19–9 has a primary 4–20 ma analog signal. The gauge can accept one RTD (Resistance Temperature Detector) input signal. The gauge can be configured to display the level, calculated volume, or standard volume. A microwave level gauge with meter is shown in Figure 19–9.

Review Questions

1. Describe the sequence of operations required to (a) pump sumps and (b) fill tanks.
2. Draw the normally open and normally closed contact symbols for a float switch.
3. What type of float switch does not have a differential setting?
4. What is the advantage of the bubble type system for sensing liquid level?
5. Assume a pipe has an inside diameter of 1 square inch. How much air pressure would be required to bubble air though 25 feet of water?

UNIT 20

FLOW SWITCHES AND SENSORS

OBJECTIVES

After studying this unit, the student will be able to:

- Describe the purpose and functions of flow switches.
- Connect a flow switch to other electrical devices.
- Draw and read wiring diagrams of systems using flow switches.

A flow switch is a device that can be inserted in a pipe so that when liquid or air flows against a part of the device called a paddle, a switch is activated (Figure 20–1). This switch either closes or opens a set of electrical contacts. The contacts may be connected to energize motor starter coils, relays, or indicating lights. In general, a flow switch contains both normally open and normally closed electrical contacts (Figure 20–2).

Figure 20–3 shows a flow switch installed in a pipe line tee. Half couplings are welded into larger pipes for flow switch installations.

Typical applications of flow switches are shown in Figures 20–4 through 20–7. These applications are commonly found in the chemical and petroleum industries. Vaporproof electrical connections must be used with vaporproof switches. The insulation of the wire leading to the switches must be adequate to withstand the high temperature of the liquid inside the pipe. (Consult the *National Electrical Code*® for insulation temperature ratings.)

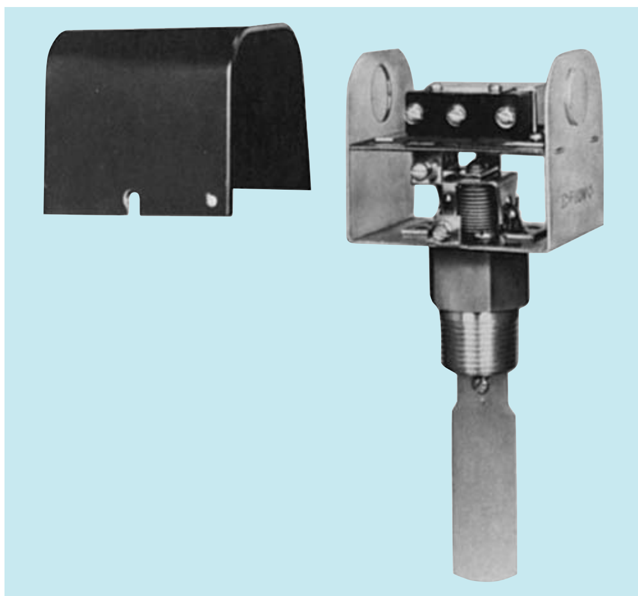


Figure 20–1 Flow switch. (Courtesy McDonnell & Miller ITT, Fluid Handling Division.)

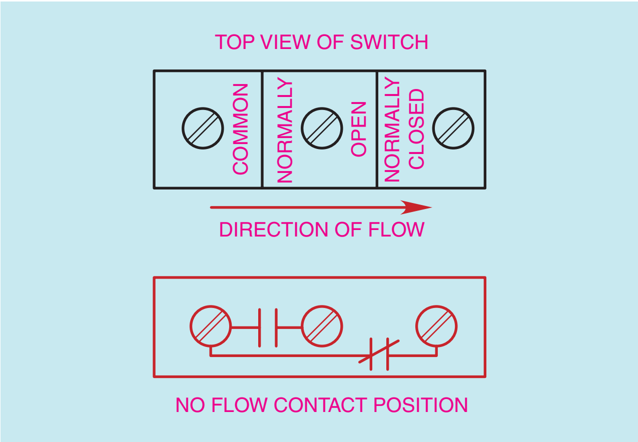


Figure 20–2 Electrical terminals and contact arrangement of a flow switch.

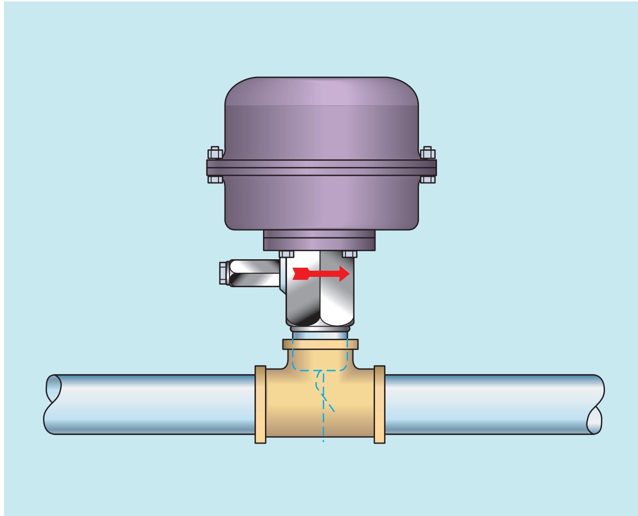


Figure 20–3 Flow switch installed.

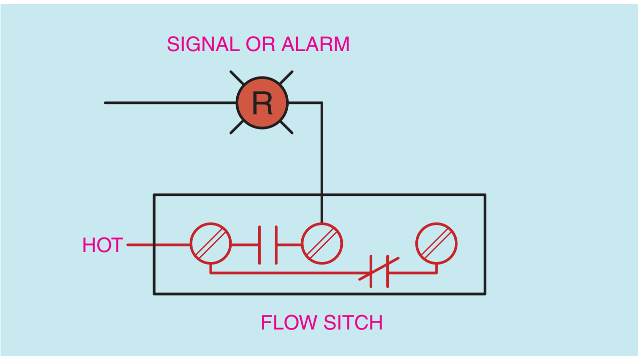


Figure 20–4 Flow switch used to sound alarm or light signal when flow occurs.

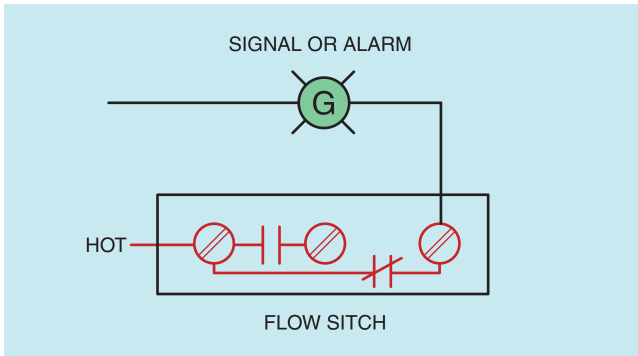


Figure 20–5 Flow switch used to sound alarm or light signal when there is no flow.

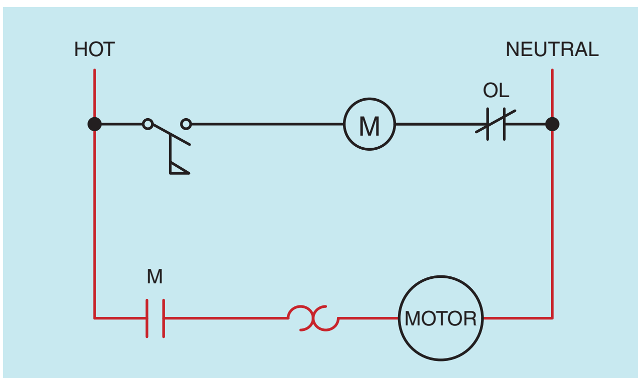


Figure 20–6 Flow switch used with single-phase circuit; starts motor when flow occurs, stops motor when there is no flow.

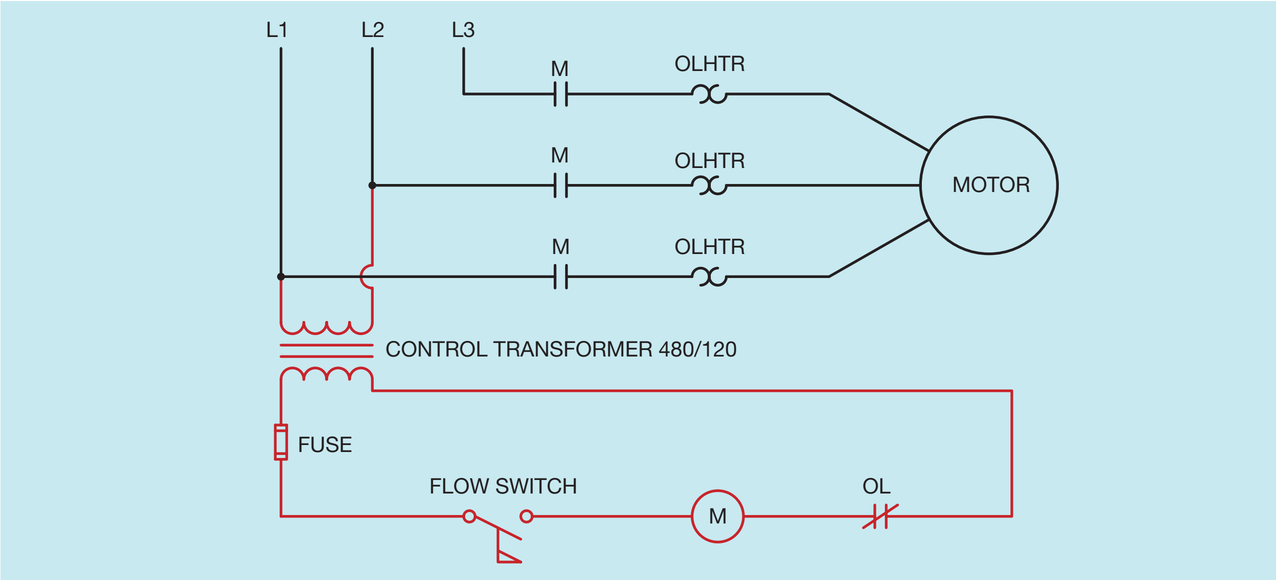


Figure 20–7 Flow switch used with three-phase circuit; starts motor when flow occurs, stops motor when there is no flow.

Airflow or sail switches are also used in ducts in air conditioning systems. Another use of these switches is to prevent duct heaters from energizing when there is no air movement in the duct. While the construction of airflow switches is different from that of liquid flow switches, the electrical connections are similar.

The schematic symbols for a flow switch are shown in Figure 20–8.

The normally open switch is identified by the fact that the movable contact is drawn below and is not touching the stationary contact. The normally closed switch is shown with the movable contact drawn above and touching the stationary contact. Now refer to the normally open held closed switch. The switch is normally open because the movable contact is drawn below the stationary contact. In this example, however, the movable contact is touching the stationary. This switch is actually connected normally open, but some condition in the circuit is keeping the switch closed. If the flow is stopped, the contact will open. A similar situation can be seen with the normally closed held open switch. The switch is normally closed because the movable contact is drawn above the stationary contact. Since the movable contact is not touching the stationary, it is being held open. If the flow is stopped, the contact will close.

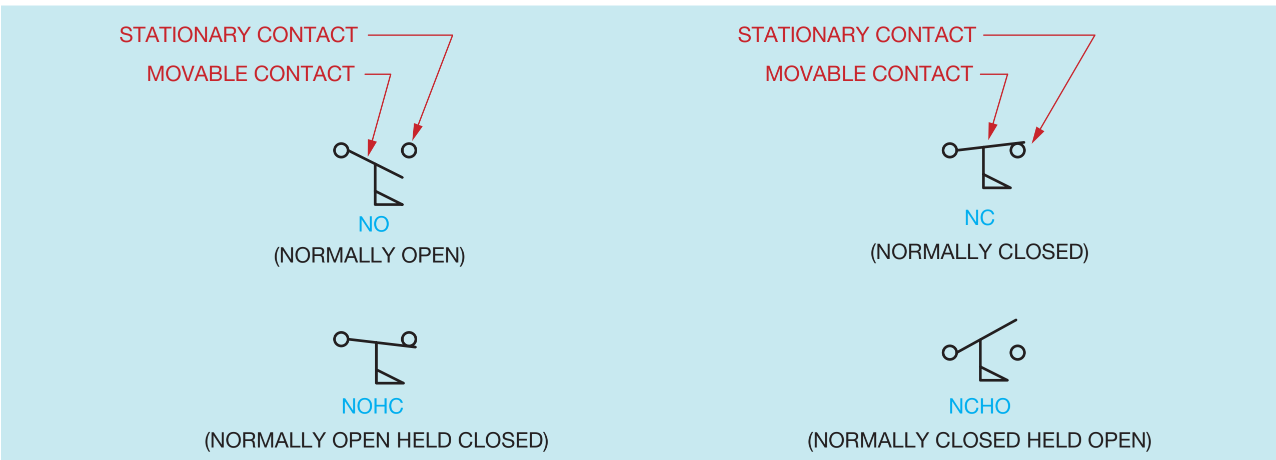


Figure 20–8 Schematic symbols for flow switches.

Flow Sensors

Flow switches are used to detect liquid flowing through a pipe or air flowing through a duct. Flow switches, however, cannot detect the amount of liquid or air flow. To detect the amount of liquid or air flow, a *transducer* must be used. A transducer is a device that converts one form of energy into another. In this case, the kinetic energy of a moving liquid or gas is converted into electrical energy. Many flow sensors are designed to produce an output current of 4 to 20 mA. This current can be used as the input signal to a programmable controller or as the input to a meter designed to measure the flow rate of the liquid or gas being metered (Figure 20–9).

Liquid Flow Sensors

There are several methods that can be used to measure the flow rate of a liquid in a pipe. One method uses a *turbine* type sensor (Figure 20–10). The turbine sensor consists of a turbine blade which must be inserted inside the pipe containing the liquid. The moving liquid causes the turbine blade to turn. The speed at which the blade turns is proportional to the amount of flow in

Figure 20–9 Several different flow sensors shown with a meter used to measure the flow rate of liquid. (Courtesy ©1998 Rosemount, Inc., used by permission.)

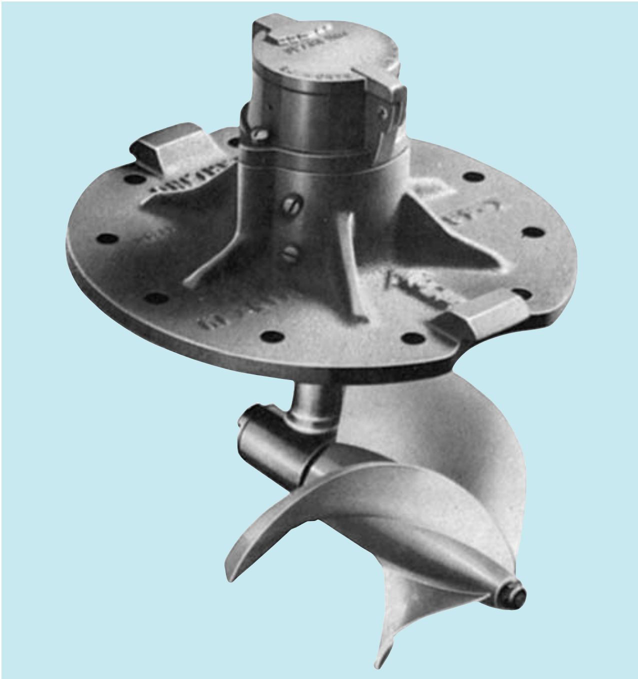


Figure 20–10 Turbine type flow sensor. (Courtesy Sparling Instruments Co., Inc.)

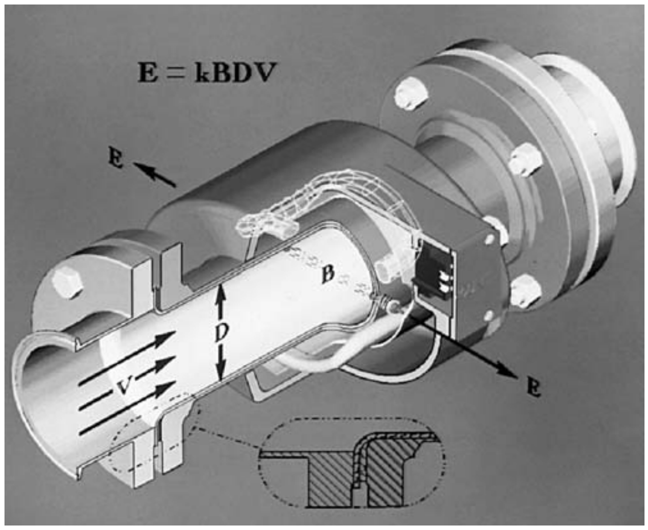


Figure 20–11A Operating principle of an electromagnetic flow sensor. (Courtesy ©1998 Rosemount, Inc., used by permission.)

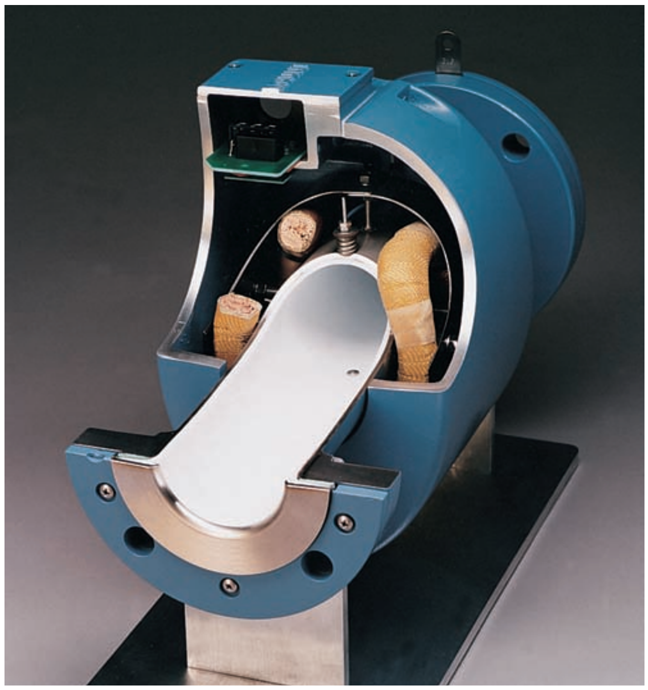


Figure 20–11B Cut-away view of an electromagnetic flow sensor with ceramic liner. (Courtesy ©1998 Rosemount, Inc., used by permission.)

the pipe. The sensor's electrical output is determined by the speed of the turbine blade. One disadvantage of the turbine type sensor is that the turbine blade offers some resistance to the flow of the liquid.

Electromagnetic Flow Sensors

Another type of flow sensor is the *electromagnetic* flow sensor. These sensors operate on the principle of Faraday's Law concerning conductors moving through a magnetic field. This law states that when a conductor moves through a magnetic field, a voltage will be induced into the conductor. The amount of induced voltage is proportional to the strength of the magnetic field and the speed of the moving conductor. In the case of the electromagnetic flow sensor, the moving liquid is the conductor. As a general rule, liquids should have a minimum conductivity of about 20 microhms per centimeter.

Flow rate is measured by small electrodes mounted inside the pipe of the sensor. The electrodes measure the amount of voltage induced in the liquid as it flows through the magnetic field produced by the sensor (Figure 20-11A). Since the strength of the magnetic field is known, the induced voltage will be proportional to the flow rate of the liquid. A cut-away view of an electromagnetic flow sensor with a ceramic liner is shown in Figure 20–11B.

Orifice Plate Flow Sensors

Orifice plate flow sensors operate by inserting a plate with an orifice of known size into the flow path (Figure 20–12). The plate is installed between two

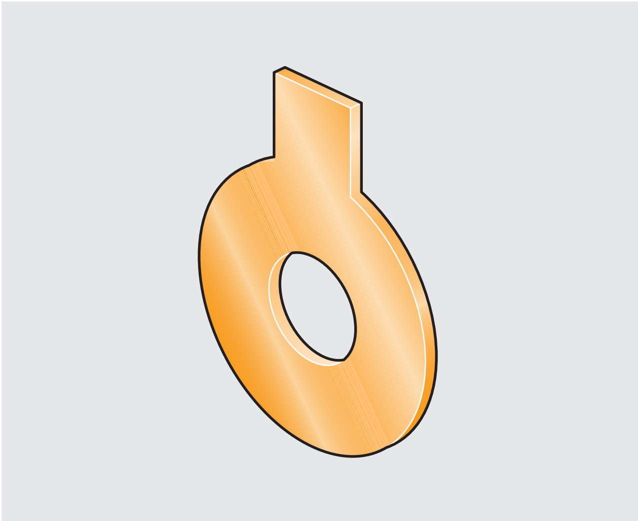


Figure 20–12 Concentric orifice plate.

special flanges (Figure 20–13). The flanges are constructed to permit a differential pressure meter to be connected across the plate. When liquid flows through the orifice a difference of pressure is produced across the plate. Since the orifice is of known size, the pressure difference is proportional to flow rate. It is the same principle as measuring the voltage drop across a known resistance to determine the amount of current flow in a circuit. The disadvantage of the orifice plate sensor is that it does add restriction to the line. A differential pressure sensor is shown in Figure 20–14.

Vortex Flow Sensors

Vortex flow sensors operate on the principle that when a moving liquid strikes an object, a swirling current, called a vortex, is created. Vortex sensors insert a *shedder bar* in the line to produce a swirling current or vortex (Figure 20–15). This swirling current causes the shedder bar to alternately flex from side to side. The shedder bar is connected to a pressure sensor that can sense the amount of movement of the shedder bar (Figure 20–16). The amount of movement of the shedder bar is proportional to the flow rate. Several different sizes of vortex flow sensors are shown in Figure 20–17.

Airflow Sensors

Large volumes of air flow can be sensed by prop-driven devices similar to the liquid flow sensor shown in Figure 20–10. Solid state devices similar to the one shown in Figure 20–18 are commonly used to sense smaller amounts of air or gas flow. This device operates on the principle that air or gas flowing across a surface causes heat transfer. The sensor contains a thin film thermally isolated bridge with a heater and temperature sensors. The output voltage is dependent on the temperature of the sensor surface. Increased air flow through the inlet and outlet ports will cause a greater amount of heat transfer, reducing the surface temperature of the sensor.

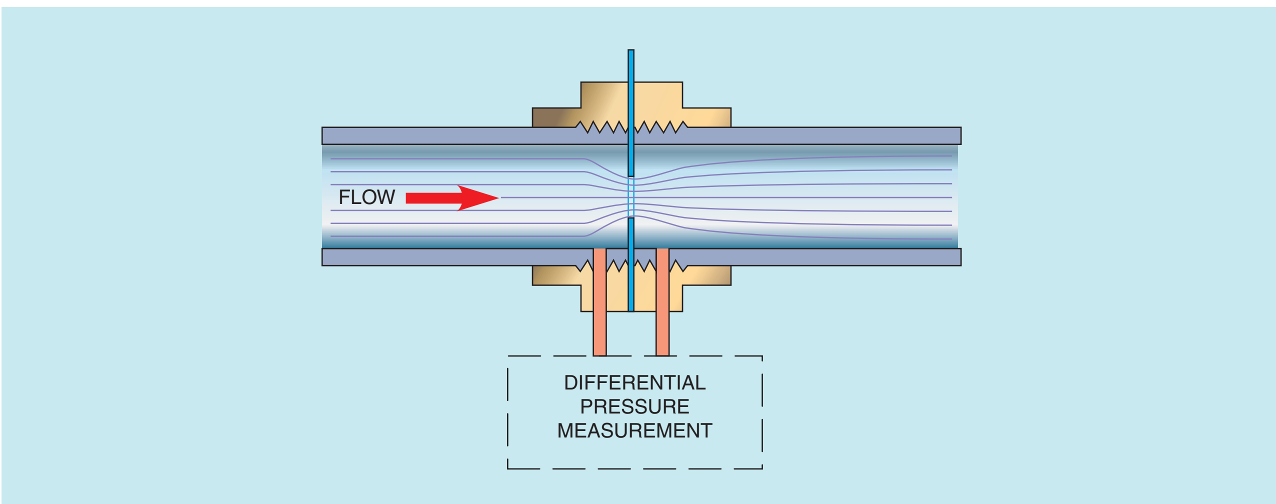


Figure 20–13 A difference in pressure is produced across the orifice plate.

Figure 20–14 Differential pressure sensor. (Courtesy ©1998 Rosemount, Inc., used by permission.)

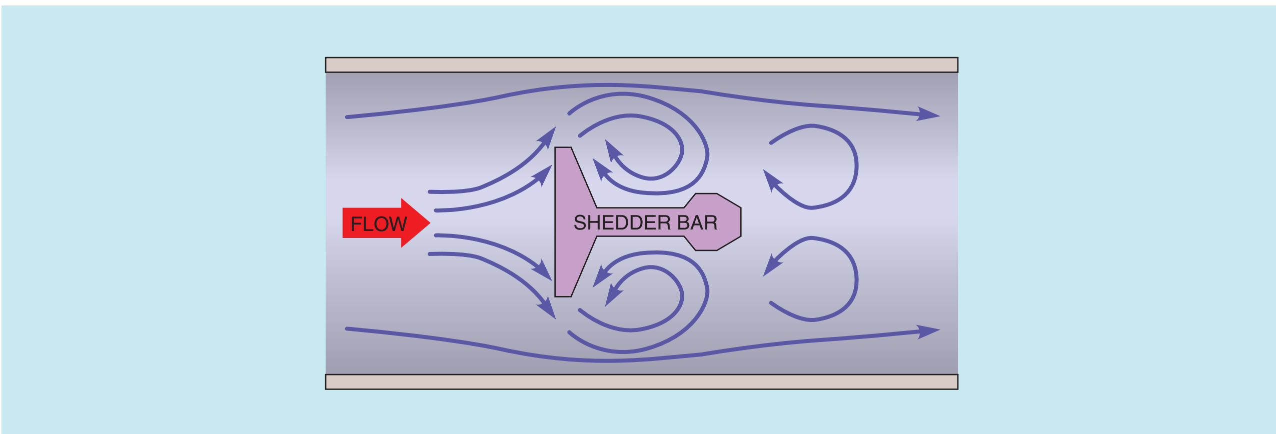


Figure 20–15 The shedder bar causes the liquid to swirl producing vortexes that produce alternating pressures on the bar.

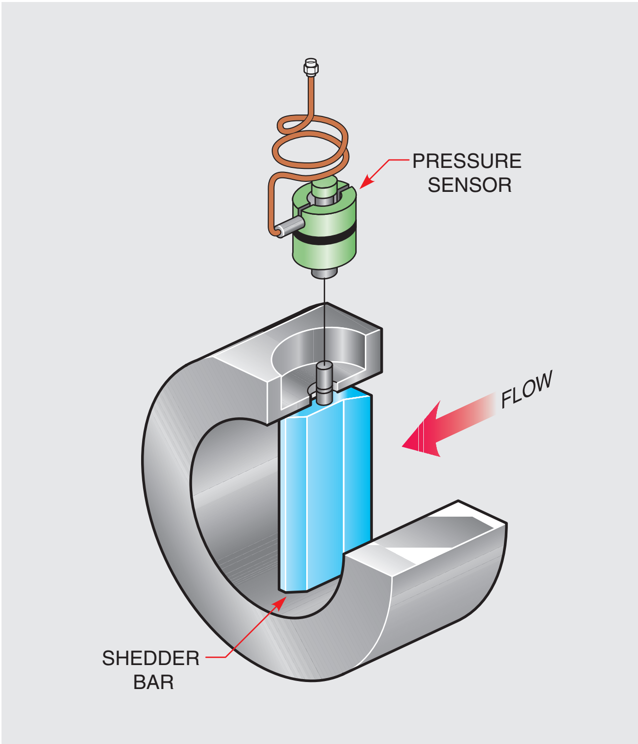


Figure 20–16 Movement against the shedder bar causes pressure against the pressure sensor.

Figure 20–17 Vortex flow sensors. (Courtesy © 1998 Rosemount, Inc., used by permission.)

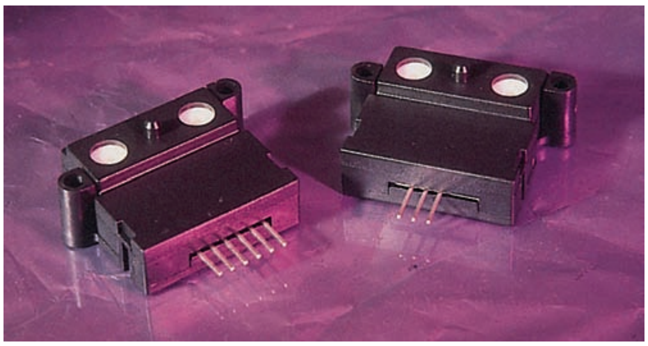


Figure 20–18 Solid state airflow sensor. (Courtesy Honeywell's Micro Switch Division.)

Review Questions

1. What are typical uses of flow switches?
2. Draw a line diagram to show that a green light will glow when liquid flow occurs.
3. Draw a one-line diagram showing a bell that will ring in the absence of flow. Include a switch to turn off the bell manually.
4. What is a transducer?
5. What is the most common output current for flow sensors?
6. What is Faraday's Law concerning conductors moving through a magnetic field?
7. What type of flow sensors used Faraday's Law as their principle of operation?
8. What is the operating principle of the solid state airflow sensor described in this text?

UNIT 21

LIMIT SWITCHES

OBJECTIVES

After studying this unit, the student will be able to:

- Explain the use of limit switches in the automatic operation of machines and machine tools.
- Wire a simple two-wire circuit using a limit switch.
- Read and draw normally open (NO) and normally closed (NC) wiring symbols.

The automatic operation of machinery requires the use of switches that can be activated by the motion of the machinery. The repeat accuracy of the switches must be reliable and the response virtually instantaneous.

The size, operating force, stroke, and manner of mounting are all critical factors in the installation of limit switches due to mechanical limitations in the machinery. The electrical ratings of the switches must be carefully matched to the loads to be controlled.

In general, the operation of a limit switch begins when the moving machine or moving part of a machine strikes an operating lever which actuates the switch (Figure 21–1). The limit switch, in turn, affects the electrical circuit controlling the machine and its movement.

Limit switches are used as pilot devices in the control circuits of magnetic starters to start, stop, speed up, slow down or reverse electric motors. Limit switches may be used either as control devices for regular operation or as emergency switches to prevent the improper functioning of machinery. They may be momentary contact (spring return) or maintained contact types.

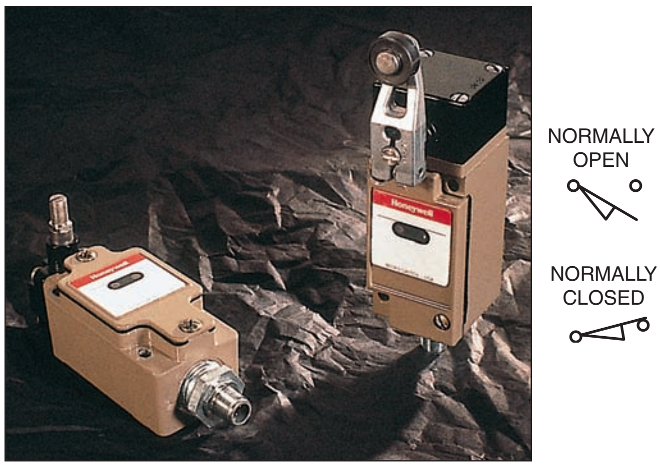


Figure 21–1 Limit switches. (Courtesy Micro Switch, a Honeywell Division.)

Limit switch contacts are often drawn differently than the symbols shown in Figure 21–1 on control schematics. The contact symbols shown in Figure 21–1 are the standard NEMA symbols for normally open and

Figure 21–2 Other switch symbols.

normally closed limit switch contacts. The contact symbol shown in Figure 21–2A shows a limit switch that is "normally open held closed." This means the contact is wired as a normally open contact, but when the circuit is in its normal off state, some part of the machine holds the contact closed. This symbol can be recognized as normally open because the movable contact arm is shown below the stationary contact point.

Figure 21–2B shows a limit switch wired "normally closed held open." The contact symbol is normally closed because the movable contact arm is drawn above the stationary contact point, but some part of the machine is holding the contact open.

Other contacts such as pressure switches, float switches, and flow switches can also be connected in this manner. The electrician is more likely to encounter limit switches used in this manner, however, because of the number of limit switches used in industry and the manner in which they are used.

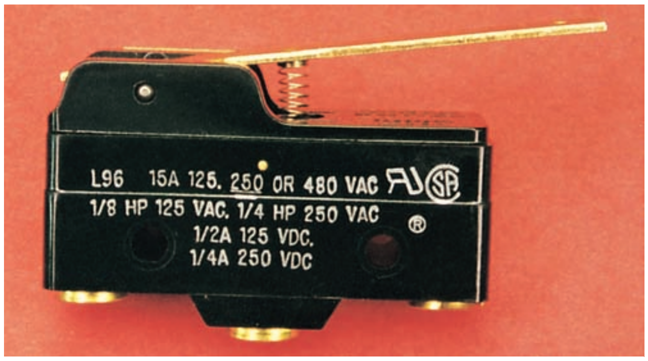


Figure 21–3 Micro limit switch.

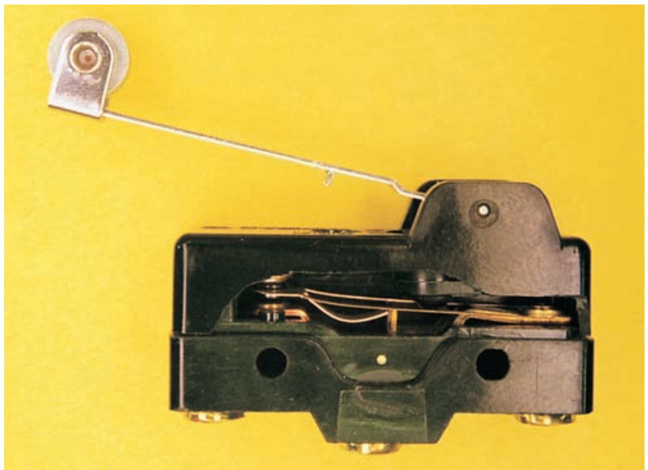


Figure 21–4 Spring loaded contacts of a basic micro switch.

Micro Limit Switches

Another type of limit switch often used in different types of control circuits is the micro limit switch or *micro switch*. Micro switches are much smaller in size than the limit switch shown in Figure 21–1, which permits them to be used in small spaces that would never be accessible to the larger device. Another characteristic of the micro switch is that the actuating plunger requires only a small amount of travel to cause the contacts to change position. The micro switch shown in Figure 21–3 has an activating plunger located at the top of the switch. This switch requires that the plunger be depressed approximately 0.015 inch or 0.38 mm. Switching the contact position with this small amount of movement is accomplished by spring loading the contacts as shown in Figure 21–4. A small amount of movement against the spring will cause the movable contact to snap from one position to another.

Electrical ratings for the contacts of the basic micro switch are generally in the range of 250 volts ac and 10 to 15 amps depending on the type of switch. The basic micro switch can be obtained with a variety of different activating arms as shown in Figure 21–5.

Figure 21–5 Micro switches can be obtained with different types of activating arms. (Courtesy Micro Switch, a Honeywell Division.)

Subminiature Micro Switches

The *subminiature micro switch* employs a similar spring contact arrangement as the basic micro switch (Figure 21–6). The subminiature switches are approximately $\frac{1}{2}$ to $\frac{1}{4}$ the size of the basic switch, depending on the model. Due to their reduced size, the contact rating of subminiature switches range from about 1 ampere to about 7 amperes depending on the switch type. Two different types of subminiature micro switches are shown in Figure 21–7.

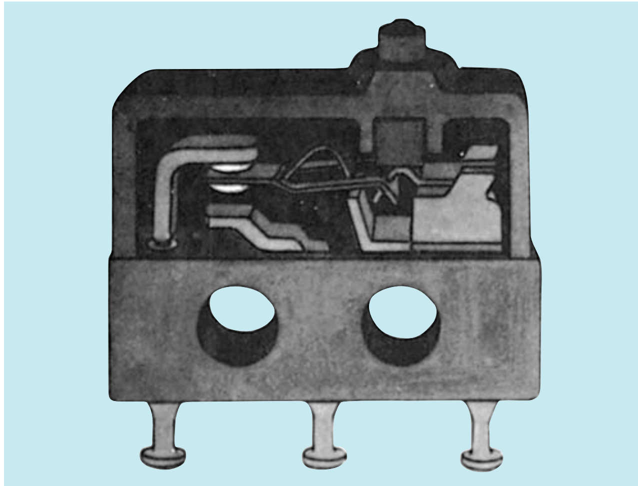
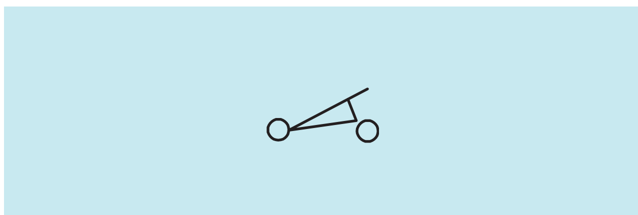


Figure 21–6 Cutaway view of a subminiature micro switch. (Courtesy Honeywell's Micro Switch Division.)

Figure 21–7 Subminiature micro switch. (Courtesy Square D Company.)

Review Questions

1. Draw a simple circuit showing how a red pilot light is energized when a limit switch is operated by a moving object.
2. Draw the schematic symbol for a limit switch that is normally open, but held closed.
3. What is the approximate amount of travel required to cause the contacts of a micro limit switch to change position?
4. Is the limit switch shown below: normally open, normally closed, normally open held closed, or normally closed held open?



5. A circuit is to be constructed that will permit a moving piece of machinery to strike a limit switch. When the switch is struck, it will cause a solenoid valve to turn on. Should the limit switch be connected normally open or normally closed?

UNIT 22
PHASE FAILURE RELAYS

OBJECTIVES

After studying this unit, the student will be able to:

- Explain the purpose of phase failure relays.
- List the hazards of phase failure and phase reversal.

If two phases of the supply to a three-phase induction motor are interchanged, the motor will reverse its direction of rotation. This action is called phase reversal. In the operation of elevators and in many industrial applications, phase reversal may result in serious damage to the equipment and injury to people using the equipment. In other situations, if a fuse blows or a wire to a motor breaks while the motor is running, the motor will continue to operate on single phase but will experience serious overheating. To protect motors against these conditions, phase failure and reversal relays are used.

A solid-state phase monitoring relay is shown in Figure 22–1. This relay provides protection in the event of a voltage unbalance or a phase reversal. The unit automatically resets after the correct voltage conditions return. An indicating light shows when the relay is activated.

Figure 22–1 Solid-state phase monitor relay.

Review Questions

1. What is the purpose of phase failure relays?

2. What are the hazards of phase failure and phase reversal?

UNIT 23

SOLENOID AND MOTOR OPERATED VALVES

OBJECTIVES

After studying this unit, the student will be able to:

- Describe the purpose and operation of two-way solenoid valves.
- Describe the purpose and operation of four-way solenoid valves.
- Connect and troubleshoot solenoid valves.
- Read and draw wiring symbols for solenoid valves.

Valves are mechanical devices designed to control the flow of fluids such as oil, water, air, and other gases. Many valves are manually operated, but electrically operated valves are most often used in industry because they can be placed close to the devices they operate, thus minimizing the amount of piping required. Remote control is accomplished by running a single pair of control wires between the valve and a control device such as a manually operated switch or an automatic device.

A solenoid valve is a combination of two basic units: an assembly of the solenoid (the electromagnet) and plunger (the core), and a valve containing an opening in which a disc or plug is positioned to regulate the flow. The valve is opened or closed by the movement of the magnetic plunger. When the coil is energized, the plunger (core) is drawn into the solenoid (electromagnet). The valve operates when current is applied to the solenoid. The valve returns automatically to its original position when the current ceases.

Most control pilot devices operate a single-pole switch, contact, or solenoid coil. The wiring diagrams of these devices are not difficult to understand and the actual devices can be connected easily into systems. It is recommended that the electrician know the *purpose* of and understand the *action* of the *total* industrial system for which various electrical control elements are to be used. In this way, the electrician will find it easier to design or assist in designing the electrical control system. It will also be easier for the electrician to install and maintain the control system.

Two-Way Solenoid Valves

Two-way (in and out) solenoid valves (Figure 23–1) are magnetically operated valves which are used to control the flow of Freon, methyl chloride, sulphur dioxide, and other liquids in refrigeration and air conditioning systems. These valves can also be used to control water, oil, and air flow.

Standard applications of solenoid valves generally require that the valve be mounted directly in line in the piping with the inlet and outlet connections directly opposite each other. Simplified valve mounting is possible with the use of a bottom outlet which eliminates elbows and bends. In the bottom outlet arrangement, the normal side outlet is closed with a standard pipe plug.

The valve body is usually a special brass forging which is carefully checked and tested to ensure that there will be no seepage due to porosities. The armature, or plunger, is made from a high grade stainless steel. The effects of residual magnetism are eliminated by the use of a kickoff pin and spring which prevent the armature from sticking. A shading coil ensures that the armature will make a complete seal with the flat surface above it to eliminate noise and vibration.

It is possible to obtain dc coils with a special winding that will prevent the damage that normally results from an instantaneous voltage surge when the circuit is broken. Surge capacitors are not required with this type of coil.

To ensure that the valve will always seat properly it is recommended that strainers be used to prevent grit or dirt from lodging in the orifice or valve seat. Dirt in these locations will cause leakage. The inlet and outlet connections of the valve must not be reversed. The tightness of the valve depends to a degree on pressure acting downward on the sealing disc. This pressure is possible only when the inlet is connected to the proper point as indicated on the valve.

Four-Way Solenoid Valves

Electrically operated, four-port, four-way air valves are used to control a double-acting cylinder (Figure 23–2).

When the coil is de-energized, one side of the piston is at atmospheric pressure, and the other side is acted upon by the line pressure. When the valve magnet coil is energized, the valve exhausts the high pressure

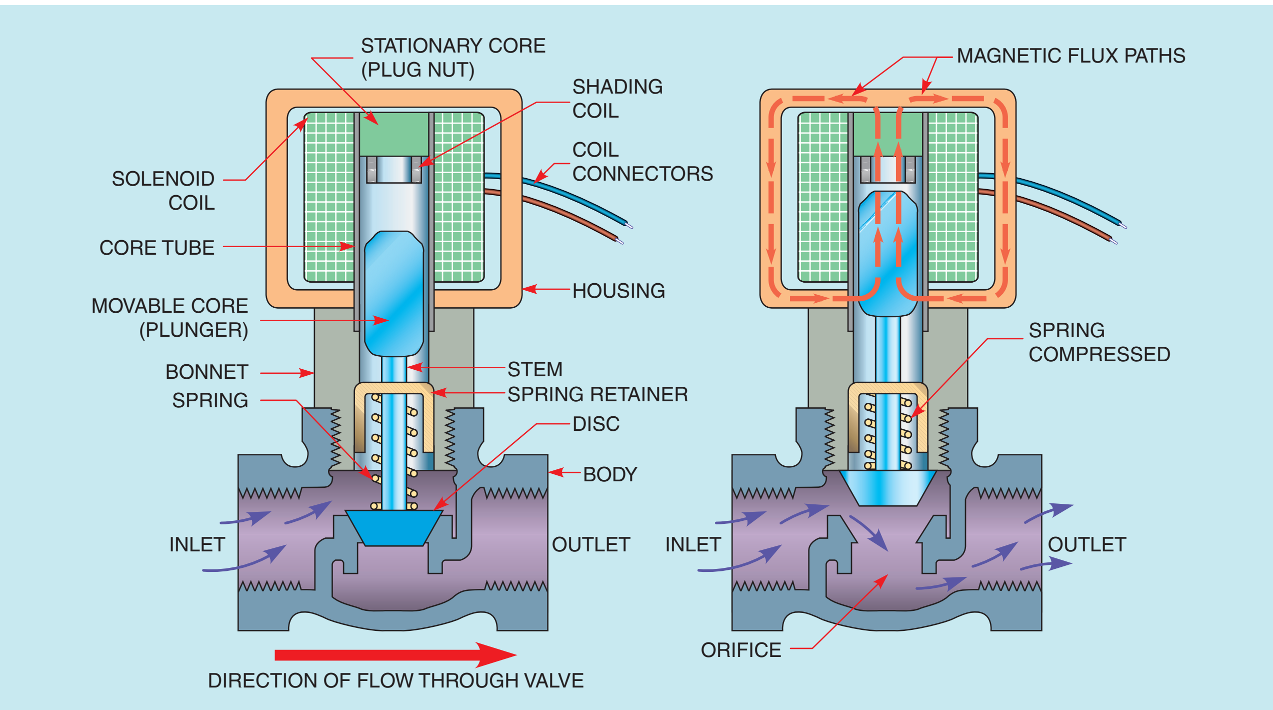


Figure 23–1 Two-way solenoid valve. (Courtesy Automatic Switch Co.)

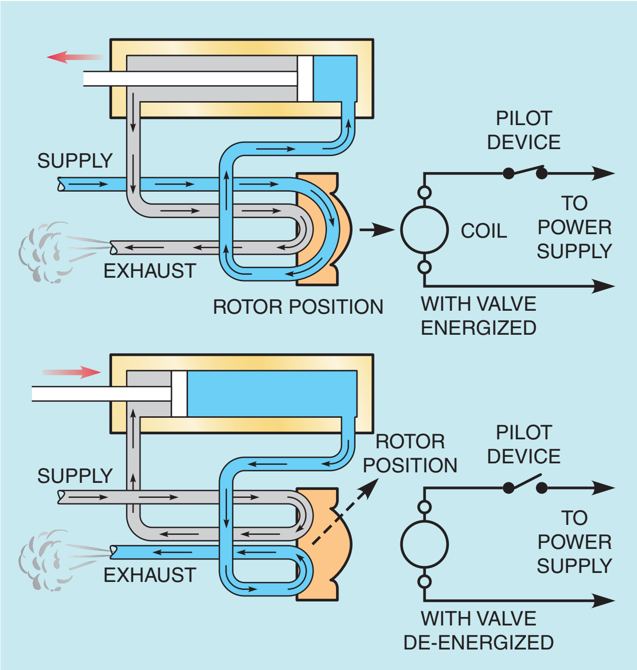


Figure 23–2 Control of double-acting cylinder by a four-way, electrically operated valve shown with elementary diagrams.

side of the piston to atmospheric pressure. As a result, the piston and its associated load reciprocate in response to the valve movement.

Four-way valves are used extensively in industry to control the operation of the pneumatic cylinders used on spot welders, press clutches, machine and assembly jig clamps, tools, and lifts.

Motor Operated Valves

Motor operated valves (MOVs) are used extensively in industries where the control of liquids or gasses is required. Pipe line companies and the petrol-chemical industry are just two examples of these types of industries. Motor operated valves are valves that employ an electric motor to open or close the valve (Figure 23–3). There are generally two sections to the control system for MOVs, local and remote. The local controls are housed with the valve at the field location and the remote controls are housed in a control room some distance away.

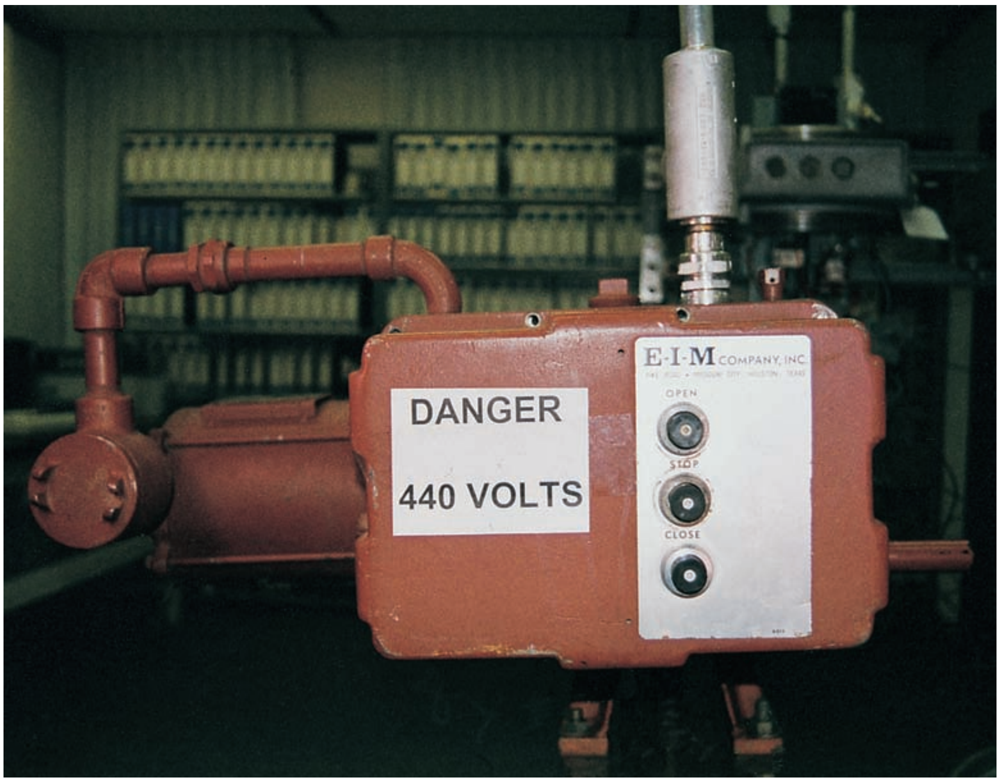


Figure 23–3 Motor operated valve.

The control system is basically a forward/reverse control with the addition of a special limit switch that detects when the valve is open or closed and a torque switch which can be used to ensure that the valve is tightly seated (Figure 23–4). It is common practice to use the limit switch (Figure 23–5) to determine when the valve is completely open, and the torque switch (Figure 23–6) to determine when the valve is closed. The schematic for an MOV is shown in Figure 23–7. The schematic is drawn to assume that the valve is in the open position and all limit switches are drawn to reflect this condition.

The control circuit for an MOV is of particular interest because a two-wire circuit is used to control the opening and closing of the valve from a remote location. This two-wire circuit consists mainly of an 80-volt transformer, relay coils K1A, K1B, K2A, and K2B, and push-buttons. Two-wire control is accomplished by converting the 80 volts ac into half-wave rectified dc with a voltage of 36 volts.

$$80 \text{ VAC} \times 0.9 \text{ (RMS to Average)} = 72 \text{ VDC (Full-Wave)}$$

$$\frac{72 \text{ VDC (Full-Wave)}}{2} = 36 \text{ VDC (Half-Wave)}$$

With the valve in the open position, normally closed limit switch LSC connected in series with coil K2B is closed and normally closed limit switch LSO connected in series with coil K2A is held open. This permits a current path through coil K2B, and diode D4 to the coils of K1A and K1B. At this point, current cannot flow through coil K1A because diode Dl is reverse biased. Current can flow through coil K1B and diode D2, however. Coils K2A and K2B have a voltage rating of 36 VDC, and coils K1A and K1B have a voltage rating of 24 VDC. Since coils K1B and K2B are connected in series, the voltage drops across both these coils must equal the applied voltage of 36 VDC. The coil resistances are such that 24 VDC is dropped across coil K1B and 12 VDC is dropped across coil K2B.

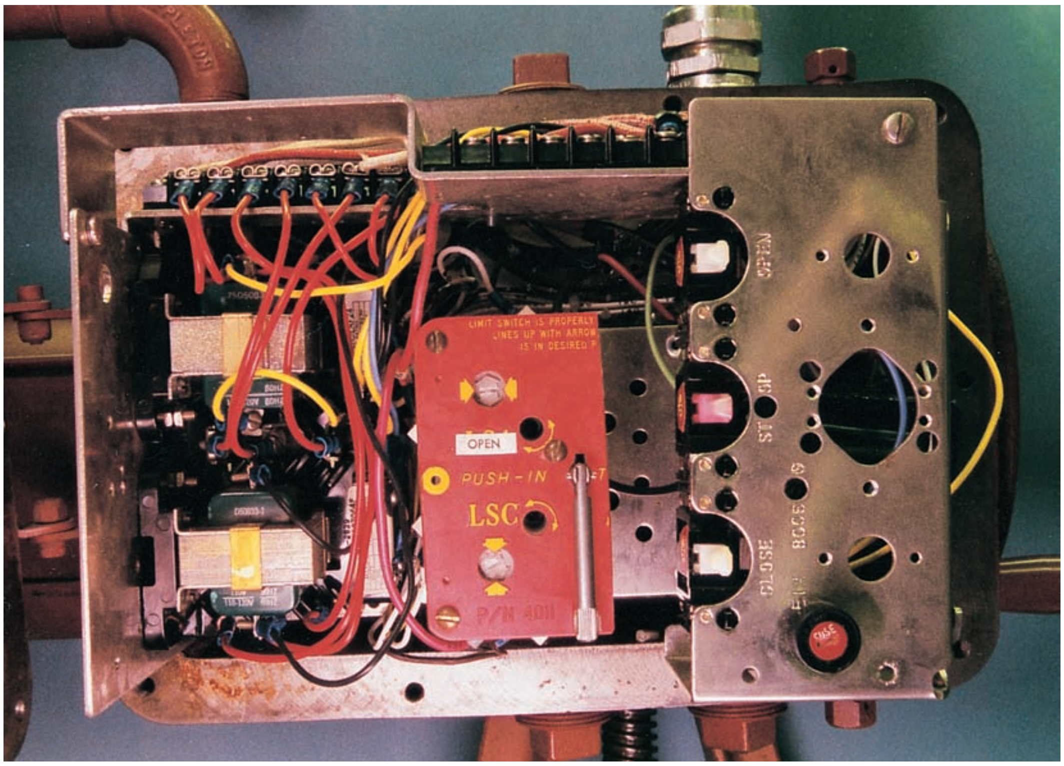


Figure 23–4 The MOV control circuit is basically a forward/reverse circuit.

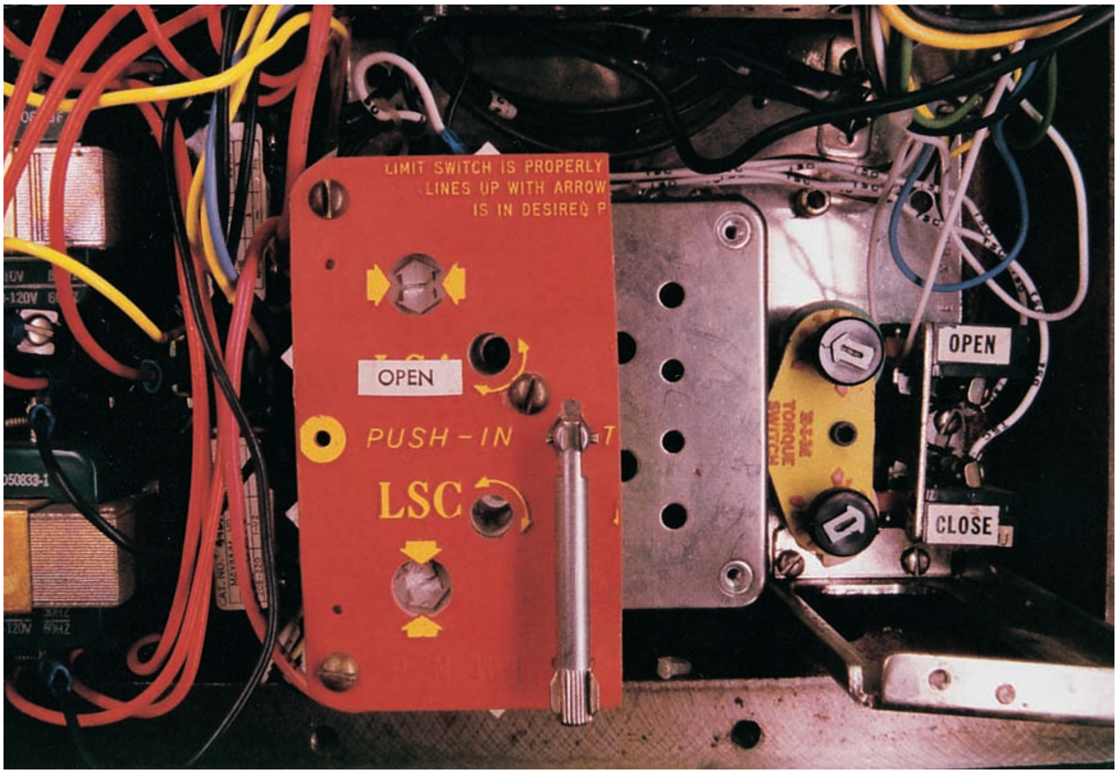


Figure 23–5 MOV limit switch.

Since coil K1B has a voltage rating of 24 VDC, it energizes and closes a contact to turn on the OPEN indicator light. Coil K2B has a voltage rating of 36 VDC. The 12 VDC applied to it is not enough to energize it, so its contacts remain in their normal position.

Now assume that the CLOSE push-button is pressed at the remote location. This short-circuits coil K1B, which causes the entire 36 VDC to be applied across coil K2B. When coil K2B energizes, C contactor energizes and the motor begins closing the valve. As the valve closes, limit switch LSC connected in series with coil K2B opens, breaking the current path through coils K1B and K2B.

When the valve reaches the closed position, limit switch LSO connected in series with coil K2A closes. A current path now exists through coils K2A, diode D3, coil K1A, and diode D1. Relay K1A energizes and turns on the CLOSED indicator light. Although the torque switch is generally used to stop the motor when the valve is closed, the limit switch is adjusted to indicate that the valve is in the closed position.

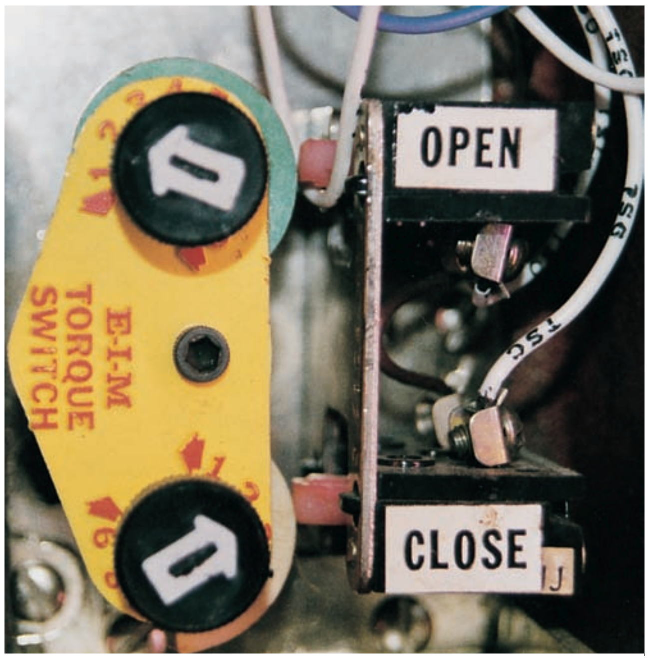


Figure 23–6 MOV torque switch.

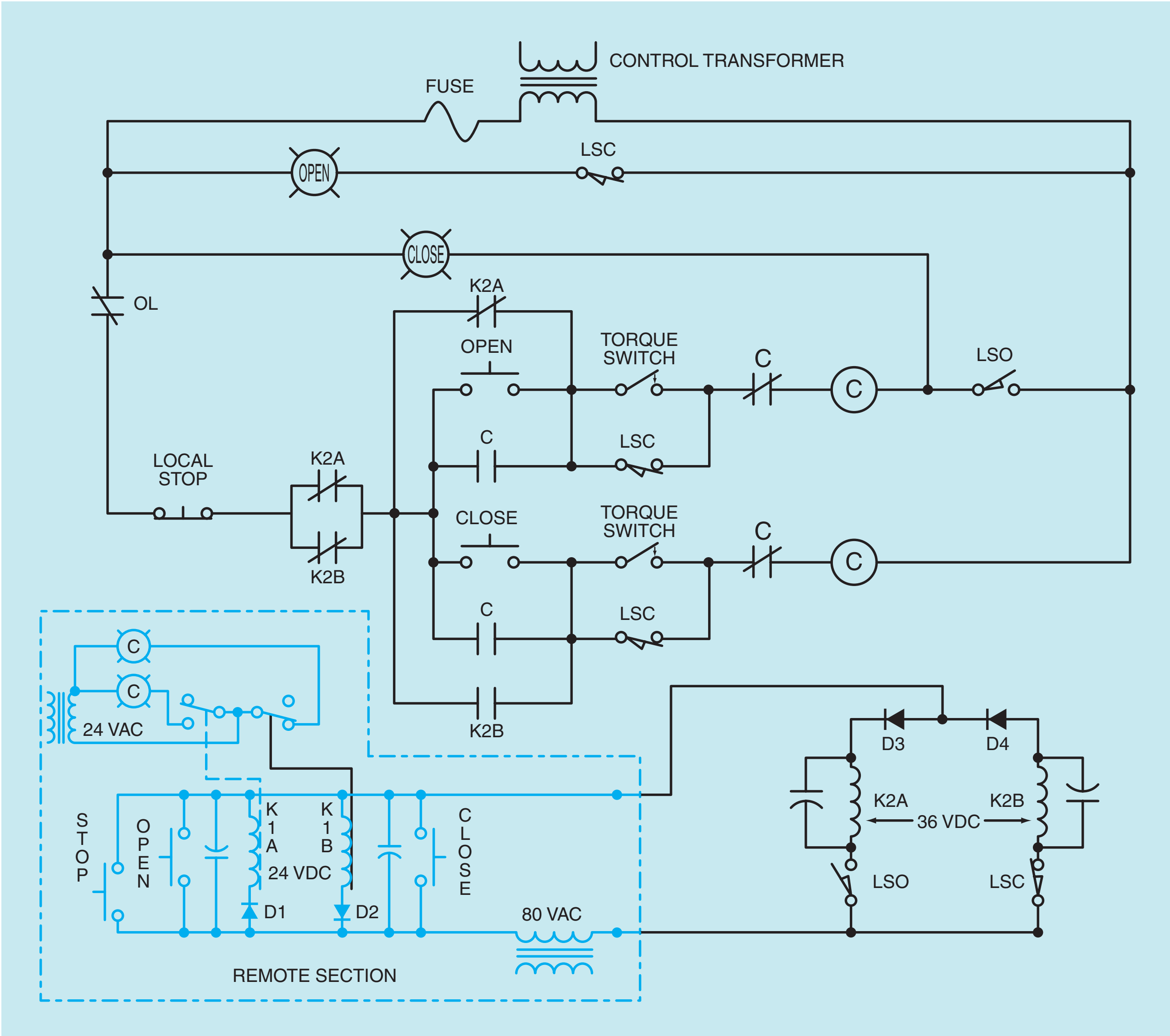


Figure 23–7 Control circuit for a motor operated valve.

Review Questions

1. Why is it important to understand the purpose and action of the total operational system when working with controls?
2. If an electrically controlled, two-way solenoid valve is leaking, what is the probable cause?
3. What is the difference between a two-way solenoid valve and a flow switch?

UNIT 24

TEMPERATURE SENSING DEVICES

OBJECTIVES

After studying this unit, the student will be able to:

- Describe different methods for sensing temperature.
- Discuss different devices intended to be operated by a change of temperature.
- List several applications for temperature sensing devices.
- Read and draw the NEMA symbols for temperature switches.

There are many times when the ability to sense temperature is of great importance. The industrial electrician will encounter some devices designed to change a set of contacts with a change of temperature and other devices used to sense the amount of temperature. The method used depends a great deal on the applications of the circuit and the amount of temperature that must be sensed.

Expansion of Metal

A very common and reliable method for sensing temperature is by the expansion of metal. It has long been known that metal expands when heated. The amount of expansion is proportional to two factors:

1. The type of metal used.
2. The amount of temperature.

Consider the metal bar shown in Figure 24–1. When the bar is heated, its length expands. When the

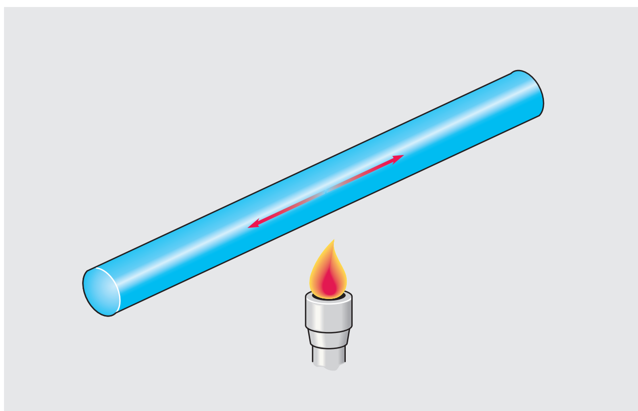


Figure 24–1 Metal expands when heated.

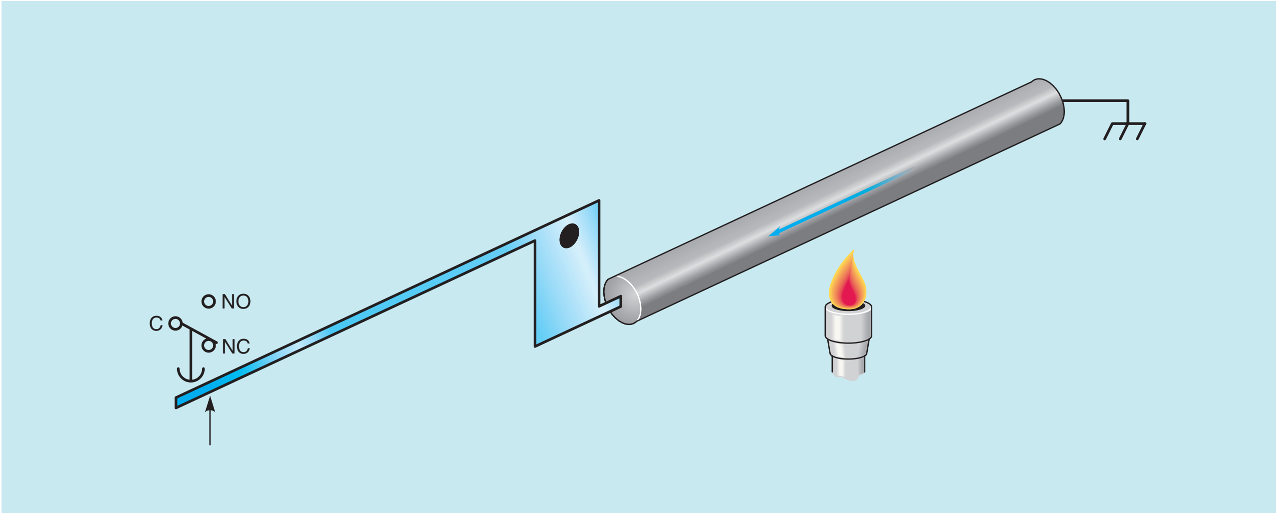


Figure 24–2 Expanding metal operates a set of contacts.

metal is permitted to cool, it will contract. Although the amount of movement due to contractions and expansion is small, a simple mechanical principle can be used to increase the amount of movement (Figure 24–2).

The metal bar is mechanically held at one end. This permits the amount of expansion to be in one direction only. When the metal is heated and the bar expands, it pushes against the mechanical arm. A small movement of the bar causes a great amount of movement in the mechanical arm. This increased movement in the arm can be used to indicate the temperature of the bar by attaching a pointer and scale, or to operate a switch as shown. It should be understood that illustrations are used to convey a principle. In actual practice, the switch shown in Figure 24–2 would be spring loaded to provide a "snap" action for the contacts. Electrical contacts must never be permitted to open or close slowly. This produces poor contact pressure and will cause the contacts to burn or will cause erratic operation of the equipment they are intended to control.

Hot-wire Starting Relay

A very common device that uses the principle of expanding metal to operate a set of contacts is the *hot-wire starting relay* found in the refrigeration industry. The hot-wire relay is so named because it uses a length of resistive wire connected in series with the motor to sense motor current. A diagram of this type relay is shown in Figure 24–3.

When the thermostat contact closes, current can flow from line L1 to terminal L of the relay. Current then flows through the resistive wire, the movable arm, and the normally closed contacts to the run and start windings. When current flows through the resistive wire, its temperature increases. This increase of temperature causes the wire to expand in length. When the length increases, the movable arm is forced downward. This downward pressure produces tension on the springs of both contacts. The relay is so designed that the start contact will snap open first, disconnecting the motor start winding from the circuit. If the motor current is not excessive, the wire will never become hot enough to cause the overload contact to open. If the motor current should become too great, however, the temperature of the resistive wire will become high enough to cause the wire to expand to the point that it will cause the overload contact to snap open and disconnect the motor run winding from the circuit.

The Mercury Thermometer

Another very useful device that works on the principle of contraction and expansion of metal is the *mercury thermometer.* Mercury is a metal that remains in a liquid state at room temperature. If the mercury is confined in a glass tube as shown in Figure 24–4, it will rise up the tube as it expands due to an increase in temperature. If the tube is calibrated correctly, it provides an accurate measurement for temperature.

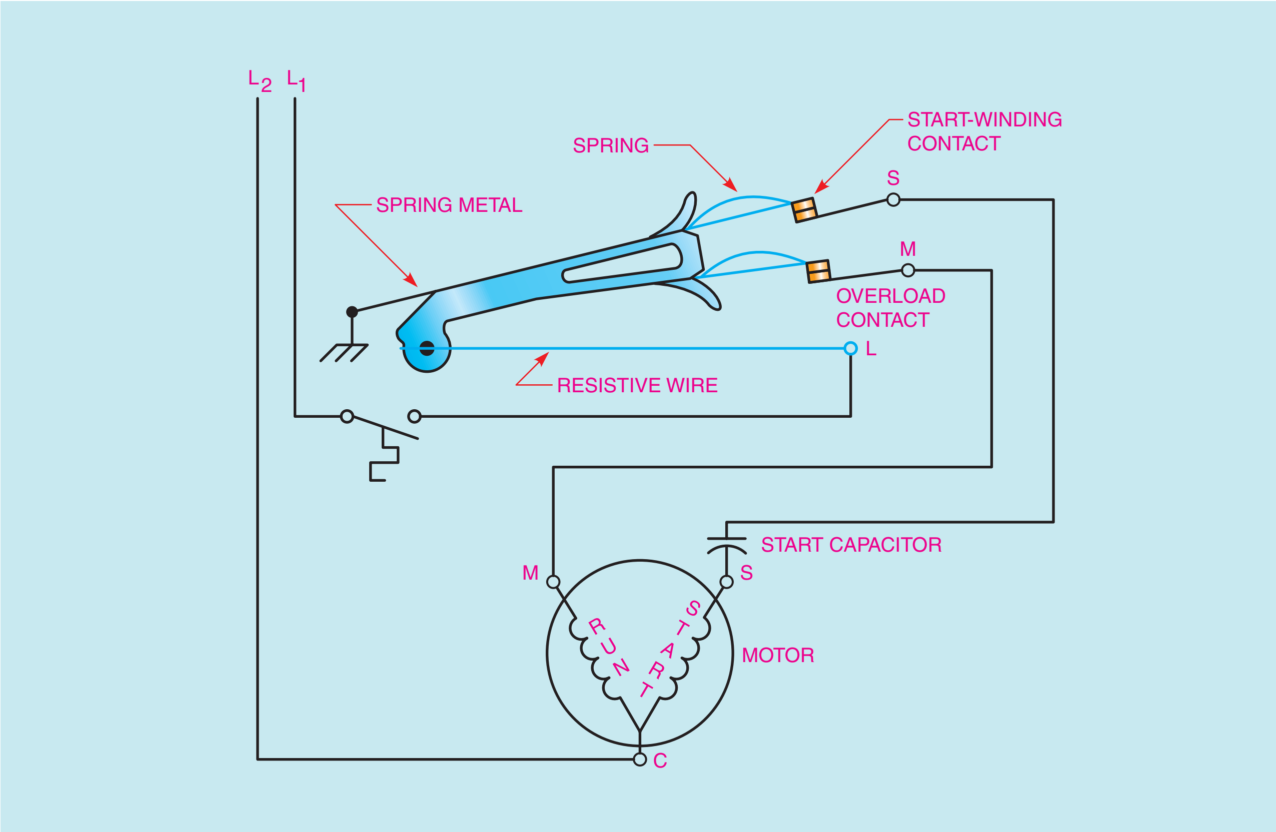


Figure 24–3 Hot-wire relay connection.

The Bimetal Strip

The *bimetal strip* is another device that operates by the expansion of metal. It is probably the most common heat sensing device used in the production of room thermostats and thermometers. The bimetal strip is made by bonding two dissimilar types of metal together (Figure 24–5). Since these two metals are not alike, they have different expansion rates. This causes the strip to bend or warp when heated (Figure 24–6). A bimetal strip is often formed into a spiral shape as shown in Figure 24–7. The spiral permits a longer bimetal strip to be used in a small space. A long bimetal strip is desirable because it exhibits a greater amount of movement with a change of temperature.

If one end of the strip is mechanically held and a pointer is attached to the center of the spiral, a change in temperature will cause the pointer to rotate. If a calibrated scale is placed behind the pointer, it becomes a thermometer. If the center of the spiral is held in position and a contact is attached to the end of the bimetal

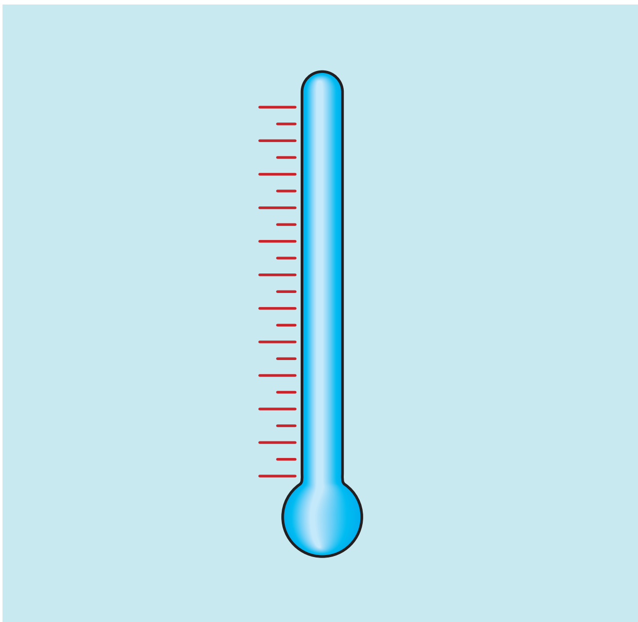


Figure 24–4 A mercury thermometer operates by the expansion of metal.

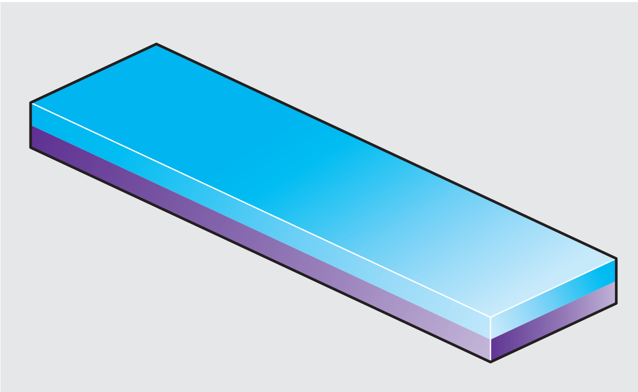


Figure 24–5 A bimetal strip.

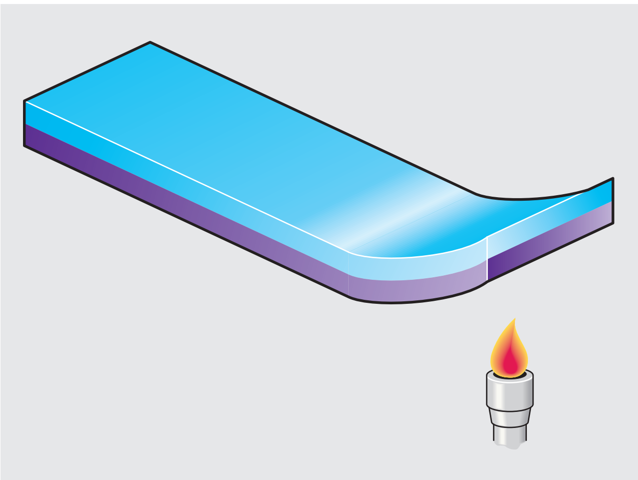


Figure 24–6 A bimetal strip warps with a change of temperature.

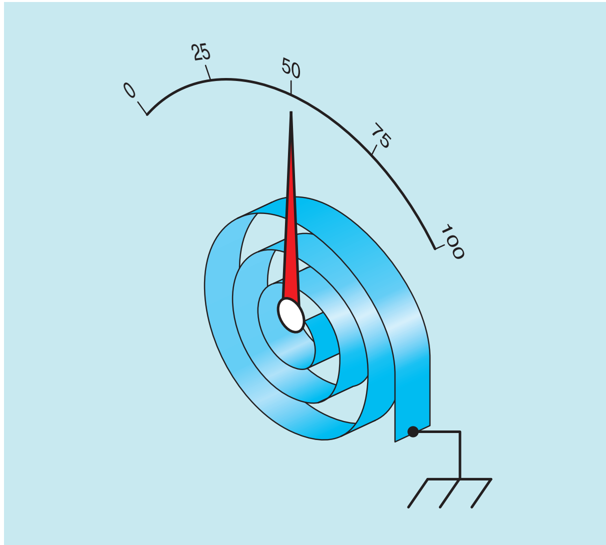


Figure 24–7 A bimetal strip used as a thermometer.

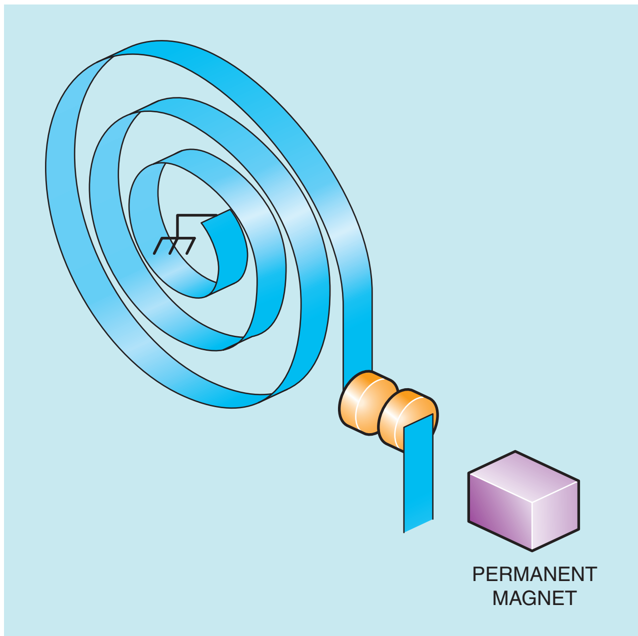


Figure 24–8 A bimetal strip used to operate a set of contacts.

strip, it becomes a thermostat. A small permanent magnet is used to provide a snap action for the contacts (Figure 24–8). When the moving contact reaches a point that is close to the stationary contact, the magnet attracts the metal strip and causes a sudden closing of the contacts. When the bimetal strip cools, it pulls away from the magnet. When the force of the bimetal strip becomes strong enough, it overcomes the force of the magnet and the contacts snap open.

Thermocouples

In 1822, a German scientist named Seebeck discovered that when two dissimilar metals are joined at one end, and that junction is heated, a voltage is produced (Figure 24–9). This is known as the *Seebeck effect.* The device produced by the joining of two dissimilar metals for the purpose of producing electricity with heat is called a *thermocouple.* The amount of voltage produced by a thermocouple is determined by:

1. The type materials used to produce the thermocouple.
2. The temperature difference of the two junctions.

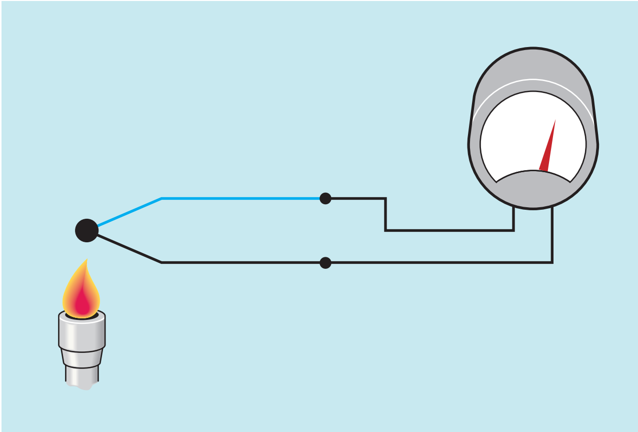


Figure 24–9 Thermocouple.

The chart in Figure 24–10 shows common types of thermocouples. The different metals used in the construction of thermocouples is shown as well as their normal temperature ranges.

The amount of voltage produced by a thermocouple is small, generally in the order of millivolts (1 millivolt = 0.001 volt). The polarity of the voltage of some thermocouples is determined by the temperature. For example, a type "J" thermocouple produces zero volts at about 32°F. At temperatures above 32°F, the iron wire is positive and the constantan wire is negative. At temperatures below 32°F, the iron wire becomes negative and the constantan wire becomes positive. At a temperature of +300°F, a type "J" thermocouple will produce a voltage of about +7.9 millivolts. At a temperature of −300°F, it will produce a voltage of about −7.9 millivolts.

Since thermocouples produce such low voltages, they are often connected in series as shown in Figure 24–11. This connection is referred to as a *thermopile.* Thermocouples and thermopiles are generally used for making temperature measurements and are sometimes used to detect the presence of a pilot light in appliances which operate with natural gas. The thermocouple is heated by the pilot light. The current

TYPE	MATERIAL		DEGREES F	DEGREES C
J	IRON	CONSTANTAN	−328 to +32 +32 to +1432	−200 to 0 0 to 778
K	CHROMEL	ALUMEL	−328 to +32 +32 to 2472	−200 to 0 0 to 1356
T	COPPER	CONSTANTAN	−328 to +32 +32 to 752	−200 to 0 0 to 400
E	CHROMEL	CONSTANTAN	−328 to +32 +32 to 1832	−200 to 0 0 to 1000
R	PLATINUM 13% RHODIUM	PLATINUM	+32 to + 3232	0 to 1778
S	PLATINUM 10% RHODIUM	PLATINUM	+32 to +3232	0 to 1778
B	PLATINUM 30% RHODIUM	PLATINUM 6% RHODIUM	+992 to +3352	533 to 1800

Figure 24–10 Thermocouple chart.

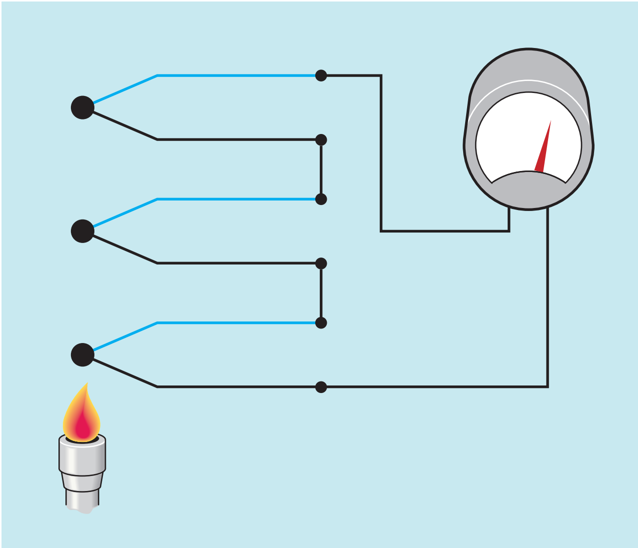


Figure 24–11 Thermopile.

produced by the thermocouple is used to produce a magnetic field that holds a gas valve open and permits gas to flow to the main burner. If the pilot light should go out, the thermocouple ceases to produce current and the valve closes (Figure 24–12).

Resistance Temperature Detectors

The *resistance temperature detector* (RTD) is made of platinum wire. The resistance of platinum changes greatly with temperature. When platinum is heated, its resistance increases at a very predictable rate; this makes the RTD an ideal device for measuring temperature very accurately. RTDs are used to measure temperatures that range from −328 to +1166 degrees Fahrenheit (−200° to +630 C°). RTDs are made in different styles to perform different functions. Figure 24–13 illustrates a typical RTD used as a probe. A very small coil of platinum wire is encased inside a copper tip. Copper is used to provide good thermal contact. This permits the probe to be very fast-acting. The chart in Figure 24–14 shows resistance versus temperature for a typical RTD probe. The temperature is given in degrees Celsius and the resistance is given in ohms. RTDs in several different case styles are shown in Figure 24–15.

Thermistors

The term *thermistor* is derived from the words "thermal resistor." Thermistors are actually thermally sensitive semi-conductor devices. There are two basic

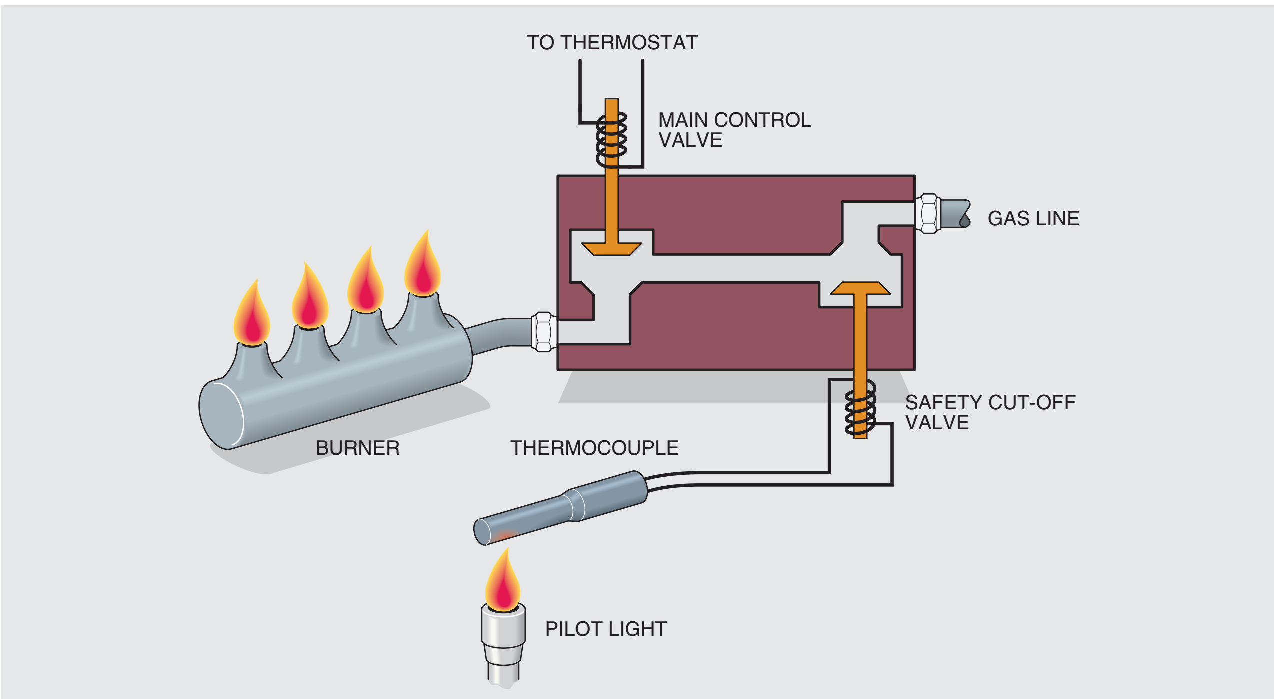


Figure 24–12 A thermocouple provides power to the safety cut-off valve.

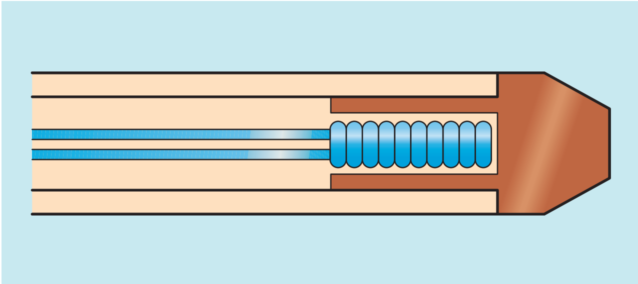


Figure 24–13 Resistance temperature detector.

Degrees C	Resistance
0	100
50	119.39
100	138.5
150	157.32
200	175.84
250	194.08
300	212.03
350	229.69
400	247.06
450	264.16
500	280.93
550	297.44
600	313.65

Figure 24–14 Temperature and resistance for a typical RTD.

types of thermistors: one type has a negative temperature coefficient (NTC) and the other has a positive temperature coefficient (PTC). A thermistor that has a negative temperature coefficient will decrease its resistance as the temperature increases. A thermistor that has a positive temperature coefficient will increase its resistance as the temperature increases. The NTC thermistor is the most widely used.

Thermistors are highly nonlinear devices. For this reason they are difficult to use for measuring temperature. Devices that measure temperature with a thermistor must be calibrated for the particular type of thermistor being used. If the thermistor is ever replaced, it has to be an exact replacement or the circuit will no longer operate correctly. Because of their nonlinear characteristics, thermistors are often used as *set point detectors* as opposed to actual temperature measurement. A set point detector is a device that activates some process or circuit when the temperature reaches a certain level. For example, assume a thermistor has been

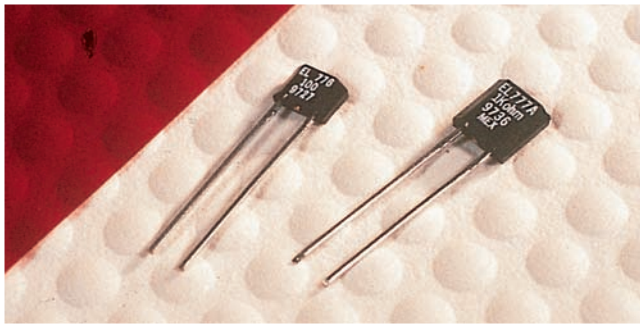


Figure 24–15 RTDs in different case styles. (Courtesy Honeywell's Micro Switch Division.)

placed inside the stator winding of a motor. If the motor should become overheated, the windings could become severely damaged or destroyed. The thermistor can be used to detect the temperature of the windings. When the temperature reaches a certain point, the resistance value of the thermistor changes enough to cause the starter coil to drop out and disconnect the motor from the line. Thermistors can be operated in temperatures that range from about −100° to +300 F°.

One common use for thermistors is in the solid-state starting relays used with small refrigeration compressors (Figure 24–16). Starting relays are used with hermetically sealed motors to disconnect the start windings from the circuit when the motor reaches about 0.75% of its full speed. Thermistors can be used for this application because they exhibit an extremely rapid change of resistance with a change of temperature. A schematic diagram showing the connection for a solid state relay is shown in Figure 24–17.

When power is first applied to the circuit, the thermistor is cool and has a relatively low resistance.

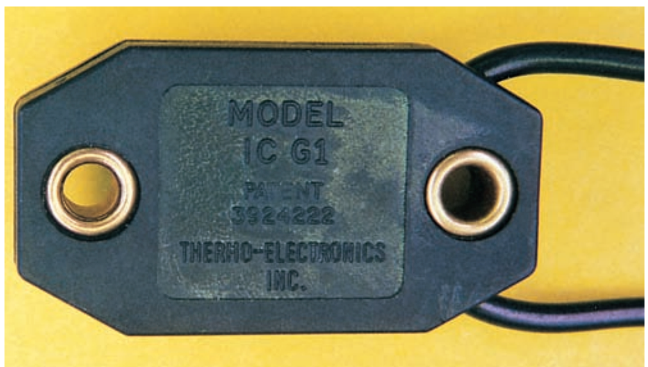


Figure 24–16 Solid state starting relay.

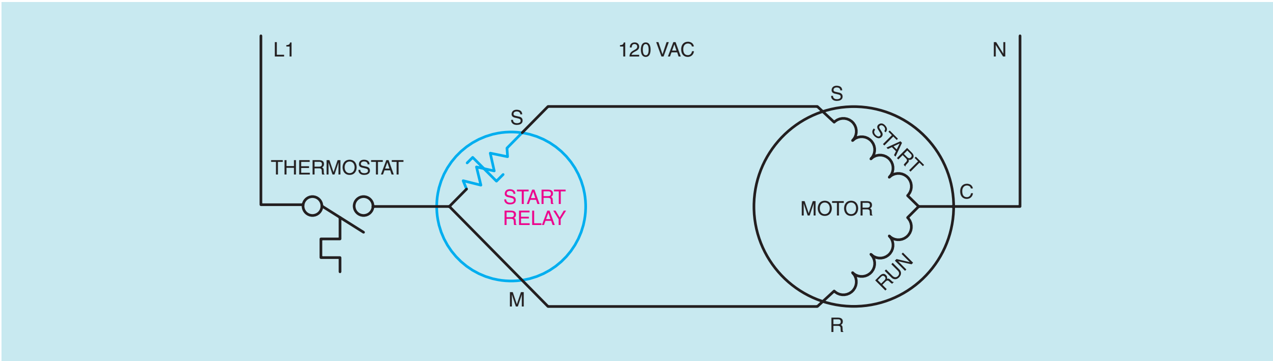


Figure 24–17 Connection of solid-state starting relay.

This permits current to flow through both the start and run windings of the motor. The temperature of the thermistor increases because of the current flowing through it. The increase of temperature causes the resistance to change from a very low value of 3 or 4 ohms to several thousand ohms. This increase of resistance is very sudden and has the effect of opening a set of contacts connected in series with the start winding. Although the start winding is never completely disconnected from the power line, the amount of current flow through it is very small, typically 0.03 to 0.05 amps, and does not affect the operation of the motor. This small amount of *leakage current* maintains the temperature of the thermistor and prevents it from returning to a low resistance. After power has been disconnected from the motor, a cool-down period of about 2 minutes should be allowed before restarting the motor. This cool-down period is needed for the thermistor to return to a low value of resistance.

The PN Junction

Another device that has the ability to measure temperature is the PN junction or diode. The diode is becoming a very popular device for measuring temperature because it is accurate and linear.

When a silicon diode is used as a temperature sensor, a constant current is passed through the diode. Figure 24–18 illustrates this type of circuit. In this circuit, resistor R1 limits the current flow through the transistor and sensor diode. The value of R1 also determines the amount of current that flows through the diode. Diode D1 is a 5.1 volt zener used to produce a constant voltage drop between the base and emitter of the PNP transistor. Resistor R2 limits the amount of current flow through the zener diode and the base of the transistor. D1 is a common silicon diode. It is being used as the temperature sensor for the circuit. If a digital voltmeter is connected across the diode, a voltage drop between 0.8 and 0 volts can be seen. The amount of voltage drop is determined by the temperature of the diode.

Another circuit that can be used as a constant current generator is shown in Figure 24–19. In this circuit, a field effect transistor (FET) is used to produce a current generator. Resistor R1 determines the amount of current that will flow through the diode. Diode D1 is the temperature sensor.

If the diode is subjected to a lower temperature, say by touching it with a piece of ice, the voltage drop across the diode will increase. If the diode temperature is increased, the voltage drop will decrease because the

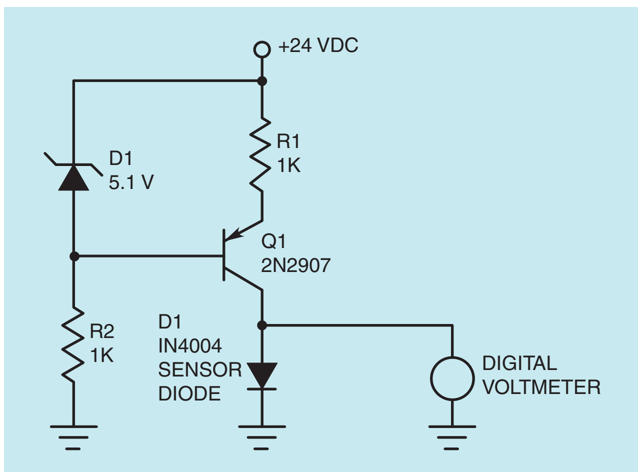


Figure 24–18 Constant current generator.

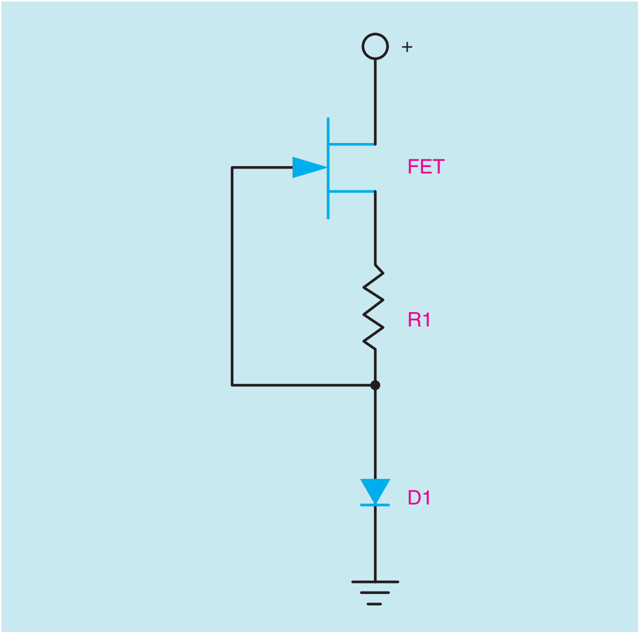


Figure 24–19 Field effect transistor used to produce a constant current generator.

diode has a negative temperature coefficient. As its temperature increases, its voltage drop becomes less.

In Figure 24–20, two diodes connected in a series are used to construct an electronic thermostat. Two diodes are used to increase the amount of voltage drop as the temperature changes. A field effect transistor and resistor are used to provide a constant current to the two diodes used as the heat sensor. An operational amplifier is used to turn a solid state relay on or off as the temperature changes. In the example shown, the circuit will operate as a heating thermostat. The output of the amplifier will turn on when the temperature decreases sufficiently. The circuit can be converted to a cooling thermostat by reversing the connections of the inverting and noninverting inputs of the amplifier.

Expansion Due to Pressure

Another common method of sensing a change of temperature is by the increase of pressure of some chemicals. Refrigerants confined in a sealed container, for

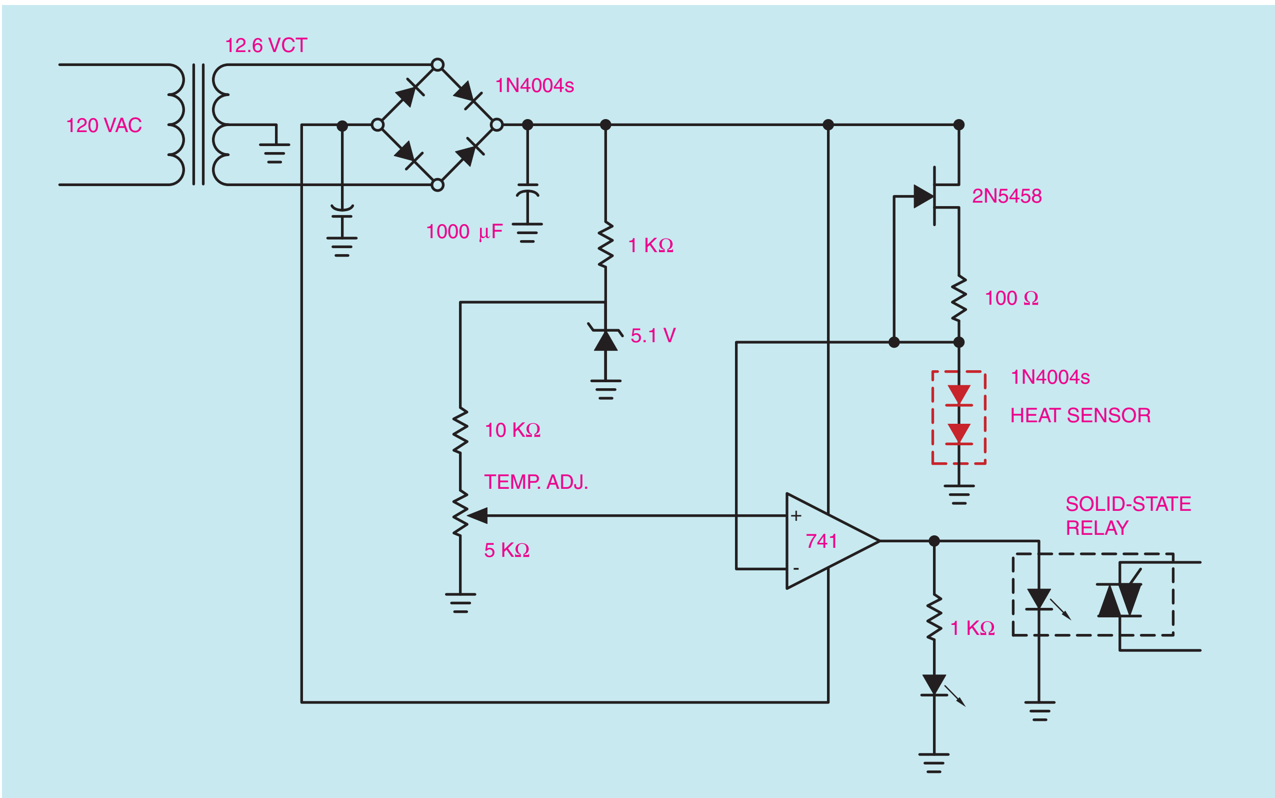


Figure 24–20 Solid-state thermostat using diodes as heat sensors.

example, will increase the pressure in the container with an increase of temperature. If a simple bellows is connected to a line containing refrigerant (Figure 24–21) the bellows will expand as the pressure inside the sealed system increases. When the surrounding air temperature decreases, the pressure inside the system decreases and the bellows contracts. When the air temperature increases, the pressure increases and the bellows expands. If the bellows controls a set of contacts, it becomes a bellows type thermostat. A bellows thermostat and the standard NEMA symbols used to represent a temperature operated switch are shown in Figure 24–22.

Smart Temperature Transmitters

Standard temperature transmitters generally send a 4–20 ma. signal to indicate the temperature. They are calibrated for a specific range of temperature such as 0 to 100 degrees. Standard transmitters are designed to operate with one type of sensor such as RTD, thermocouple, etc. Any changes to the setting require a recalibration of the unit.

Smart transmitters contain an internal microprocessor and can be calibrated from the control room by sending a signal to the transmitter. It is also possible to check the transmitter for problems from a remote location. A cutaway view of a smart temperature transmitter is shown in Figure 24–23. The transmitter illustrated

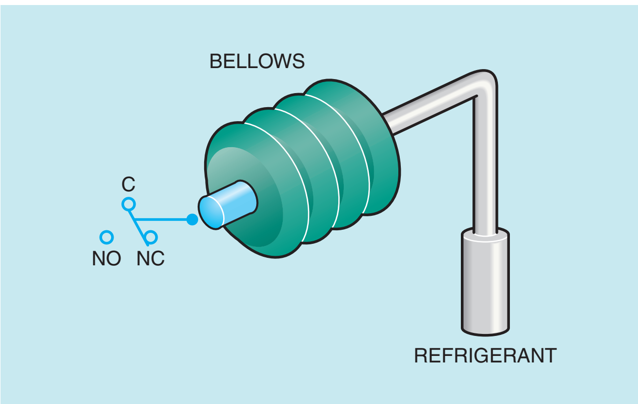


Figure 24–21 Bellows contracts and expands with a change of refrigerant pressure.

Figure 24–22 Industrial temperature switch.

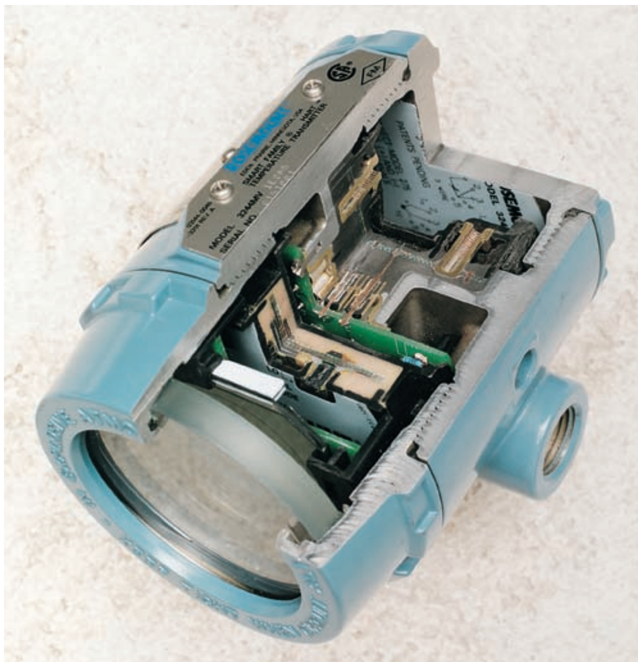


Figure 24–23 Cut-away view of a smart temperature transmitter. (Courtesy © 1998 Rosemount, Inc. used by permission.)

in Figure 24–23 use HART (Highway Addressable Remote Transducer) protocol. This transmitter can accept RTD, differential RTD, thermocouple, ohm, and millivolt inputs. A smart temperature transmitter with meter is shown in Figure 24–24.

Figure 24–24 Smart temperature transmitter with meter. (Courtesy © 1998 Rosemount, Inc. used by permission.)

Review Questions

1. Should a metal bar be heated or cooled to make it expand?
2. What type of metal remains in a liquid state at room temperature?
3. How is a bimetal strip made?
4. Why are bimetal strips often formed into a spiral shape?
5. Why should electrical contacts never be permitted to open or close slowly?
6. What two factors determine the amount of voltage produced by a thermocouple?
7. What is a thermopile?
8. What do the letters RTD stand for?
9. What type of wire is used to make an RTD?
10. What material is a thermistor made of?
11. Why is it difficult to measure temperature with a thermistor?
12. If the temperature of a NTC thermistor increases, will its resistance increase or decrease?
13. How can a silicon diode be made to measure temperature?
14. Assume that a silicon diode is being used as a temperature detector. If its temperature increases, will its voltage drop increase or decrease?
15. What type of chemical is used to cause a pressure change in a bellows type thermostat?

UNIT 25

HALL EFFECT SENSORS

OBJECTIVES

After studying this unit, the student will be able to:

- Describe the Hall effect.
- Discuss the principles of operation of a Hall generator.
- Discuss applications in which Hall generators can be used.

Principles of Operation

The Hall effect is a simple principle that is widely used in industry today. The Hall effect was discovered by Edward H. Hall at Johns Hopkins University in 1879. Mr. Hall originally used a piece of pure gold to produce the Hall effect, but today a piece of semiconductor material is used because semiconductor material works better and is less expensive to use. The device is often referred to as the Hall generator.

Figure 25–1 illustrates how the Hall effect is produced. A constant current power supply is connected to opposite sides of a piece of semiconductor material. A sensitive voltmeter is connected to the other two sides. If the current flows straight through the semiconductor material, no voltage is produced across the voltmeter connection.

Figure 25–2 shows the effect of bringing a magnetic field near the semiconductor material. The magnetic field causes the current flow path to be deflected to one side of the material. This causes a potential or voltage to be produced across the opposite sides of the semiconductor material.

If the polarity of the magnetic field is reversed, the current path is deflected in the opposite direction as shown in Figure 25–3. This causes the polarity of the voltage produced by the Hall generator to change. Two

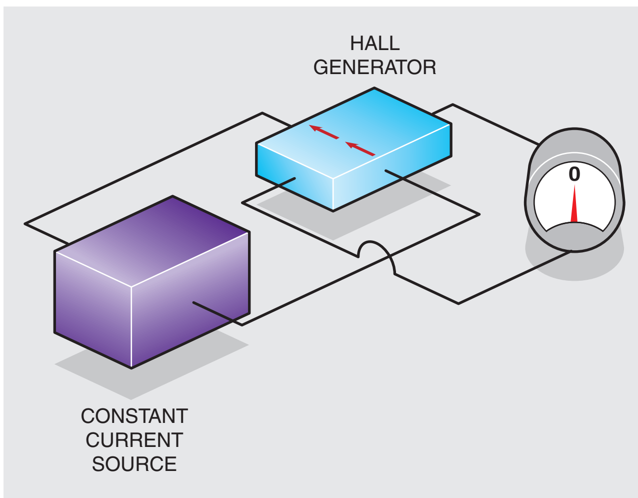


Figure 25–1 Constant current flows through a piece of semiconductor material.

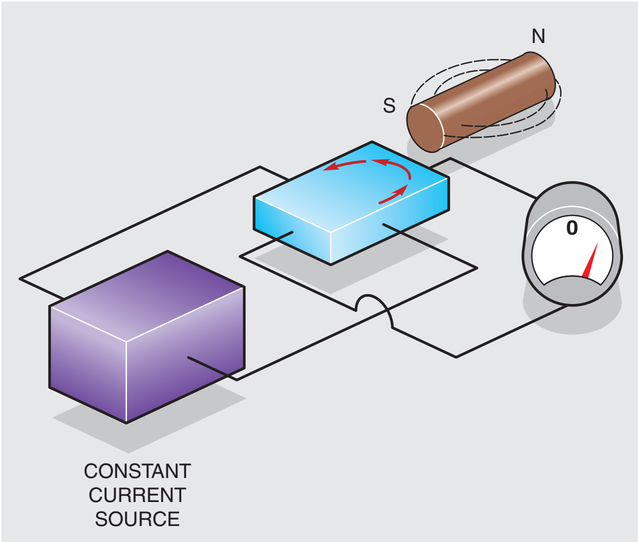


Figure 25–2 A magnetic field deflects the path of current flow through the semiconductor.

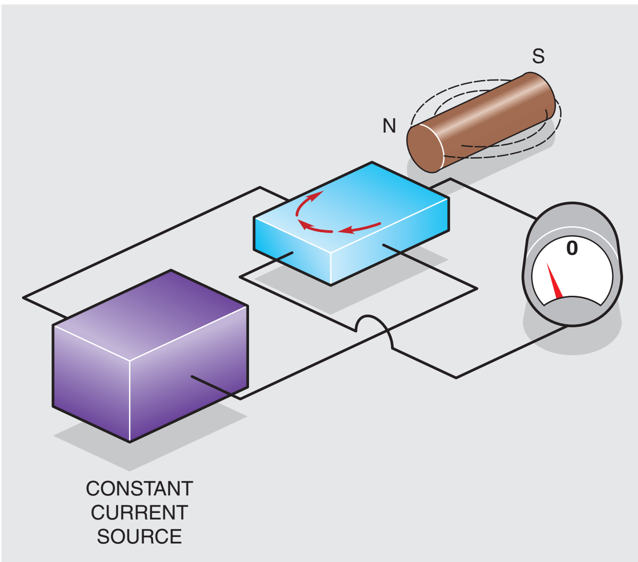


Figure 25–3 The current path is deflected in the opposite direction.

factors determine the polarity of the voltage produced by the Hall generator:

1. the direction of current flow through the semiconductor material; and
2. the polarity of the magnetic field used to deflect the current.

The amount of voltage produced by the Hall generator is determined by

1. the amount of current flowing through the semiconductor material; and
2. the strength of the magnetic field used to deflect the current path.

The Hall generator has many advantages over other types of sensors. Since it is a solid-state device, it has no moving parts or contacts to wear out. It is not affected by dirt, oil, or vibration. The Hall generator is an integrated circuit which is mounted in many different types and styles of cases.

Hall Generator Applications

Motor Speed Sensor

The Hall generator can be used to measure the speed of a rotating device. If a disk with magnetic poles around its circumference is attached to a rotating shaft, and a Hall sensor is mounted near the disk, a voltage will be produced when the shaft turns. Since the disk has alternate magnetic polarities around its circumference, the sensor will produce an ac voltage. Figure 25–4 shows a Hall generator used in this manner. Figure 25–5 shows the ac waveform produced by the rotating disk. The frequency of the ac voltage is proportional to the number of magnetic poles on the disk and the speed of rotation.

Another method for sensing speed is to use a *reluctor.* A reluctor is a ferrous metal disk used to shunt a magnetic field away from some other object. This type of sensor uses a notched metal disk attached to a rotating shaft. The disk separates a Hall sensor and a

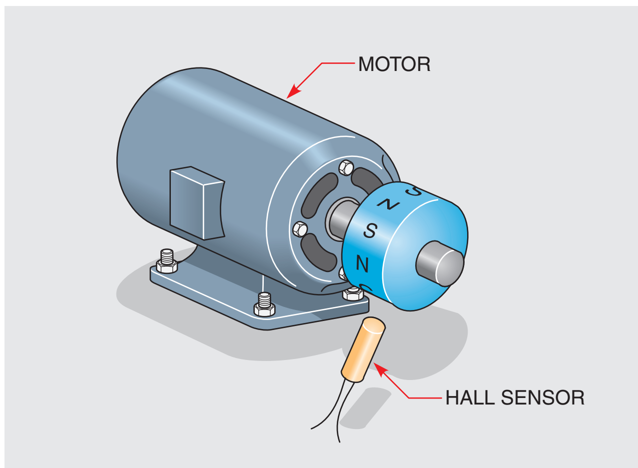


Figure 25–4 An ac voltage is produced by the rotating magnetic disk.

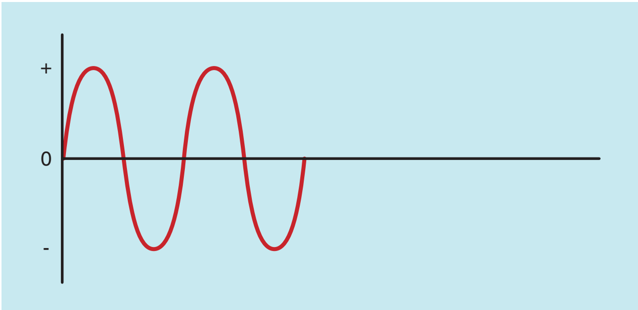


Figure 25–5 Sine Wave.

permanent magnet (Figure 25–6). When the notch is between the sensor and the magnet, a voltage is produced by the Hall generator. When the solid metal part of the disk is between the sensor and magnet, the magnetic field is shunted away from the sensor. This causes a significant drop in the voltage produced by the Hall generator.

Since the polarity of the magnetic field does not change, the voltage produced by the Hall generator is pulsating direct current instead of alternating current. Figure 25–7 shows the dc pulses produced by the generator. The number of pulses produced per second is proportional to the number of notches on the reluctor and the speed of the rotating shaft.

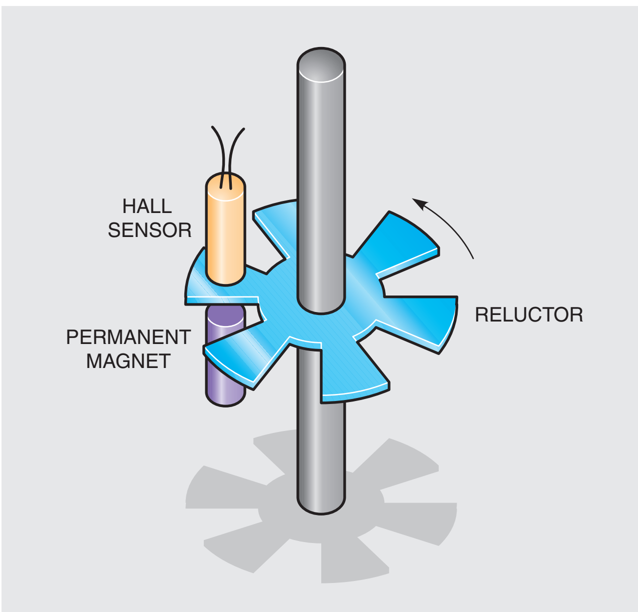


Figure 25–6 Reluctor shunts magnetic field away from sensor.

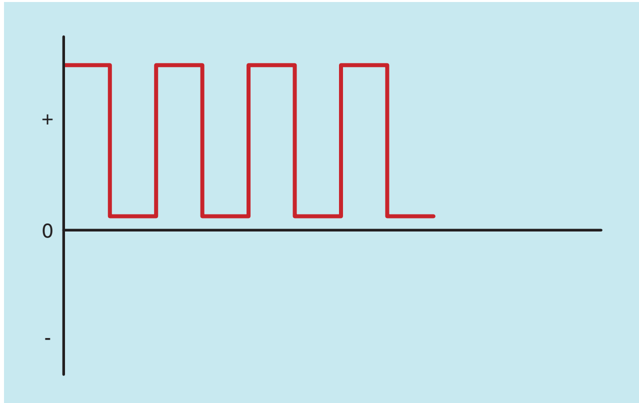


Figure 25–7 Square wave pulses produced by the Hall generator.

Position Sensor

The Hall generator can be used in a manner similar to a limit switch. If the sensor is mounted beside a piece of moving equipment, and a permanent magnet is attached to the moving equipment, a voltage will be produced when the magnet moves near the sensor (Figure 25–8). The advantages of the Hall sensor are that it has no lever arm or contacts to wear like a common limit switch, and it can operate through millions of operations of the machine.

A Hall effect position sensor is shown in Figure 25–9. Notice that these type sensors vary in size and style to fit almost any application. Position sensors operate as a digital device in that they sense the presence or absence of magnetic field. They do not have the ability to sense the intensity of the field.

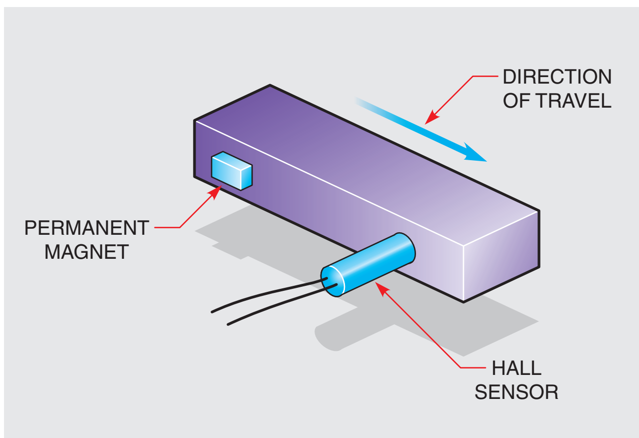


Figure 25–8 Hall generator used to sense position of moving device.

Figure 25–9 Hall effect position sensors. (Courtesy Turck, Inc.)

Hall Effect Limit Switches

Another Hall effect device used in a very similar application is the Hall effect limit switch (Figure 25–10). This limit switch uses a Hall generator instead of a set of contacts. A magnetic plunger is mechanically activated by the small button. Different types of levers can be fitted to the switch, which permits it to be used for many applications. These switches are generally intended to be operated by a 5 volt dc supply for TTL logic applications, or by a 6 to 24 volt dc supply for

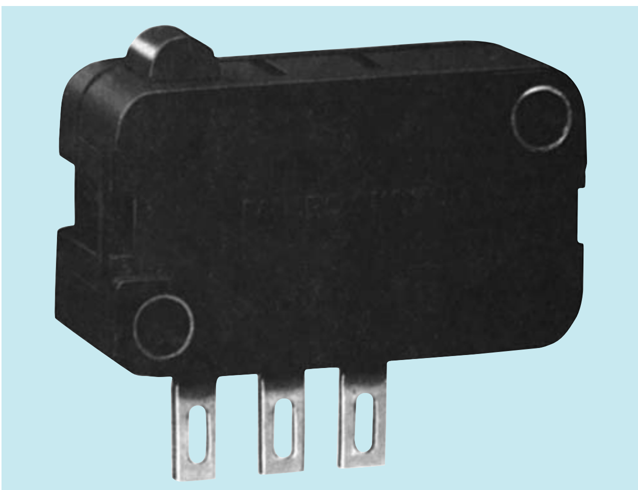


Figure 25–10 Hall effect limit switch. (Courtesy Honeywell's Micro Switch Division.)

interface with other types of electronic controls or to provide input for programmable controllers.

Current Sensor

Since the current source for the Hall generator is provided by a separate power supply, the magnetic field does not have to be moving or changing to produce an output voltage. If a Hall sensor is mounted near a coil of wire, a voltage will be produced by the generator when current flows through the wire. Figure 25–11 shows a Hall sensor used to detect when a dc current flows through a circuit. A Hall effect sensor is shown in Figure 25–12.

The Hall generator is being used more and more in industrial applications. Since the signal rise and fall time of the Hall generator is generally less than 10 microseconds, it can operate at pulse rates as high as 100,000 pulses per second. This makes it especially useful in industry.

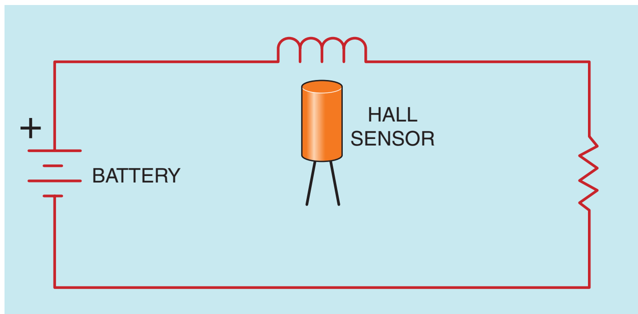


Figure 25–11 Hall sensor detects when dc current flows through the circuit.

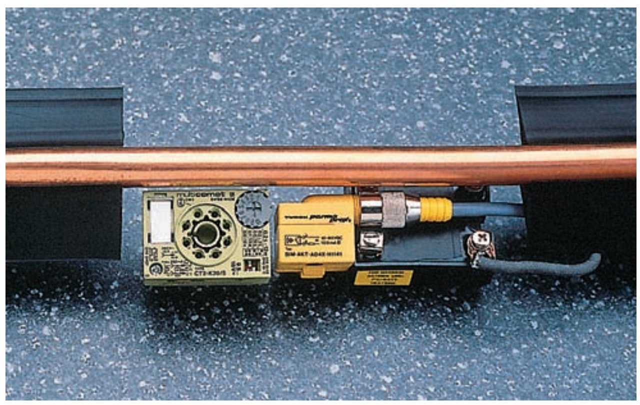


Figure 25–12 Hall effect sensor. (Courtesy Turck, Inc.)

Linear Transducers

Linear transducers are designed to produce an output voltage which is proportional to the strength of a magnetic field. Input voltage is typically 8 to 16 volts, but the amount of output voltage is determined by the type of transducer used. Hall effect linear transducers can be obtained that have two types of outputs. One type has a *regulated* output and produces voltages of 1.5 to 4.5 volts. The other type has a *ratiometric* output and produces an output voltage which is 25% to 75% of the input voltage. A Hall effect linear transducer is shown in Figure 25–13.

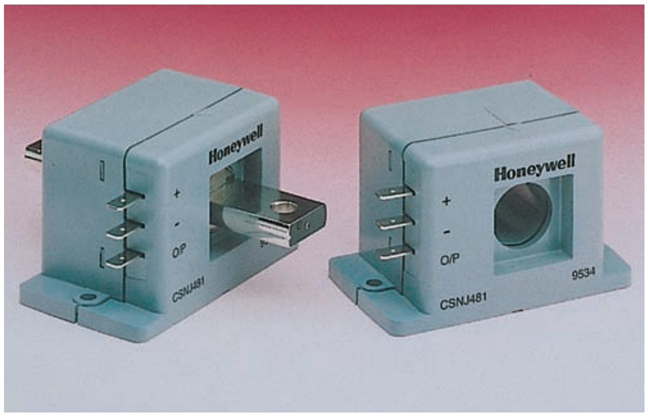


Figure 25–13 Hall effect linear transducer. (Courtesy Honeywell's Micro Switch Division.)

Review Questions

1. What material was used to make the first Hall generator?
2. What two factors determine the polarity of the output voltage produced by the Hall generator?
3. What two factors determine the amount of voltage produced by the Hall generator?
4. What is a reluctor?
5. Why does a magnetic field not have to be moving or changing to produce an output voltage in the Hall generator?

UNIT 26
PROXIMITY DETECTORS

OBJECTIVES

After studying this unit, the student will be able to:

- Describe the operation of proximity detectors.
- Describe different types of proximity detectors.

Applications

Proximity detectors are basically metal detectors. They are used to detect the presence or absence of metal without physically touching it. This prevents wear on the unit and gives the detector the ability to sense red hot metals. Most proximity detectors are designed to detect ferrous metals only, but there are some units that detect all metals.

Circuit Operation

There are several methods used to make proximity detectors. One method is shown in Figure 26–1. This is a very simple circuit intended to illustrate the principle of operation of a proximity detector. The sensor coil is connected through a series resistor to an oscillator. A voltage detector, in this illustration a voltmeter, is connected across the resistor. Since ac voltage is applied to this circuit, the amount of current flow is determined by the resistance of the resistor and the inductive reactance of the coil. The voltage drop across the resistor is proportional to its resistance and the amount of current flow.

If ferrous metal is placed near the sensor coil, its inductance increases in value. This causes an increase in inductive reactance, and a decrease in the amount of current flow through the circuit. When the current flow through the resistor is decreased, the voltage drop across the resistor decreases also (Figure 26–2). The drop in voltage can be used to turn relays or other devices on or off.

This method of detecting metal does not work well for all conditions. Another method which is more sensitive to small amounts of metal is shown in Figure 26–3. This detector uses a tank circuit tuned to the frequency of the oscillator. The sensor head contains two coils instead of one. This type of sensor is a small transformer. When the tank circuit is tuned to the frequency of the oscillator, current flow around the tank loop is high. This causes a high voltage to be induced into the secondary coil of the sensor head.

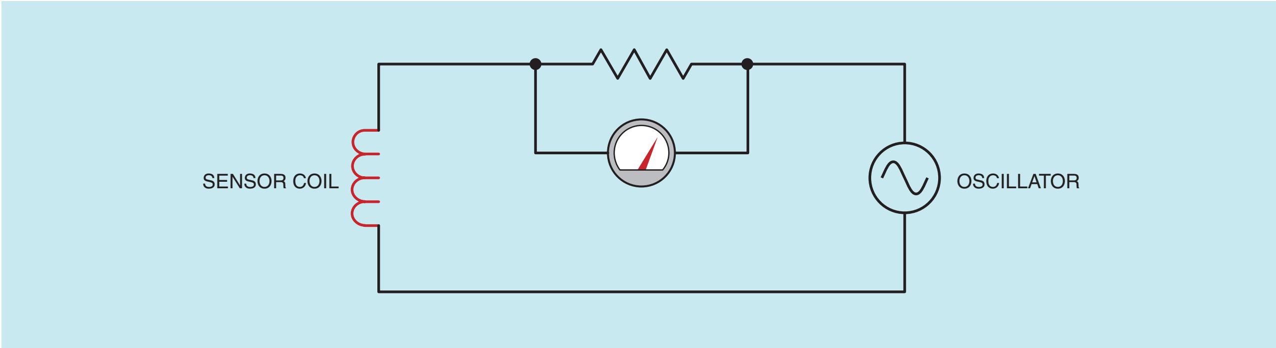


Figure 26–1 Simple proximity detector.

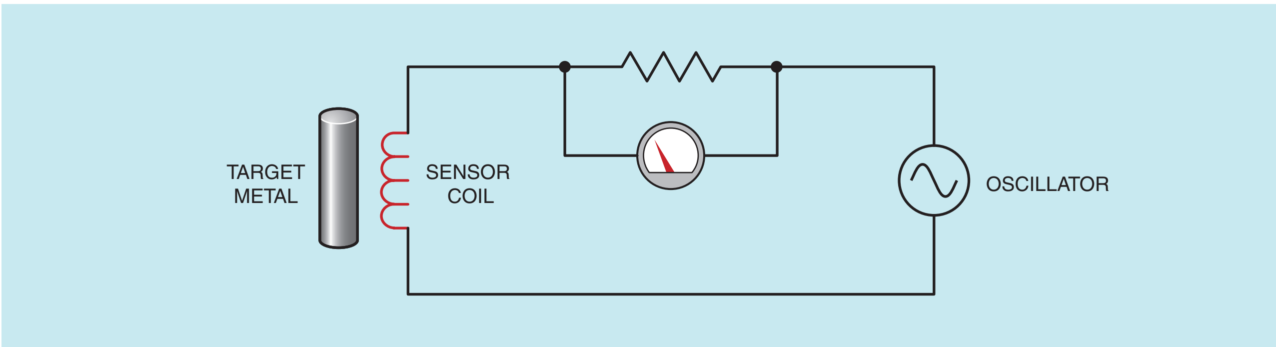


Figure 26–2 The presence of metal causes a decrease of voltage drop across the resistor.

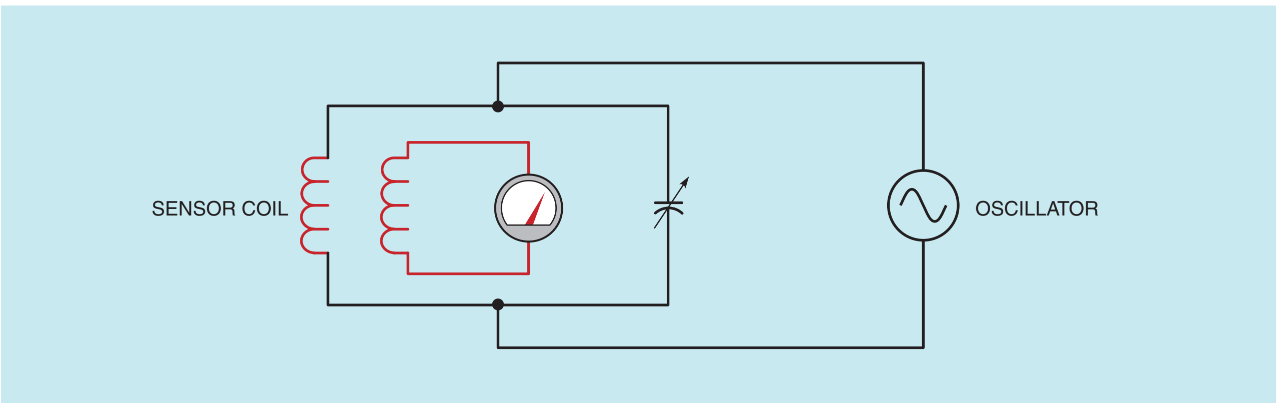


Figure 26–3 Tuned tank circuit used to detect metal.

When ferrous metal is placed near the sensor as shown in Figure 26–4, the inductance of the coil increases. When the inductance of the coil changes, the tank circuit no longer resonates to the frequency of the oscillator. This causes the current flow around the loop to decrease significantly. The decrease of current flow through the sensor coil causes the secondary voltage to drop also.

Notice that both types of circuits depend on a ferrous metal to change the inductance of a coil. If a detector is to be used to detect nonferrous metals, some means other than changing the inductance of the coil must be used. An all-metal detector uses a tank circuit as shown in Figure 26–5. All-metal detectors operate at radio frequencies, and the balance of the tank circuit is used to keep the oscillator running. If the tank circuit becomes

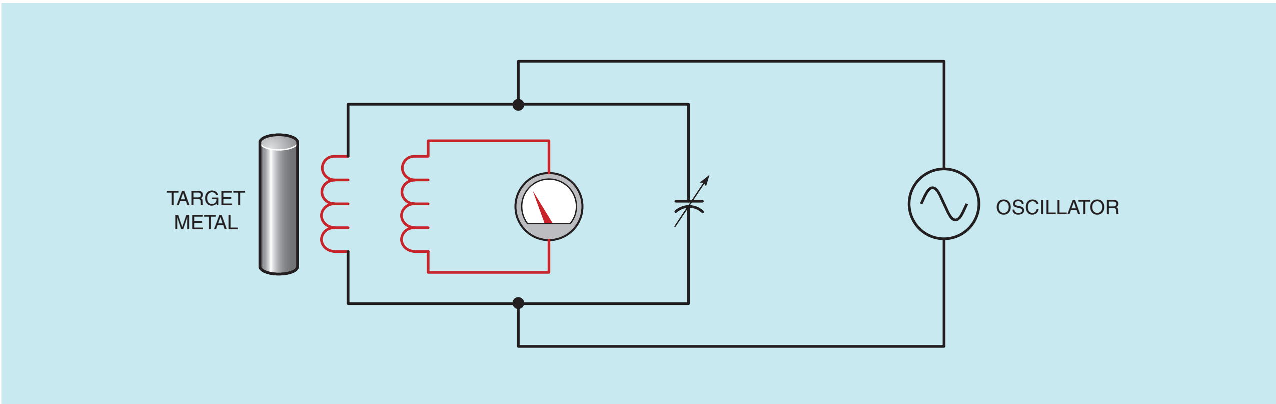


Figure 26–4 The presence of metal detunes the tank circuit.

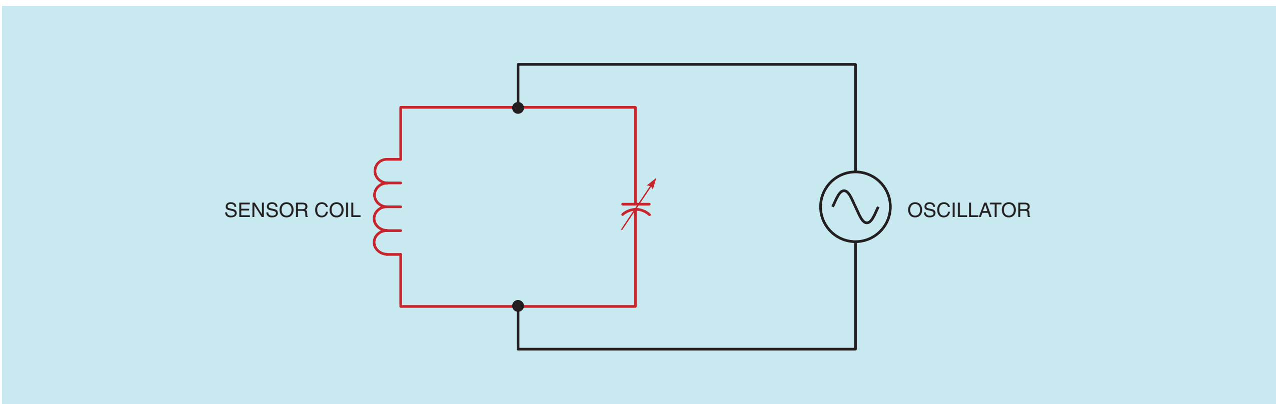


Figure 26–5 Balance of the tank circuit permits the oscillator to operate.

unbalanced, the oscillator stops operating. When a nonferrous metal, such as aluminum, copper, or brass, is placed near the sensor coil, eddy currents are induced into the surface of the metal. The induction of eddy currents into the metal causes the tank circuit to become unbalanced and the oscillator to stop operating. When the oscillator stops operating, some other part of the circuit signals an output to turn on or off.

Proximity detectors used to sense all types of metals will sense ferrous metals better than nonferrous. A ferrous metal can be sensed at about three times the distance of a nonferrous metal.

Mounting

Some proximity detectors are made as a single unit. Other detectors use a control unit which can be installed in a relay cabinet and a sensor which is mounted at a remote location. Figure 26–6 shows different types of proximity detectors. Regardless of the type of detector used, care and forethought should be used when mounting the sensor. The sensor must be near enough to the target metal to provide a strong positive signal, but it should not be so near that there is a possibility of the sensor being hit by the metal object. One advantage of the proximity detector is that no physical contact is necessary between the detector and the metal object for the detector to sense the object.

Figure 26–6 Proximity detectors. (Courtesy Turck, Inc.)

Sensors should be mounted as far away from other metals as possible. This is especially true for sensors used with units designed to detect all types of metals. In some cases it may be necessary to mount the sensor unit on a nonmetal surface such as wood or plastic. If proximity detectors are to be used in areas that contain metal shavings or metal dust, an effort should be made to place the sensor in a position that will prevent the shavings or dust from collecting around it. In some installations it may be necessary to periodically clean the metal shavings or dust away from the sensor.

Capacitive Proximity Detectors

Although proximity detectors are generally considered to be metal detectors, there are other types that sense the presence of objects that do not contain metal of any kind. One type of these detectors operate on a change of capacitance. When an object is brought into the proximity of one of these detectors, a change of capacitance causes the detector to activate. Several different types of capacitive proximity detectors are shown in Figure 26–7.

Since capacitive proximity detectors do not depend on metal to operate, they will sense virtually any material such as wood, glass, concrete, plastic, and sheet rock. They can even be used to sense liquid levels through a sight glass. One disadvantage of capacitive proximity detectors is that they have a very limited range. Most cannot sense objects over approximately one inch or 25 millimeters away. Many capacitive proximity detectors are being used to replace mechanical limit switches since they do not have to make contact with an object to sense its position. Most can be operated with a wide range of voltages such as 2–250 VAC, or 20–320 VDC.

Figure 26–7 Capacitive proximity detectors. (Courtesy Turck, Inc.)

Ultrasonic Proximity Detectors

Another type of proximity detector that does not depend on the presence of metal for operation is the *ultrasonic detector*. Ultrasonic detectors operate by emitting a pulse of high frequency sound and then detecting the echo when it bounces off an object (Figure 26–8). These detectors can be used to determine the distance to the object by measuring the time interval between the emission of the pulse and the return of the echo. Many ultrasonic sensors have an analog output of voltage or current, the value of which is determined by the distance to the object. This feature permits them to be used in applications where it is necessary to sense the position of an object (Figure 26–9). An ultrasonic proximity detector is shown in Figure 26–10.

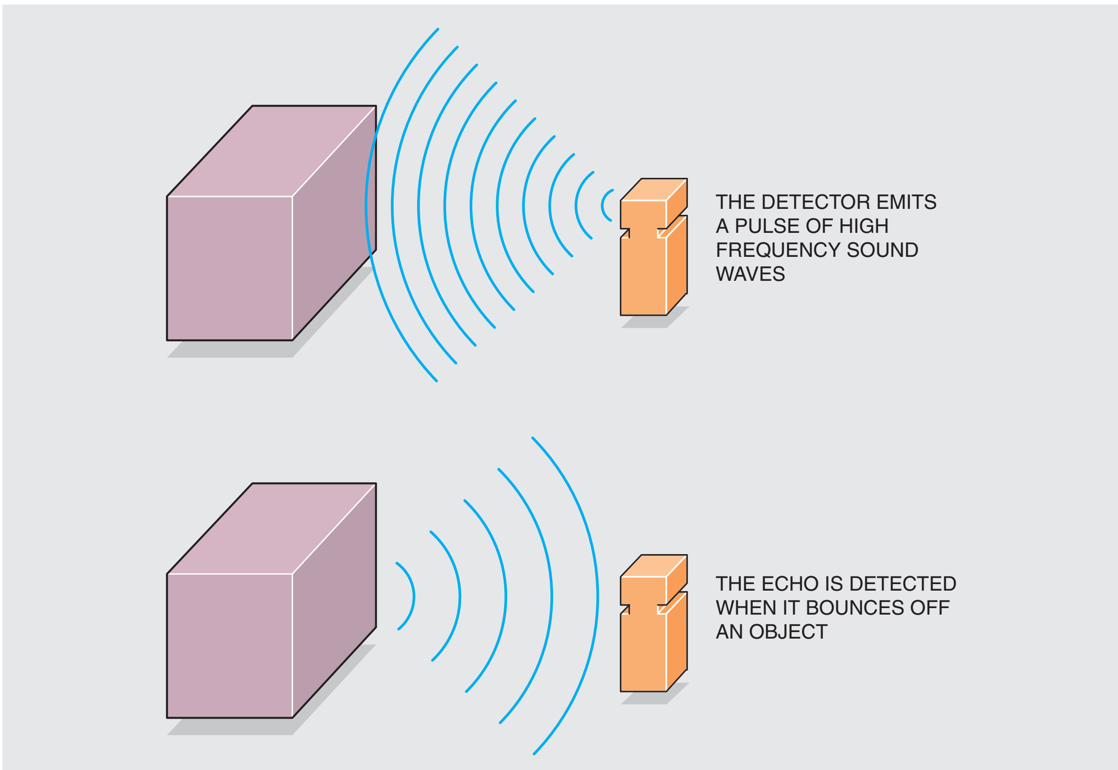


Figure 26–8 Ultrasonic proximity detectors operate by emitting high frequency sound waves.

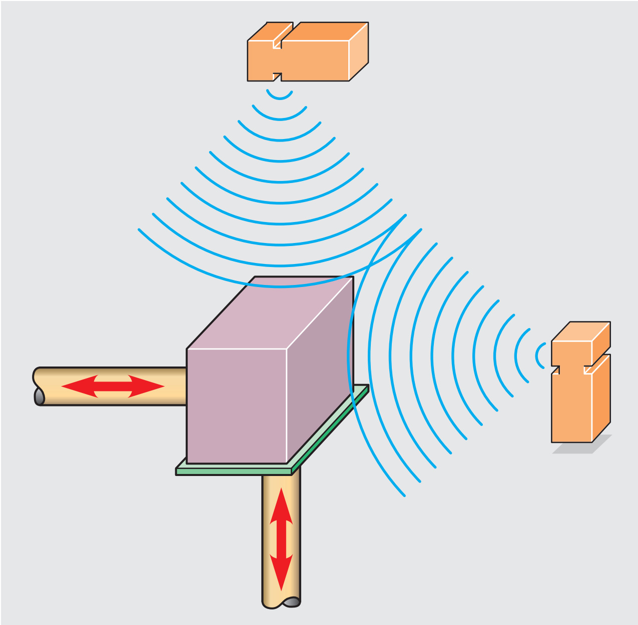


Figure 26–9 Ultrasonic proximity detectors used as position sensors.

Figure 26–10 Ultrasonic proximity detector. (Courtesy Turck, Inc.)

Review Questions

1. Proximity detectors are basically ______________ ____.
2. What is the basic principle of operation used with detectors designed to detect only ferrous metals?
3. What is the basic principle of operation used with detectors designed to detect all types of metals?
4. What type of electric circuit is used to increase the sensitivity of the proximity detector?
5. What type of proximity detector uses an oscillator that operates at radio frequencies?
6. Name two types of proximity detectors that can be used to detect objects not made of metal.
7. What is the maximum range at which most capacitive proximity detectors can be used to sense an object?
8. How is it possible for an ultrasonic proximity detector to measure the distance to an object?

UNIT 27
PHOTODETECTORS

OBJECTIVES

After studying this unit, the student will be able to:

- List different devices used as light sensors.
- Discuss the advantages of photo-operated controls.
- Describe different methods of installing photodetectors.

Applications

Photodetectors are widely used in today's industry. They can be used to sense the presence or absence of almost any object. Photodetectors do not have to make physical contact with the object they are sensing, so there is no mechanical arm to wear out. Many photodetectors can operate at speeds that cannot be tolerated by mechanical contact switches. They are used in almost every type of industry, and their uses are increasing steadily.

Types of Detectors

Photo-operated devices fall into one of three categories: photovoltaic, photoemissive, and photoconductive.

Photovoltaic

Photovoltaic devices are more often called solar cells. They are made of silicon and have the ability to produce a voltage in the presence of light. The amount of voltage produced by a cell is determined by the material it is made of. When silicon is used, the solar cell produces .5 volts in the presence of direct sunlight. If there is a complete circuit connected to the cell, current will flow through the circuit. The amount of current produced by a solar cell is determined by the surface area of the cell. For instance, assume a solar cell has a surface area of 1 square inch, and another cell has a surface area of 4 square inches. If both cells are made of silicon, both will produce .5 volts when in direct sunlight. The larger cell, however, will produce four times as much current as the small one.

Figure 27–1 shows the schematic symbol for a photovoltaic cell. Notice that the symbol is the same as

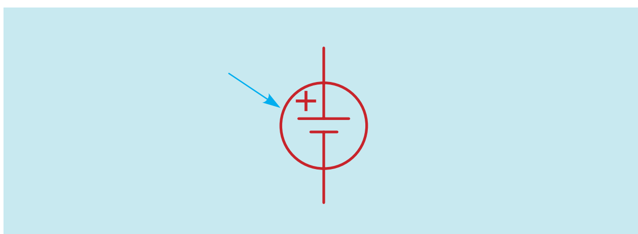


Figure 27–1 Schematic symbol for a photovoltaic cell.

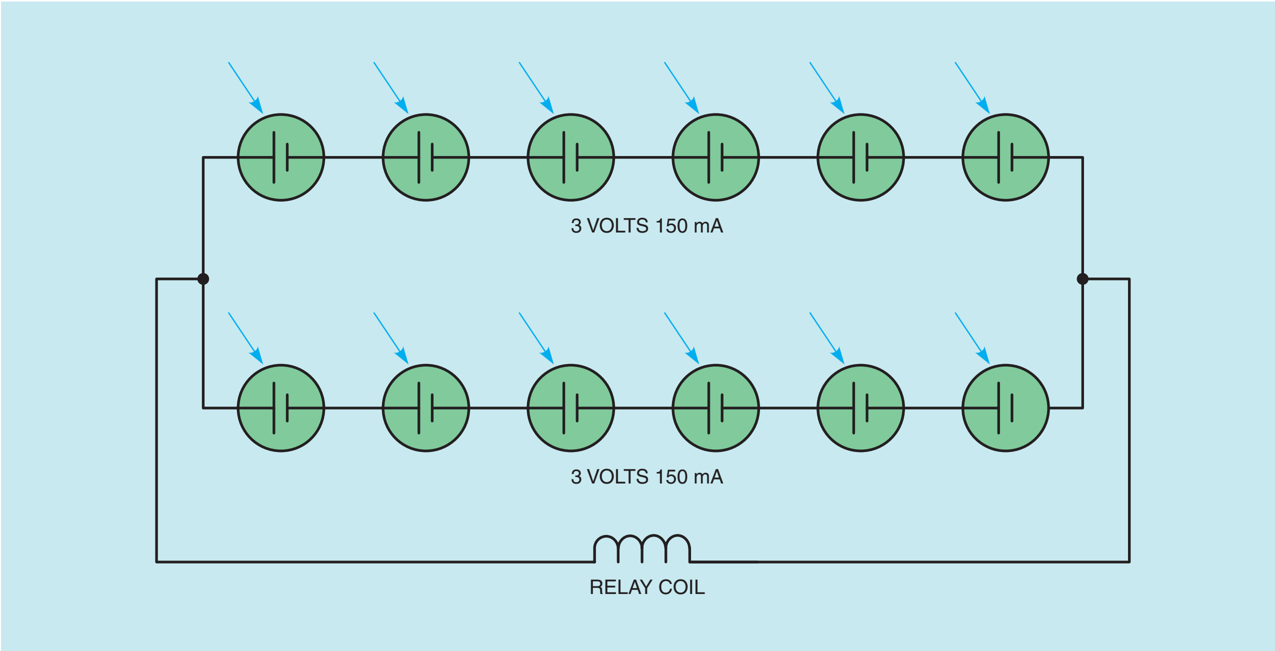


Figure 27–2 Series-parallel connection of solar cells produces 3 volts at 300 milliamps.

the symbol used to represent a single cell battery except for the arrow pointing toward it. The battery symbol means the device has the ability to produce a voltage, and the arrow means that it must receive light to do so.

Photovoltaic cells have the advantage of being able to operate electrical equipment without external power. Since silicon solar cells produce only .5 volt, it is often necessary to connect several of them together to obtain enough voltage and current to operate the desired device. For example, assume that solar cells are to be used to operate a dc relay coil that requires 3 volts at 250 milliamps. Now assume that the solar cells to be used have the ability to produce .5 volt at 150 milliamps. If six solar cells are connected in series, they will produce 3 volts at 150 milliamps (Figure 27–2). The voltage produced by the connection is sufficient to operate the relay, but the current capacity is not. Therefore, six more solar cells must be connected in series. This connection is then connected parallel to the first connection producing a circuit that has a voltage rating of 3 volts and a current rating of 300 milliamps, which is sufficient to operate the relay coil.

Photoemissive Devices

Photoemissive devices emit electrons when in the presence of light. They include such devices as the phototransistor, the photodiode, and the photo-SCR. The schematic symbols for these devices are shown in Figure 27–3. The emission of electrons is used to turn these solid-state components on. The circuit in Figure 27–4 shows a phototransistor used to turn on a

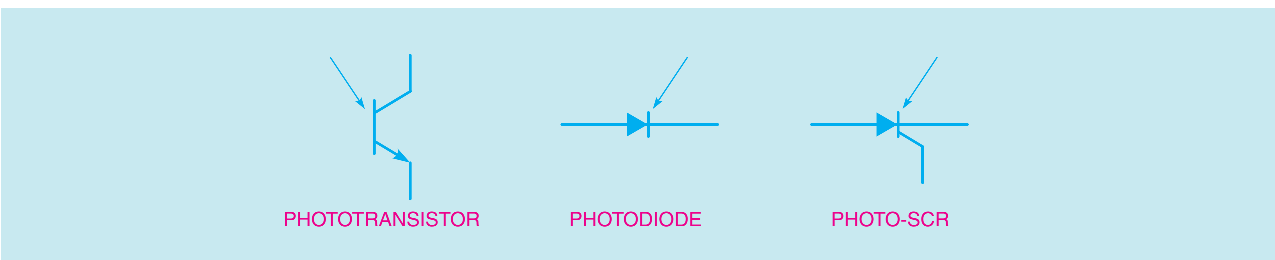


Figure 27–3 Schematic symbols for the phototransistor, the photodiode, and the photo-SCR.

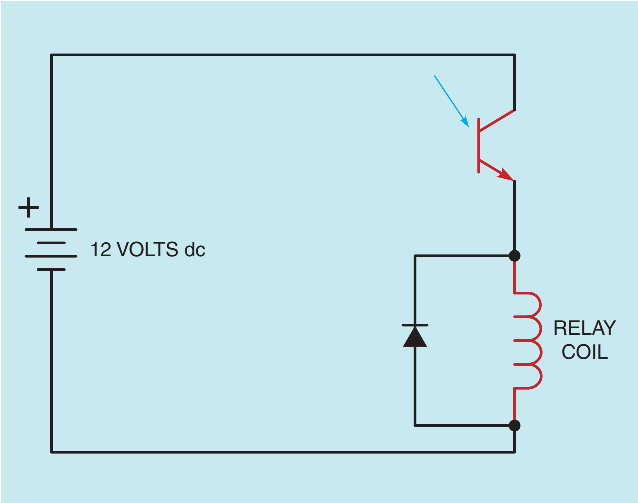


Figure 27–4 Phototransistor controls relay coil.

relay coil. When the phototransistor is in darkness, no electrons are emitted by the base junction, and the transistor is turned off. When the phototransistor is in the presence of light, it turns on and permits current to flow through the relay coil. The diode connected parallel to the relay coil is known as a kickback or freewheeling diode. Its function is to prevent induced voltage spikes from occurring when the current suddenly stops flowing through the coil and the magnetic field collapses.

In the circuit shown in Figure 27–4, the relay coil will turn on when the phototransistor is in the presence of light, and turn off when the phototransistor is in darkness. Some circuits may require the reverse operation. This can be accomplished by adding a resistor and a junction transistor to the circuit (Figure 27–5). In this circuit a common junction transistor is used to control the current flow through the relay coil. Resistor R1 limits the current flow through the base of the junction transistor. When the phototransistor is in darkness, it has a very high resistance. This permits current to flow to the base of the junction transistor and turn it on. When the phototransistor is in the presence of light, it turns on and connects the base of the junction transistor to the negative side of the battery. This causes the junction transistor to turn off. The phototransistor in the circuit is used as a *stealer* transistor. A stealer transistor steals the base current away from some other transistor to keep it turned off.

Some circuits may require the phototransistor to have a higher gain than it has under normal conditions. This can be accomplished by using the phototransistor as the driver for a Darlington amplifier circuit, Figure 27–6. A Darlington amplifier circuit generally has a gain of over 10,000.

Photodiodes and photo-SCRS are used in circuits similar to those shown for the phototransistor. The photodiode will permit current to flow through it in the presence of light. The photo-SCR has the same operating characteristics as a common junction SCR. The only difference is that light is used to trigger the gate when using a photo-SCR.

Regardless of the type of photoemissive device used, or the type circuit it is used in, the greatest advantage of the photoemissive device is speed. A photoemissive device can turn on or off in a few microseconds.

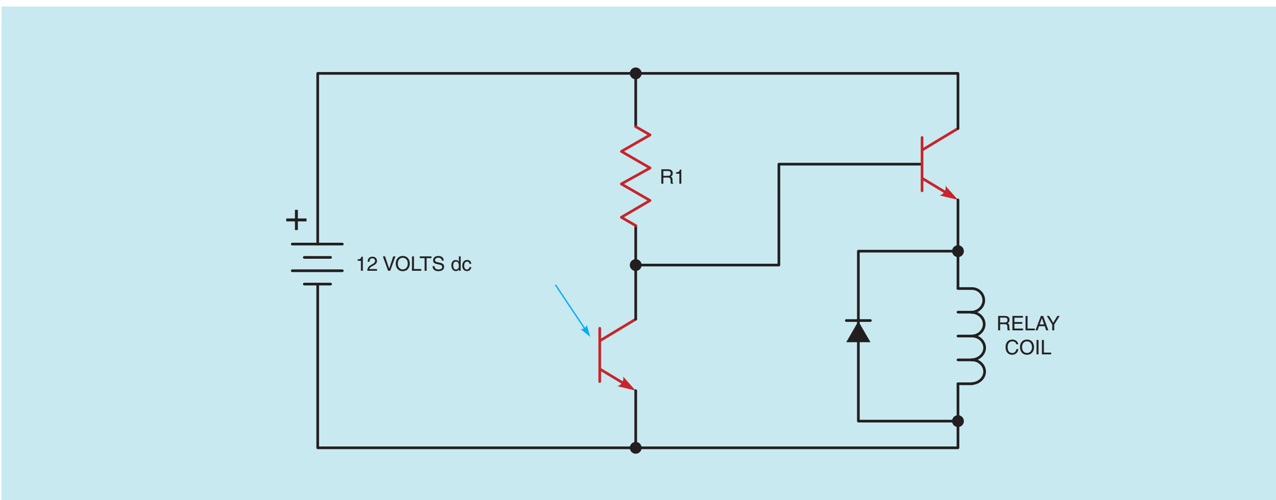


Figure 27–5 The relay turns on when the phototransistor is in darkness.

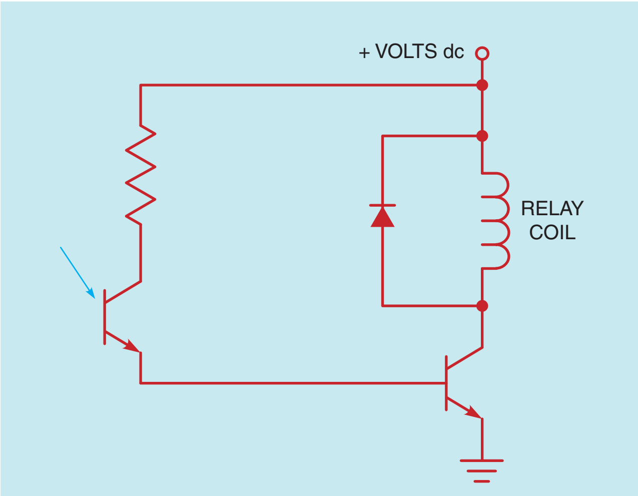


Figure 27–6 The phototransistor is used as the driver for a Darlington Amplifier.

Figure 27–8 Cad cell.

Photovoltaic or photoconductive devices generally require several milliseconds to turn on or off. This makes the use of photoemissive devices imperative in high speed switching circuits.

Photoconductive Devices

Photoconductive devices exhibit a change of resistance due to the presence or absence of light. The most common photoconductive device is the cadmium sulfide cell or cad cell. The cad cell has a resistance of about 50 ohms in direct sunlight and several hundred thousand ohms in darkness. It is generally used as a light sensitive switch. The schematic symbol for a cad cell is shown in Figure 27–7. Figure 27–8 shows a typical cad cell.

Figure 27–9 shows a basic circuit of a cad cell being used to control a relay. When the cad cell is in darkness, its resistance is high. This prevents the amount of current needed to turn the relay on from flowing through the circuit. When the cad cell is in the presence of light, its resistance is low. The amount of current needed to operate the relay can now flow through the circuit.

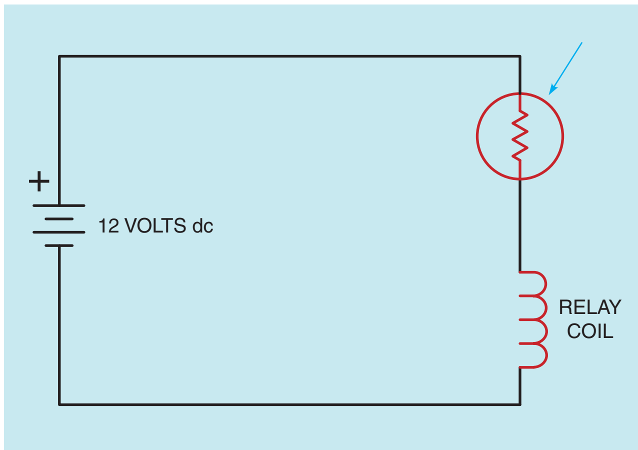


Figure 27–9 Cad cell controls relay coil.

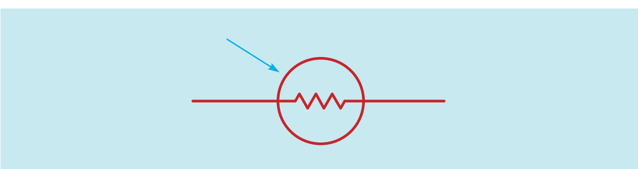


Figure 27–7 Schematic symbol for a cad cell.

Although this circuit will work if the cad cell is large enough to handle the current, it has a couple of problems.

1. There is no way to adjust the sensitivity of the circuit. Photo-operated switches are generally located in many different areas of a plant. The surrounding light intensity can vary from one area to another. It is, therefore, necessary to be able to adjust the sensor for the amount of light needed to operate it.

2. The sense of operation of the circuit cannot be changed. The circuit shown in Figure 27–9 permits the relay to turn on when the cad cell is in the presence of light. There may be conditions that would make it desirable to turn the relay on when the cad cell is in darkness.

Figure 27–10 shows a photodetector circuit that uses a cad cell as the sensor and an operational amplifier as the control circuit. The circuit operates as follows: Resistor R1 and the cad cell form a voltage divider circuit which is connected to the inverting input of the amplifier. Resistor R2 is used as a potentiometer to preset a positive voltage at the noninverting input. This control adjusts the sensitivity of the circuit. Resistor R3 limits the current to a light-emitting diode (LED). The LED is mounted on the outside of the case of the photodetector and is used to indicate when the relay coil is energized. Resistor R4 limits the base current to the junction transistor. The junction transistor is used to control the current needed to operate the relay coil. Many op amps do not have enough current rating to control this amount of current. Diode D1 is used as a kickback diode.

Assume that Resistor R2 has been adjusted to provide a potential of 6 volts at the noninverting input. When the cad cell is in the presence of light, it has a low resistance and a potential less than 6 volts is applied to the inverting input. Since the noninverting input has a higher positive voltage connected to it, the output is high also. When the output of the op amp is high, the LED and the transistor are turned on.

When the cad cell is in the presence of darkness, its resistance increases. When its resistance becomes greater than 4.7 kilohms, a voltage greater than 6 volts is applied to the inverting input. This causes the output of the op amp to change from a high state to a low state, and turn the LED and transistor off. Notice in this circuit that the relay is turned on when the cad cell is in the presence of light, and turned off when it is in darkness.

Figure 27–11 shows a connection that will reverse the operation of the circuit. The potentiometer has been reconnected to the inverting input, and the voltage divider circuit has been connected to the noninverting input. To understand the operation of this circuit, assume that a potential of 6 volts has been preset at the inverting input.

When the cad cell is in the presence of light, it has a low resistance and a voltage less than 6 volts is applied

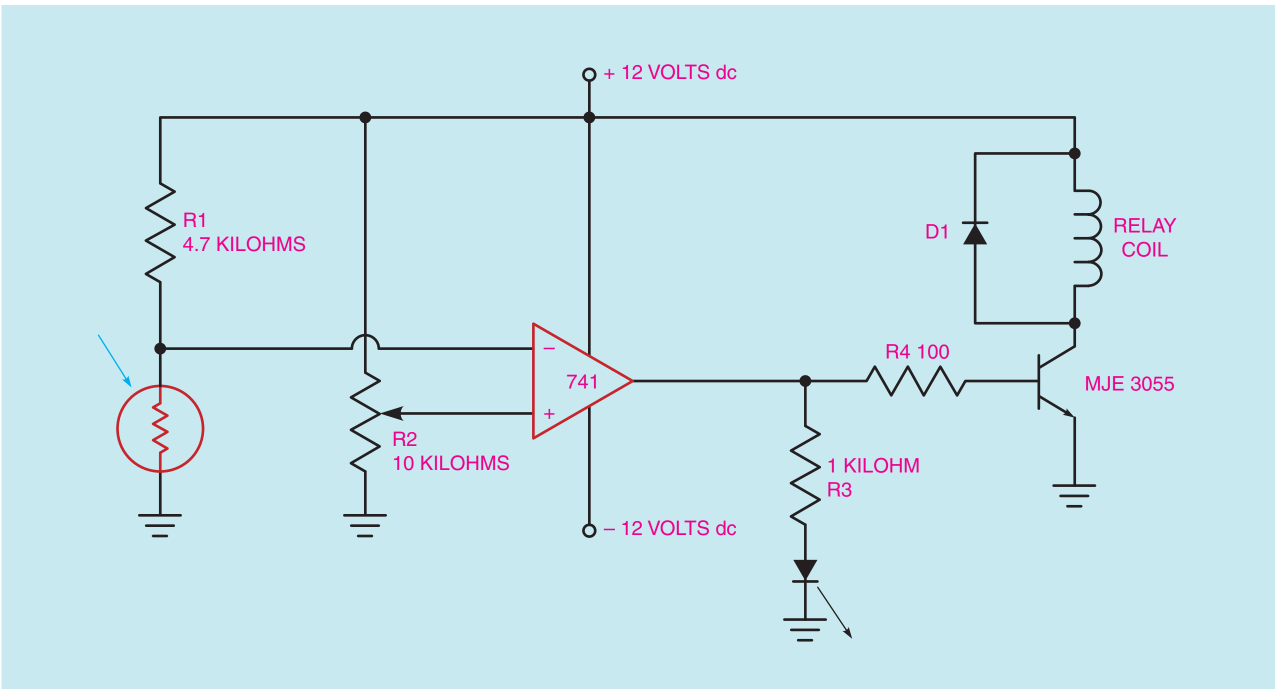


Figure 27–10 The relay coil is energized when the cad cell is in the presence of light.

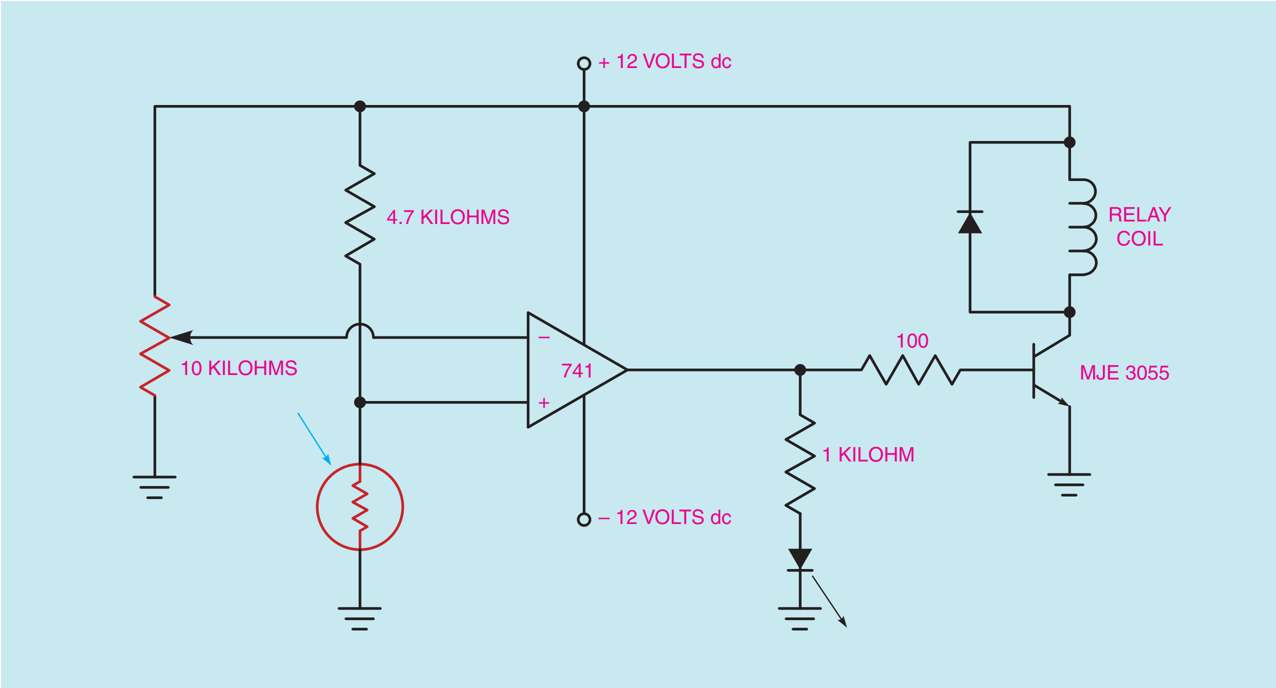


Figure 27–11 The relay is energized when the cad cell is in darkness.

to the noninverting input. Since the inverting input has a greater positive voltage connected to it, the output is low and the LED and the transistor are turned off.

When the cad cell is in darkness, its resistance becomes greater than 4.7 kilohms and a voltage greater than 6 volts is applied to the noninverting input. This causes the output of the op amp to change to a high state which turns on the LED and transistor. Notice that this circuit turns the relay on when the cad cell is in darkness and off when it is in the presence of light.

Mounting

Photodetectors designed for industrial use are made to be mounted and used in different ways. There are two basic types of photodetectors: one type has separate transmitter and receiver units; the other type has both units mounted in the same housing. The type used is generally determined by the job requirements. The transmitter section is the light source which is generally a long life incandescent bulb. There are photodetectors, however, that use an infrared transmitter. These cannot be seen by the human eye and are often used in burglar alarm systems. The receiver unit houses the photodetector and, generally, the circuitry required to operate the system.

Figure 27–12 shows a photodetector used to detect the presence of an object on the conveyor line. When the object passes between the transmitter and receiver

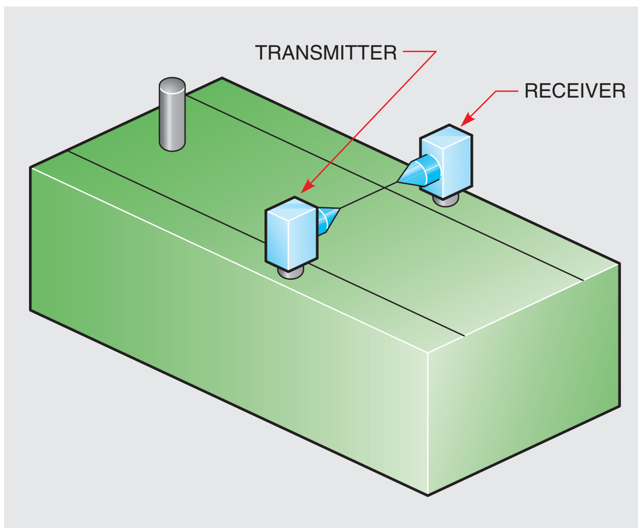


Figure 27–12 Photodetector senses presence of object on conveyor line.

units, the light beam is broken and the detector activates. Notice that no physical contact was necessary for the photodetector to sense the presence of the object.

Figure 27–13 illustrates another method of mounting the transmitter and receiver. In this example, an object is sensed by reflecting light off of a shiny surface. Notice that the transmitter and receiver must be mounted at the same angle with respect to the object to be sensed. This type of mounting will only work with objects that have the same height, such as cans on a conveyor line.

Photodetectors that have both the transmitter and the receiver units mounted in the same housing depend on a reflector for operation. Figure 27–14 shows this type of unit mounted on a conveyor line. The transmitter is aimed at the reflector. The light beam is reflected back to the receiver. When an object passes between the photodetector unit and the reflector, the light to the receiver is interrupted. This type of unit has the advantage of needing electrical connection at only one piece of equipment. This permits easy mounting of the photodetector unit, and mounting of the reflector in hard to reach positions that would make running control wiring difficult. Many of these units have a range of 20 feet and more.

Another type of unit that operates on the principle of reflected light uses an optical fiber cable. The fibers in the cable are divided in half. One half of the fibers is connected to the transmitter, and the other half is connected to the receiver (Figure 27–15). This unit has the advantage of permitting the transmitter and the receiver to be mounted in a very small area. Figure 27–16 illustrates a common use for this type of unit. The unit is used to control a label cutting machine. The labels are printed on a large roll and must be cut for individual packages. The label roll contains a narrow strip on one side which is dark colored except for shiny sections spaced at regular intervals. The optical fiber cable is

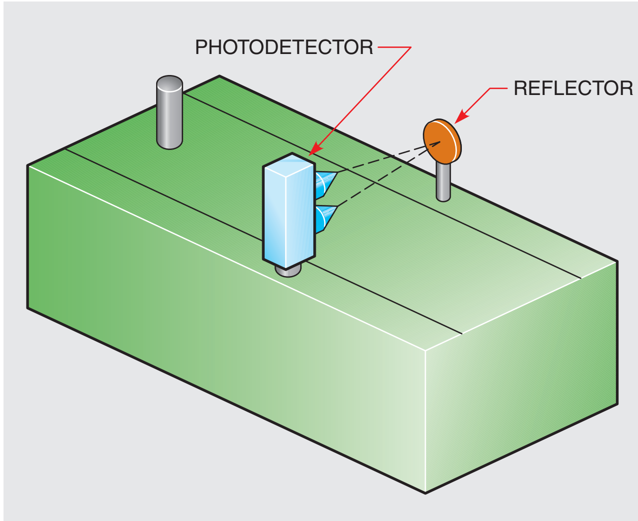


Figure 27–14 The object is sensed when it passes between the photodetector and the reflector.

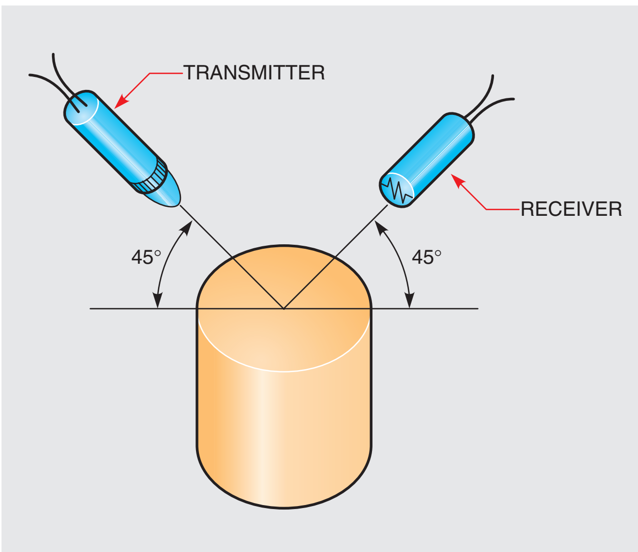


Figure 27–13 Object is sensed by reflecting light off a shiny surface.

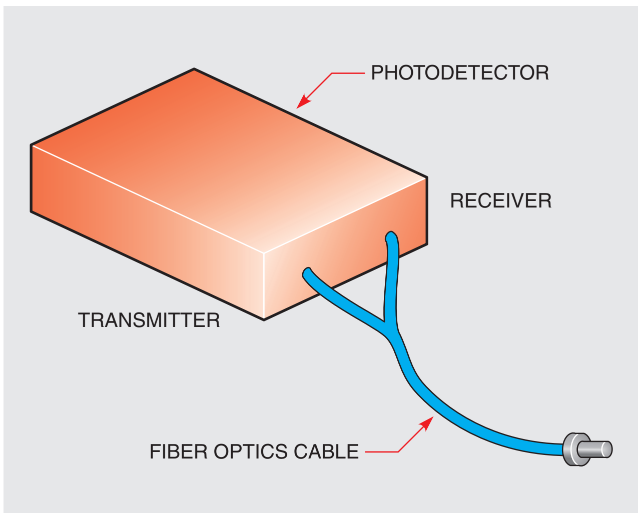


Figure 27–15 Optical cable is used to transmit and receive light.

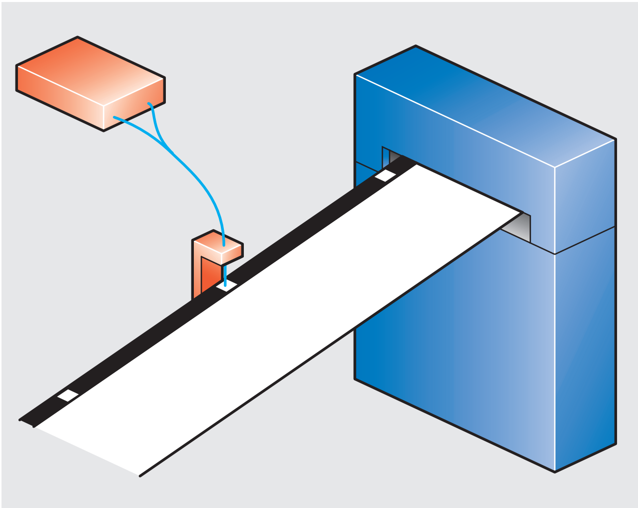


Figure 27–16 Optical cable detects shiny area on one side of label.

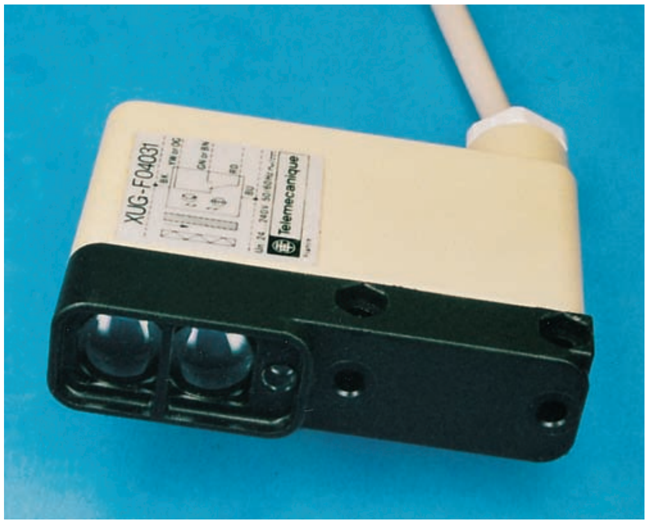


Figure 27–17 Photodetector unit with both transmitter and receiver units.

located above this narrow strip. When the dark surface of the strip is passing beneath the optical cable, no reflected light returns to the receiver unit. When the shiny section passes beneath the cable, light is reflected back to the receiver unit. The photodetector sends a signal to the control circuit and tells it to cut the label.

Photodetectors are very dependable and have an excellent maintenance and service record. They can be used to sense almost any object without making physical contact with it, and can operate millions of times without damage or wear. A photodetector is shown in Figure 27–17.

Review Questions

1. List the three major categories of photodetectors.
2. In which category does the solar cell belong?
3. In which category do phototransistors and photodiodes belong?
4. In which category does the cad cell belong?
5. The term cad cell is a common name for what device?
6. What is the function of the transmitter in a photodetector unit?
7. What is the advantage of a photodetector that uses a reflector to operate?
8. An object is to be detected by reflecting light off a shiny surface. If the transmitter is mounted at a 60 degree angle, at what angle must the receiver be mounted?
9. How much voltage is produced by a silicon solar cell?
10. What determines the amount of current a solar cell can produce?

UNIT 28
THE CONTROL TRANSFORMER

OBJECTIVES

After studying this unit, the student will be able to:

- Discuss the use of control transformers in a control circuit.
- Connect a control transformer for operation on a 240- or 480-volt system.

Most industrial motors operate on voltages that range from 240 to 480 volts. Magnetic control systems, however, generally operate on 120 volts. A control transformer is used to step the 240 or 480 volts down to 120 volts to operate the control system. There is really nothing special about a control transformer except that most of them are made with two primary windings and one secondary winding. Each primary winding is rated at 240 volts and the secondary winding is rated at 120 volts. This means there is a turns ratio of 2 : 1 (2 to 1) between each primary winding and the secondary winding. For example, assume that each primary winding contains 200 turns of wire and the secondary winding contains 100 turns. There are two turns of wire in each primary winding for every one turn of wire in the secondary.

One of the primary windings of the control transformer is labeled H1 and H2. The other primary winding is labeled H3 and H4. The secondary winding is labeled X1 and X2. If the transformer is to be used to step 240 volts down to 120 volts, the two primary windings are connected parallel to each other as shown in Figure 28–1. Notice that in Figure 28–1 the H1 and H3 leads are connected together, and the H2 and H4 leads

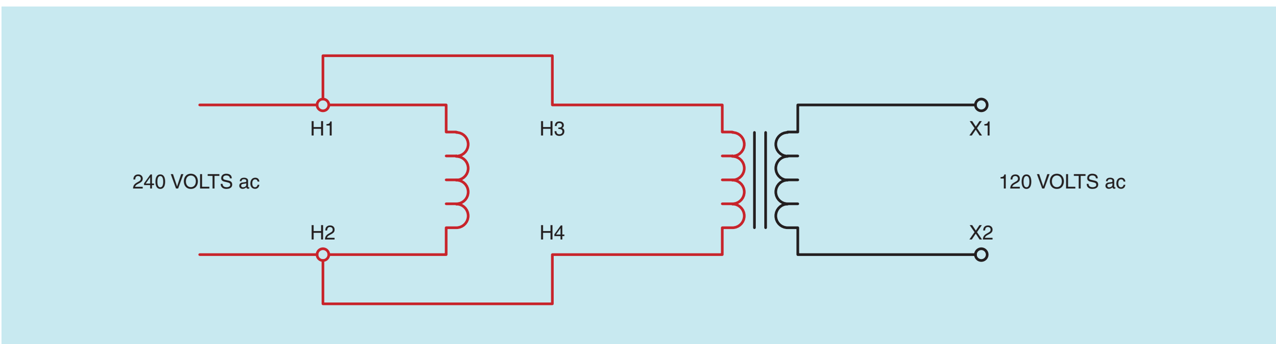


Figure 28–1 Primaries connected in parallel for 240-volt operation.

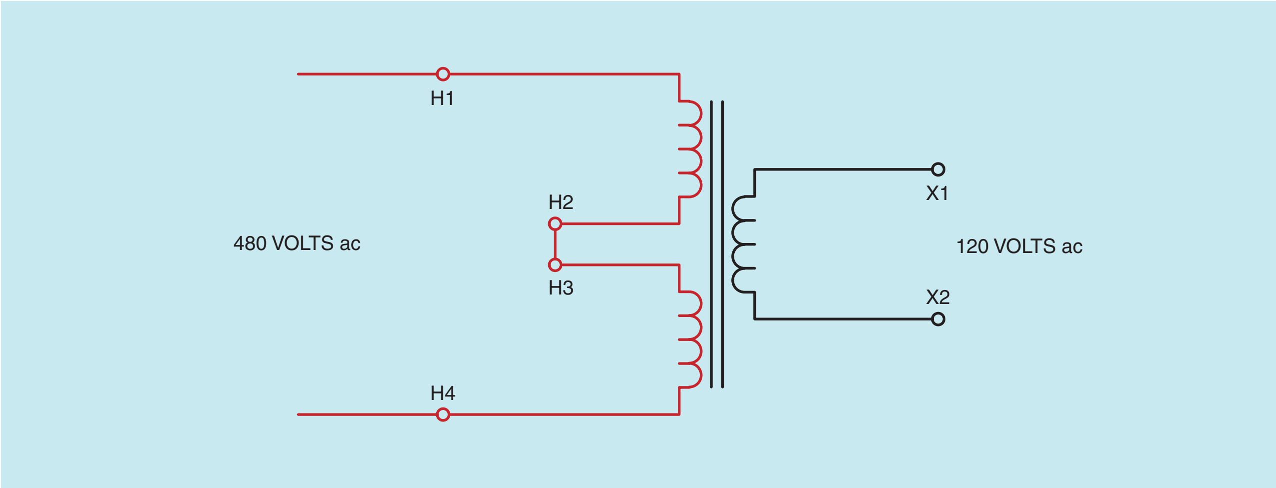


Figure 28–2 Primaries connected in series for 480-volt operation.

are connected together. Since the voltage applied to each primary winding is the same, the effect is the same as having only one primary winding with 200 turns of wire in it. This means that when the transformer is connected in this manner, the turns ratio is 2:1. When 240 volts are connected to the primary winding, the secondary voltage is 120 volts.

If the transformer is to be used to step 480 volts down to 120 volts, the primary windings are connected in series as shown in Figure 28–2. With the windings connected in series, the primary winding now has a total of 400 turns of wire, which makes a turns ratio of 4:1. When 480 volts is connected to the primary winding, the secondary winding has an output of 120 volts.

Control transformers generally have screw terminals connected to the primary and secondary leads. The H2 and H3 leads are crossed to make connection of the primary winding easier, Figure 28–3. For example, if the transformer is to be connected for 240-volt operation, the two primary windings must be connected parallel to each other as shown in Figure 28–1. This connection can be made on the transformer by using one metal link to connect leads H1 and H3, and another metal link to connect H2 and H4 (Figure 28–4).

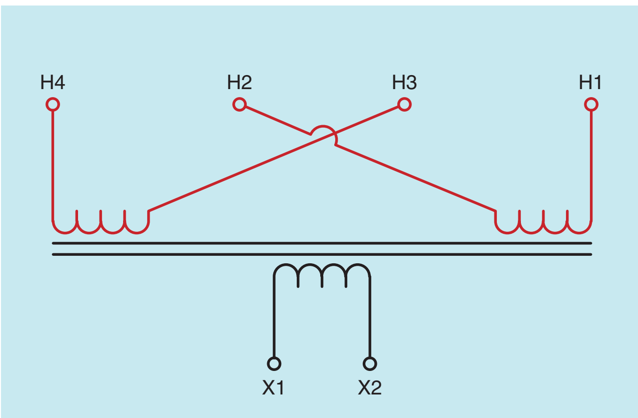


Figure 28–3 Primary leads are crossed.

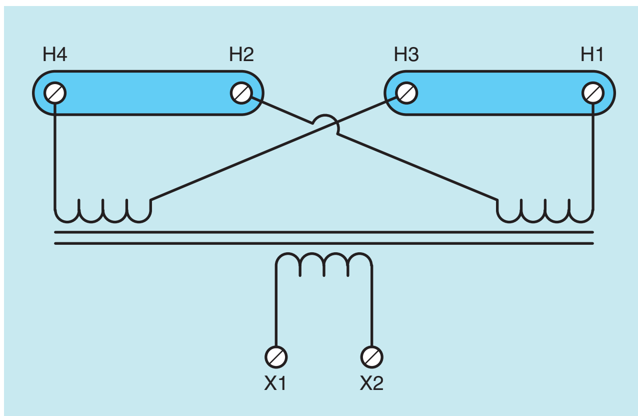


Figure 28–4 Metal links used to make a 240-volt connection.

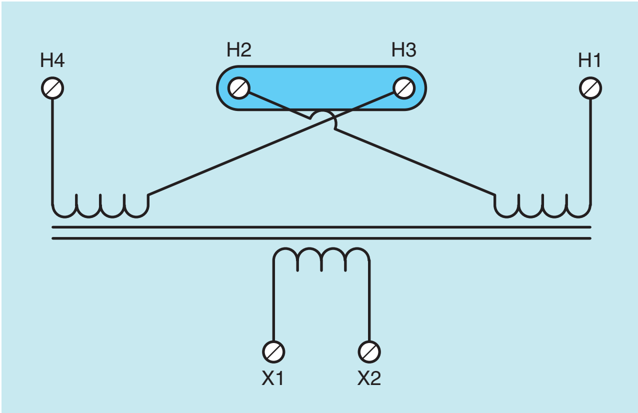


Figure 28–5 Metal link used to make a 480-volt connection.

If the transformer is to be used for 480-volt operation, the primary windings must be connected in series as shown in Figure 28–2. This connection can be made on the control transformer by using a metal link to connect H2 and H3 as shown in Figure 28–5. A typical control transformer is shown in Figure 28–6.

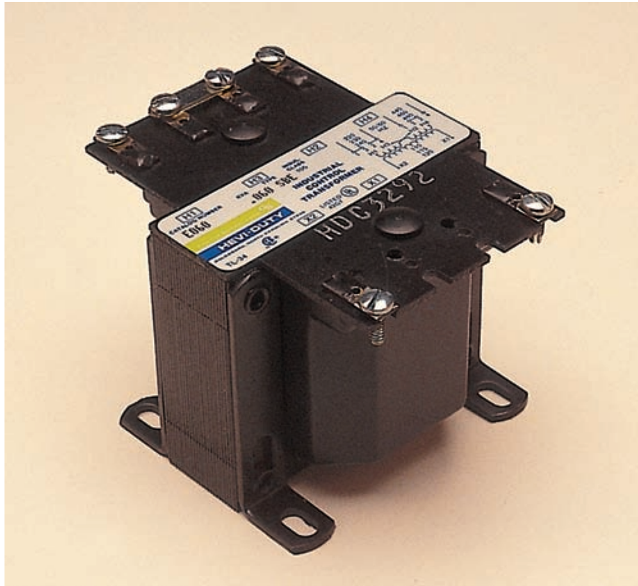


Figure 28–6 Control transformer. (Courtesy McKenzi and Dickerson.)

Review Questions

1. What is the operating voltage of most magnetic control systems?
2. How many primary windings do control transformers have?
3. How are the primary windings connected when the transformer is to be operated on a 240-volt system?
4. How are the primary windings connected when the transformer is to be operated on a 480-volt system?
5. Why are two of the primary leads crossed on a control transformer?

Section 3

CONTROL CIRCUITS

UNIT 29

BASIC CONTROL CIRCUITS

OBJECTIVES

After studying this unit, the student will be able to:

- Describe the operation of a two-wire circuit.
- Describe the operation of a three-wire circuit.

Two-Wire Controls

Magnetic control circuits are divided into two basic types: the two-wire control circuit, and the three-wire control circuit. Two-wire control circuits are operated by manual control devices such as the open starter in Figure 12–1 or the manual push-button starter in Figure 12–9B. This type of control circuit provides overload protection for the motor connected to it and provides under-voltage or no-voltage release. Figure 29–1 shows a typical two-wire control circuit. Notice that as long as the two-wire control device is closed, power can be supplied to the coil of the controller. If the motor is stopped by a power interruption, the two-wire control device will not open. Since the control device does not open, the motor will restart when power is restored to the system.

Two-wire control circuits are used in applications where this self restarting characteristic is desirable. This enables devices such as blower fans and pumps to restart after a power failure without an electrician having to walk around the plant and restart each device. Since two-wire control does permit automatic restarting of equipment, it could become a safety hazard to people working around the equipment. For this reason, two-wire controls should be used only when there is little or no danger of a person being injured if the equipment should suddenly restart after a power failure.

Three-Wire Controls

Three-wire control circuits are generally operated by momentary contact pilot devices. The simplest example of a three-wire control circuit is probably the start-stop, push-button control shown in Figure 29–2. A set of auxiliary contacts controlled by M coil is connected parallel to the start button. These contacts are generally referred to as *maintaining, sealing,* or *holding* contacts. The job of this contact is to hold the coil in the circuit after the start button has been used to energize the relay.

If the start button in Figure 29–2 is pressed, a circuit is completed between points 2 and 3, which allows current to flow through the motor starter coil and the normally closed overload contact to line 2 (L2). When current flows through the M relay coil, the relay

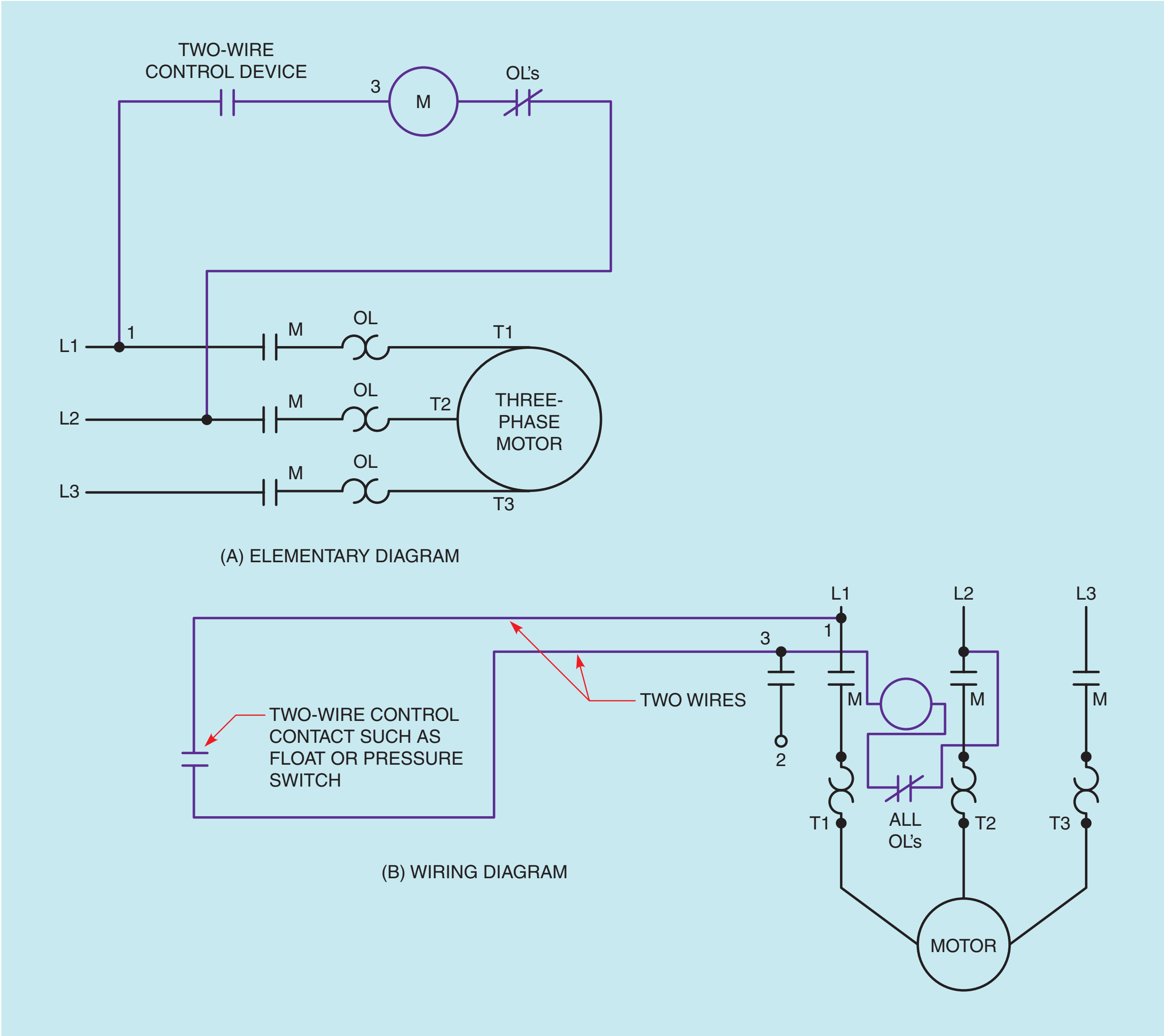


Figure 29–1 Basic two-wire control circuit.

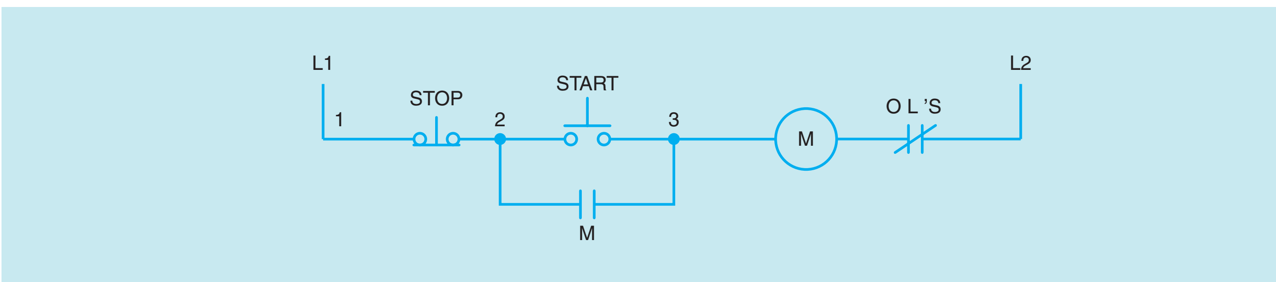


Figure 29–2 Basic three-wire control circuit.

energizes and closes all M contacts. Since the contact that is connected parallel to the start button is now closed, the start button can be returned to its normally open position. Contact M maintains a current path around the start button to keep coil M energized.

Three-wire control is used to a much greater extent than two-wire control because of its flexibility. Pilot devices such as push buttons can be located at remote locations such as control panels, while motor starters and control relays are housed in separate cabinets. Three-wire circuits also permit the use of different types of pilot devices such as float switches, pressure switches, and limit switches.

Since three-wire control circuits use holding contacts to maintain the circuit, if power is interrupted, the equipment will not restart when power is restored. If the power supplying the circuit shown in Figure 29–2 is stopped, M contacts will return to their normally open position. When power is restored, the start button must again be pressed to re-energize the M coil.

Review Questions

1. What are some advantages of using two-wire control circuits?
2. What is a possible safety hazard of two-wire control circuits?
3. What is the advantage of a three-wire control system compared to a two-wire system?
4. What are holding contacts?

UNIT 30

SCHEMATICS AND WIRING DIAGRAMS

OBJECTIVES

After studying this unit, the student will be able to:

- Interpret schematic diagrams.
- Interpret wiring diagrams.
- Connect control circuits using schematic and wiring diagrams.

Schematic and wiring diagrams are the written language of control circuits. Maintenance electricians must be able to interpret schematic and wiring diagrams to install control equipment or troubleshoot existing control circuits. Schematic diagrams are also known as line diagrams and ladder diagrams. *Schematic diagrams show components in their electrical sequence without regard to physical location.* Schematics are used more than any other type of diagram to connect or troubleshoot a control circuit.

Wiring diagrams show a picture of the control components with connecting wires. Wiring diagrams are sometimes used to install new control circuits, but they are seldom used for troubleshooting existing circuits. Figure 30–1A shows a schematic diagram of a start-stop, push-button circuit. Figure 30–1B shows a wiring diagram of the same circuit.

When reading schematic diagrams, the following rules should be remembered.

A. Read a schematic as you would a book—from top to bottom and from left to right.

B. Contact symbols are shown in their de-energized or off position.

C. When a relay is energized, all the contacts controlled by that relay change position. If a contact is shown normally open on the schematic, it will close when the coil controlling it is energized.

The following circuits are used to illustrate how to interpret the logic of a control circuit using a schematic diagram.

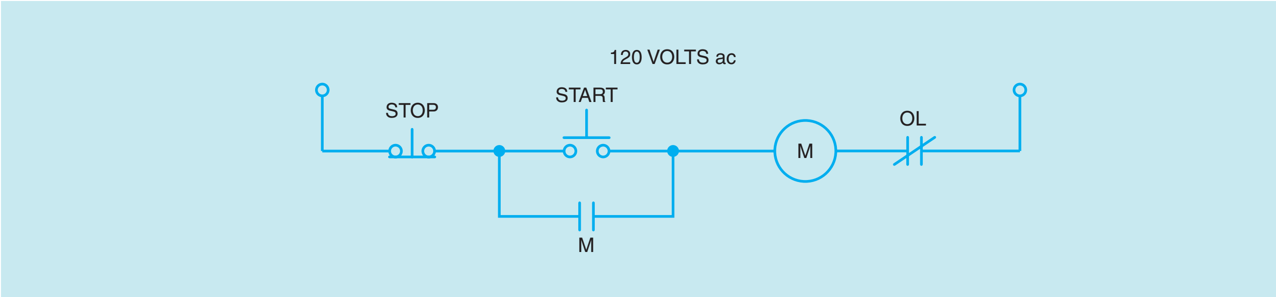


Figure 30–1A No caption.

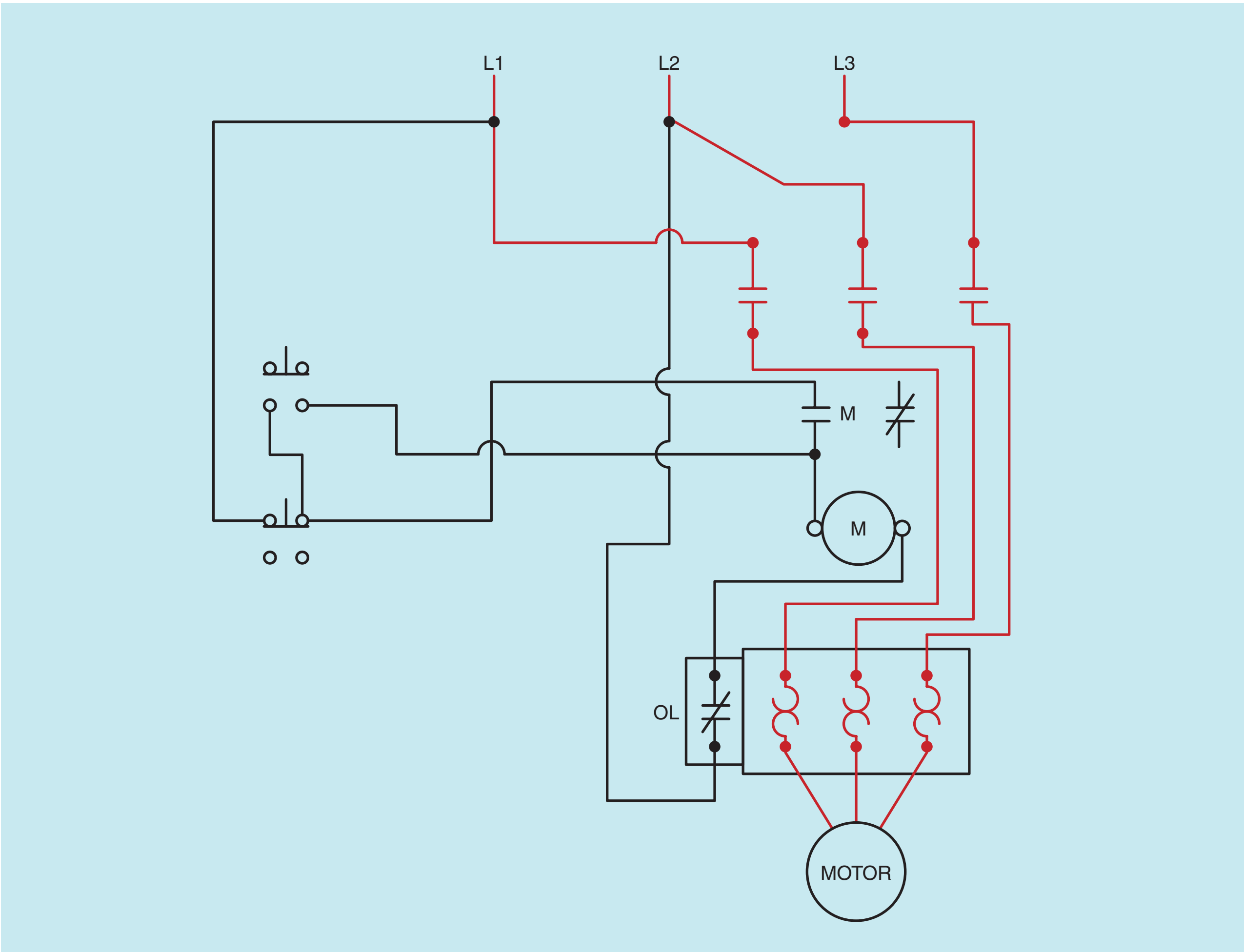


Figure 30–1B Wiring diagram of a start-stop push-button station.

Circuit #1

The circuit shown in Figure 30–2A is an alarm silencing circuit. The purpose of the circuit is to sound a horn and turn on a red warning light when the pressure of a particular system becomes too great. After the alarm has sounded, the reset button can be used to turn the horn off, but the red warning light must remain on until the pressure in the system drops to a safe level. Notice that no current can flow in the system because of the open pressure switch, PS.

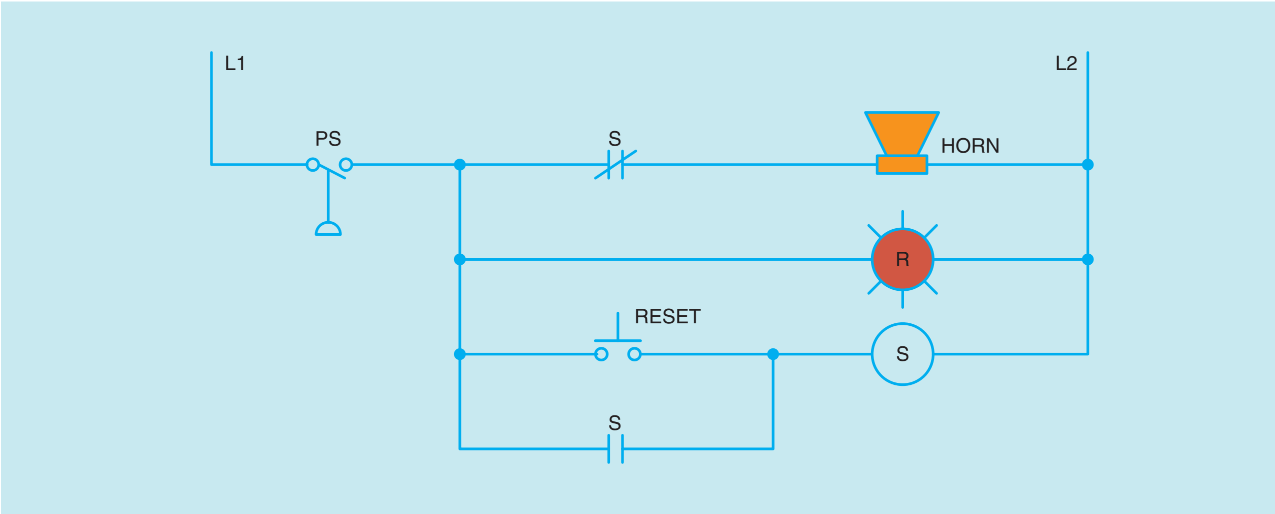


Figure 30–2A Alarm silencing circuit.

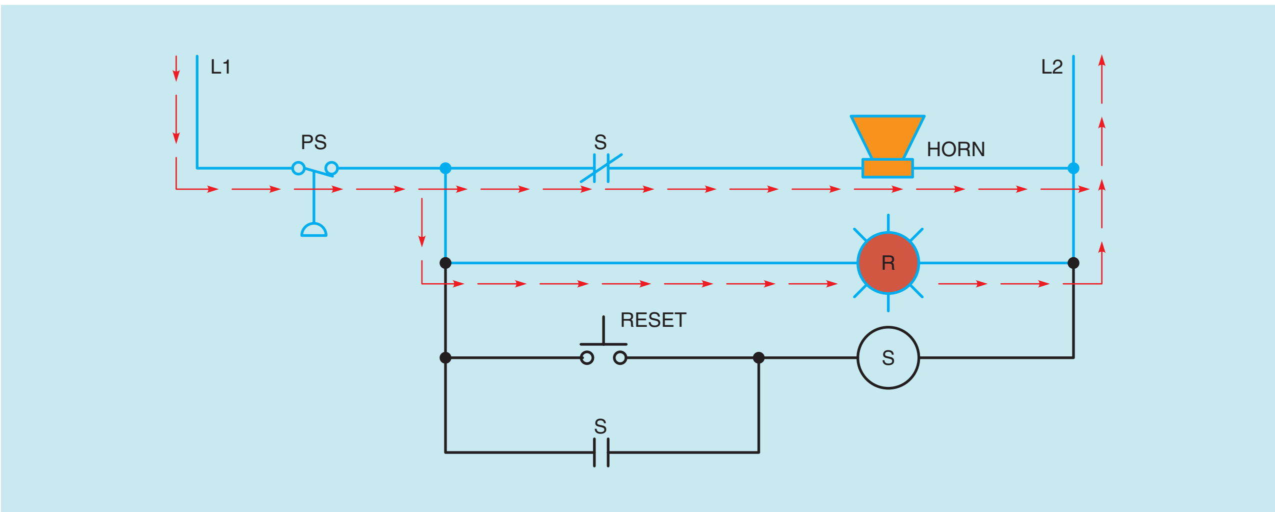


Figure 30–2B Pressure switch closes.

If the pressure rises high enough to cause pressure switch PS to close, current can flow through the normally closed S contact to the horn. Current can also flow through the red warning light. Current cannot, however, flow through the normally open reset button or the normally open S contact (Figure 30–2B).

If the reset button is pushed, a circuit is completed through the S relay coil. When relay coil S energizes, the normally closed S contact opens and the normally open S contact closes. When the normally closed S contact opens, the circuit to the horn is broken. This causes the horn to turn off. The normally open S contact is used as a holding contact to maintain current to the coil of the relay when the reset button is released (Figure 30–2C).

The red warning light will remain turned on until the pressure switch opens again. When the pressure switch

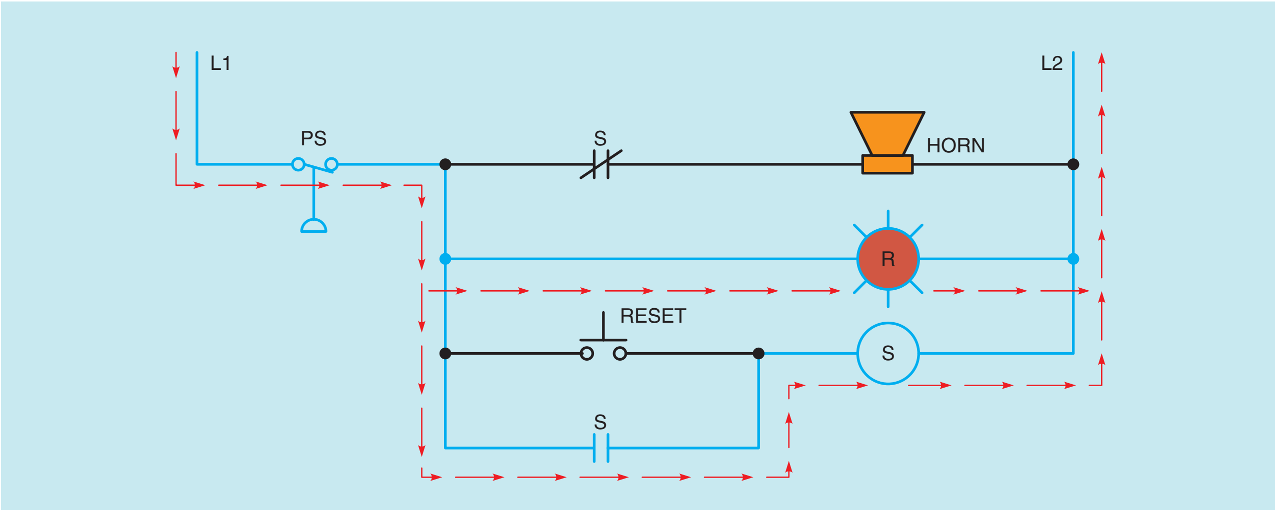


Figure 30–2C The alarm has been silenced but the warning light remains on.

opens, the circuit is broken and current flow through the system stops. This causes the red warning light to turn off, and it de-energizes the coil of relay S. When relay S de-energizes, both of the S contacts return to their original position. The circuit is now back to the same condition it was in in Figure 30–2A.

Review Questions

1. Define a schematic diagram.
2. Define a wiring diagram.
3. Referring to circuit 30-2A, explain the operation of the circuit if pressure switch PS was connected normally closed instead of normally open.

UNIT 31

TIMED STARTING FOR THREE MOTORS (CIRCUIT #2)

OBJECTIVES

After studying this unit, the student will be able to:

- Discuss the operation of circuit #2.
- Troubleshoot circuit #2 using the schematic.

A machine contains three large motors. The current surge to start all three motors at the same time is too great for the system. Therefore, when the machine is to be started, there must be a delay of 10 seconds between the starting of each motor. The circuit shown in Figure 31–1 is a start-stop, push-button control which controls three motor starters and two time-delay relays. The circuit is designed so that an overload on any motor will stop all motors.

When the start button is pressed, a circuit is completed through the start button, M1 motor starter coil, and TR1 relay coil. When coil M1 energizes, motor #1 starts and auxiliary contact M1, which is parallel to the start button, closes. This contact maintains the current flow through the circuit when the start button is released (Figure 31–2).

After a 10-second interval, contact TR1 closes. When this contact closes, a circuit is completed through motor starter coil M2 and timer relay coil TR2. When coil M2 energizes, motor #2 starts (Figure 31–3).

Ten seconds after coil TR2 energizes, contact TR2 closes. When this contact closes, a circuit is completed to motor starter coil M3, which causes motor #3 to start (Figure 31–4).

If the stop button is pressed, the circuit to coils M1 and TR1 is broken. When motor starter Ml de-energizes, motor #1 stops and auxiliary contact Ml opens. TR1 is an on-delay relay; therefore, when coil TR1 is de-energized, contact TR1 opens immediately.

When contact TR1 opens, motor starter M2 de-energizes, which stops motor #2, and coil TR2 de-energizes. Since TR2 is an on-delay relay, contact

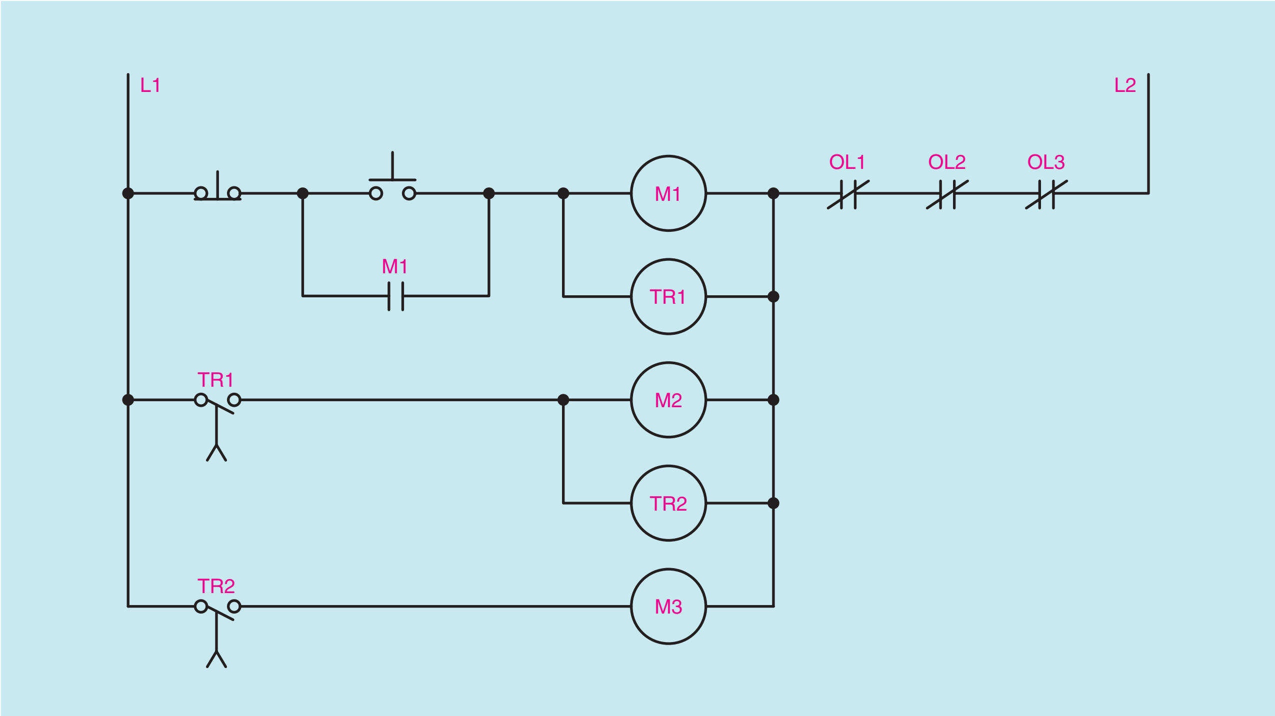


Figure 31–1 Time delay starting for three motors.

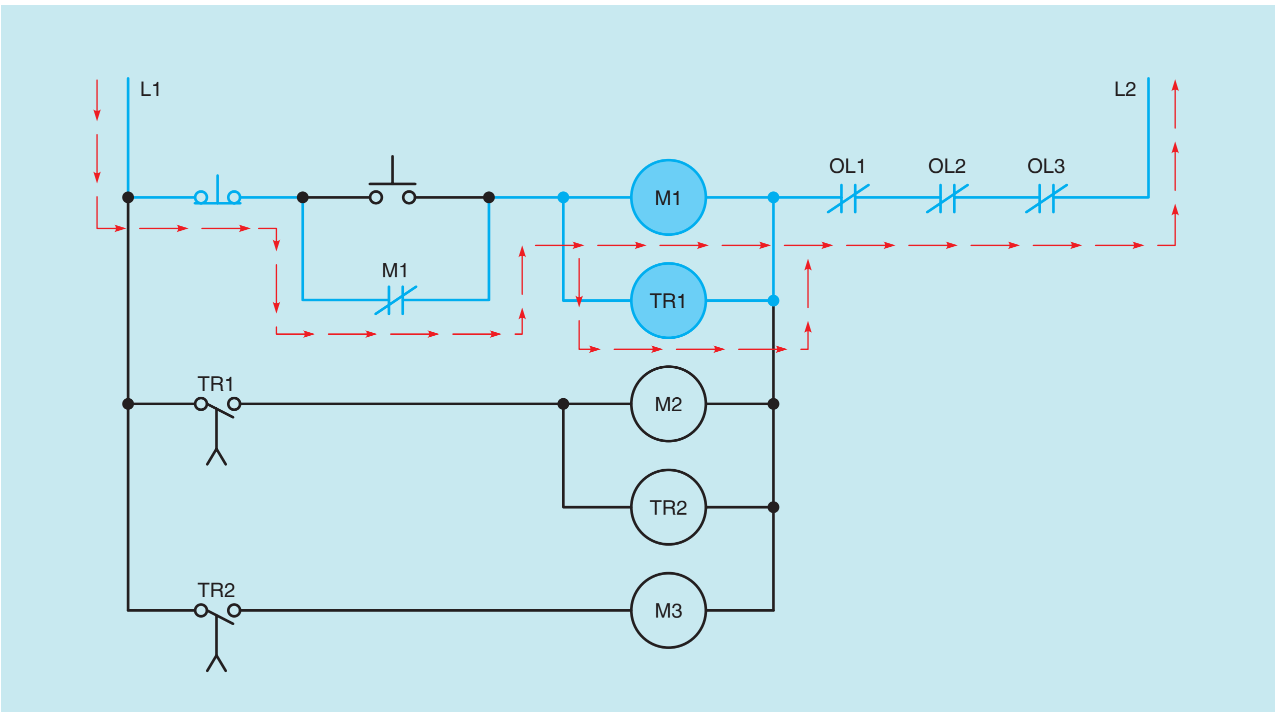


Figure 31–2 M1 motor starter and TR1 timer relay turn on.

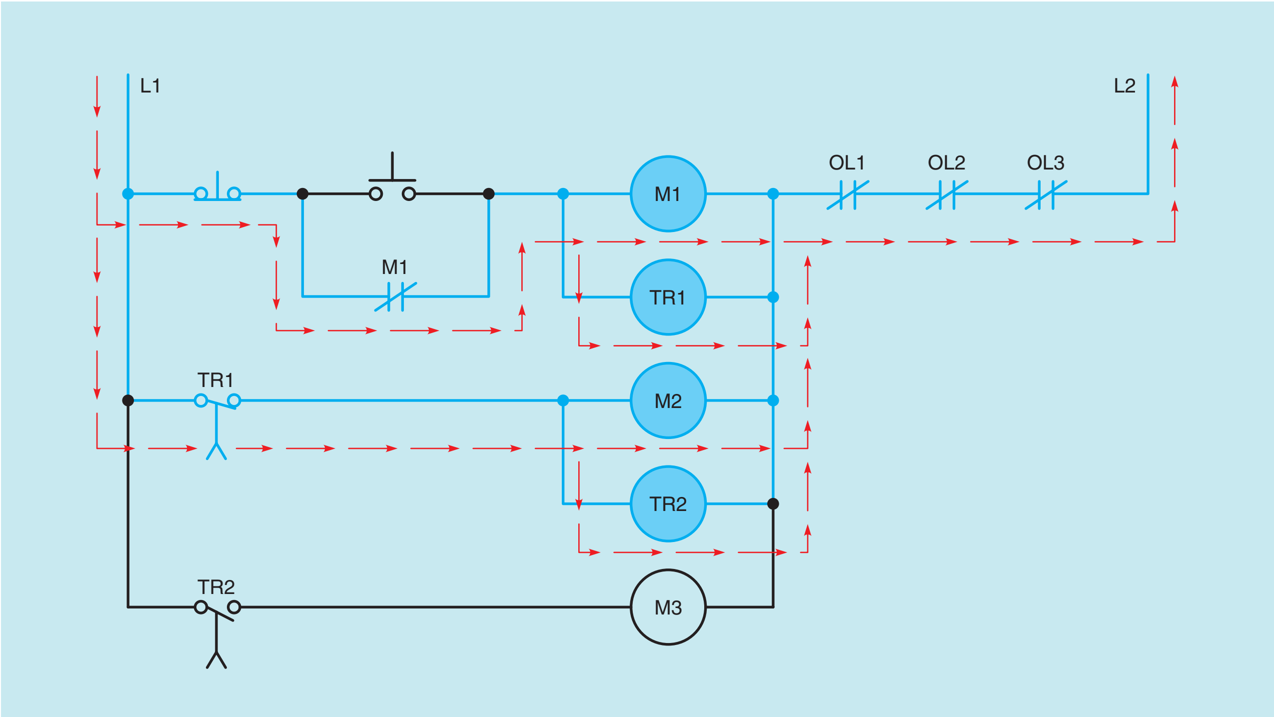


Figure 31–3 Motor 2 and TR2 have energized.

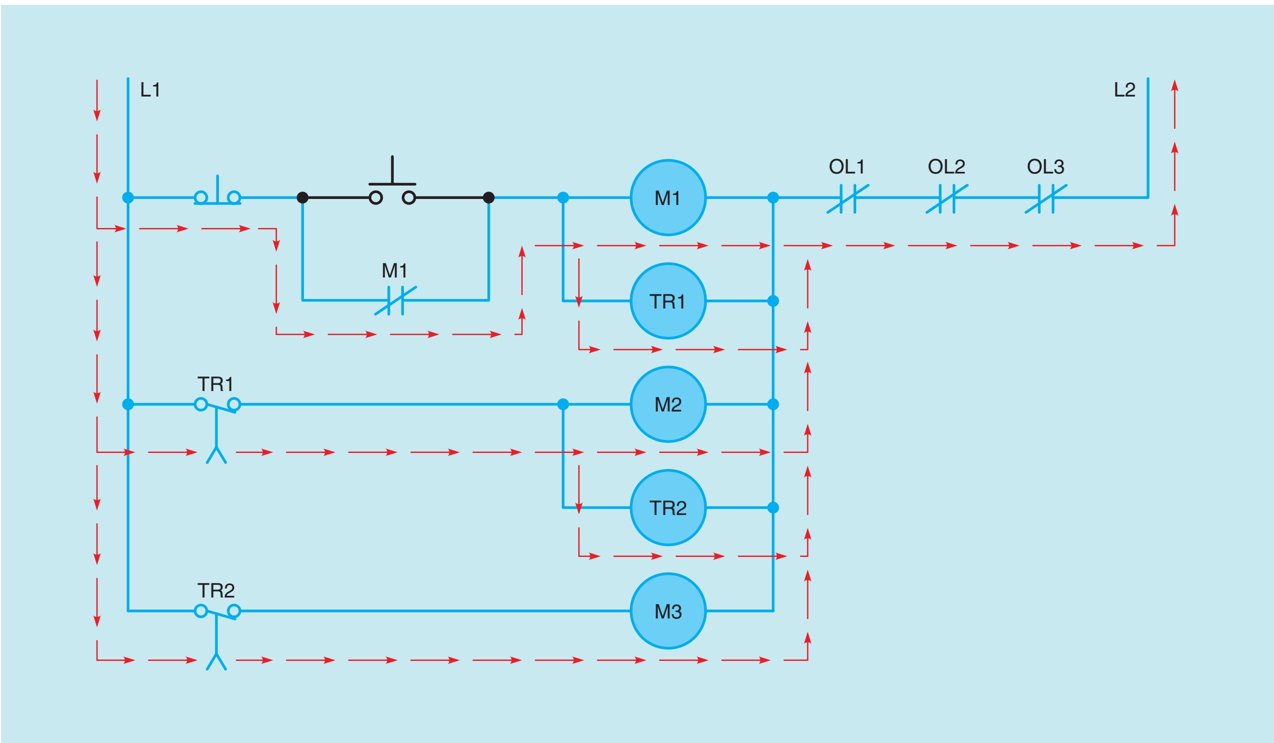


Figure 31–4 Motor 3 has energized.

TR2 opens immediately. This breaks the circuit to motor starter M3. When motor starter M3 de-energizes, motor #3 stops. Although it takes several seconds to explain what happens when the stop button is pressed, the action of the relays is almost instantaneous. If one of the overload contacts opens while the circuit is energized, the effect is the same as pressing the stop button. After the circuit stops, all contacts return to their normal positions and the circuit is the same as the original circuit shown in Figure 31–1.

Review Questions

(Refer to circuit 31–1.)

1. Explain the operation of circuit 31–1 if contact M1 did not close.
2. Explain the operation of circuit 31–1 if relay coil TR2 were burned out.

UNIT 32

FLOAT SWITCH CONTROL OF A PUMP AND PILOT LIGHTS (CIRCUIT #3)

OBJECTIVES

After studying this unit, the student will be able to:

- Discuss the operation of circuit #3.
- Troubleshoot circuit #3 using the schematic.

In this circuit, a float switch is used to operate a pump motor. The pump is used to fill a tank with water. When the tank is low on water, the float switch activates the pump motor and turns a red pilot light on. When the tank is filled with water, the float switch turns the pump motor and red pilot light off, and turns an amber pilot light on to indicate that the pump motor is not running. If the pump motor becomes overloaded, an overload relay stops the pump motor only.

The requirements for this circuit indicate that a float switch is to be used to control three different items: a red pilot light, a motor starter, and an amber pilot light. However, most pilot devices, such as float switches, pressure switches, and limit switches, seldom contain more than two contacts. When the circuit requires these pilot devices to use more contacts than they contain, it is common practice to let a set of contacts on the pilot device operate a control relay. The contacts of the control relay can be used as needed to fulfill the requirements of the circuit.

The float switch in Figure 32–1 is used to operate a control relay labeled FSCR. The contacts of the control relay are used to control the motor starter and the two pilot lights.

In the circuit shown in Figure 32–2, current can flow through the normally closed FSCR contact to the red pilot light, and through a second normally closed FSCR contact to the coil of motor starter M1. When motor starter M1 energizes, the pump motor starts and begins to fill the tank with water. As water rises in the tank, the float of float switch FS rises also. When the tank is sufficiently filled, the float switch contact closes and energizes relay FSCR (Figure 32–3).

When the coil of relay FSCR energizes, all FSCR contacts change. The normally closed contacts open and the normally open contact closes. When the normally

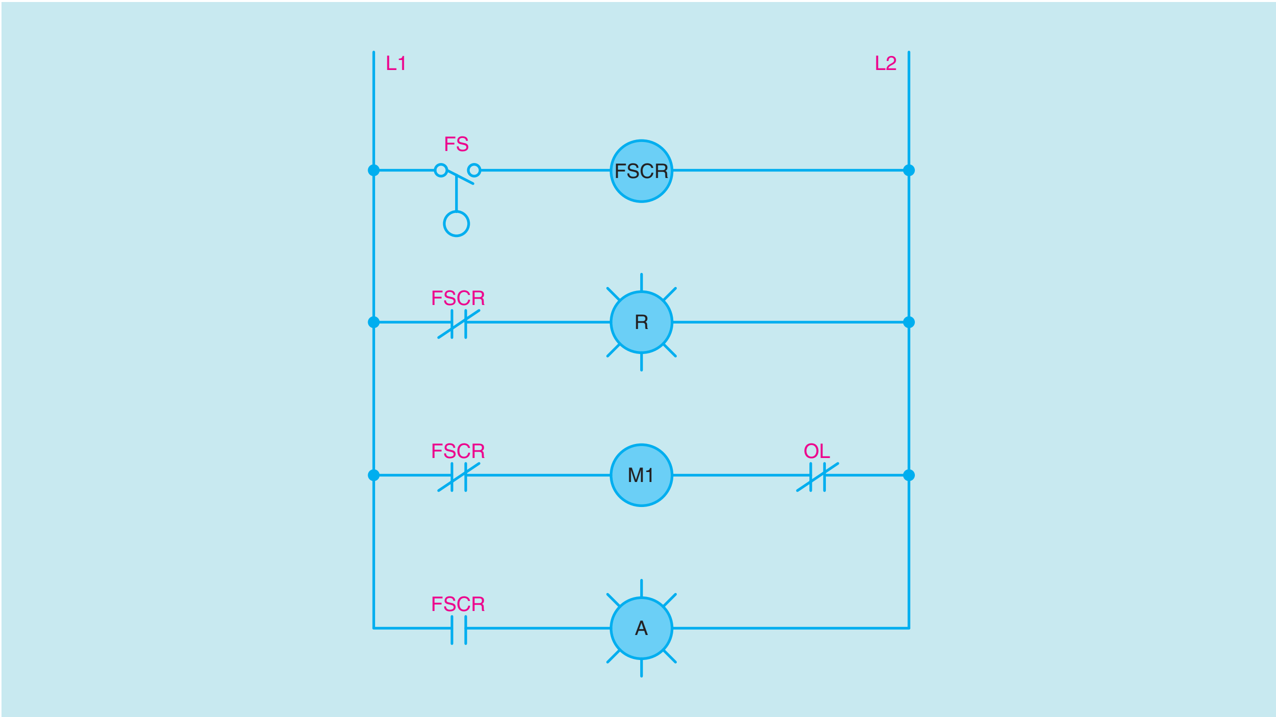


Figure 32–1 Float switch used to operate a control relay.

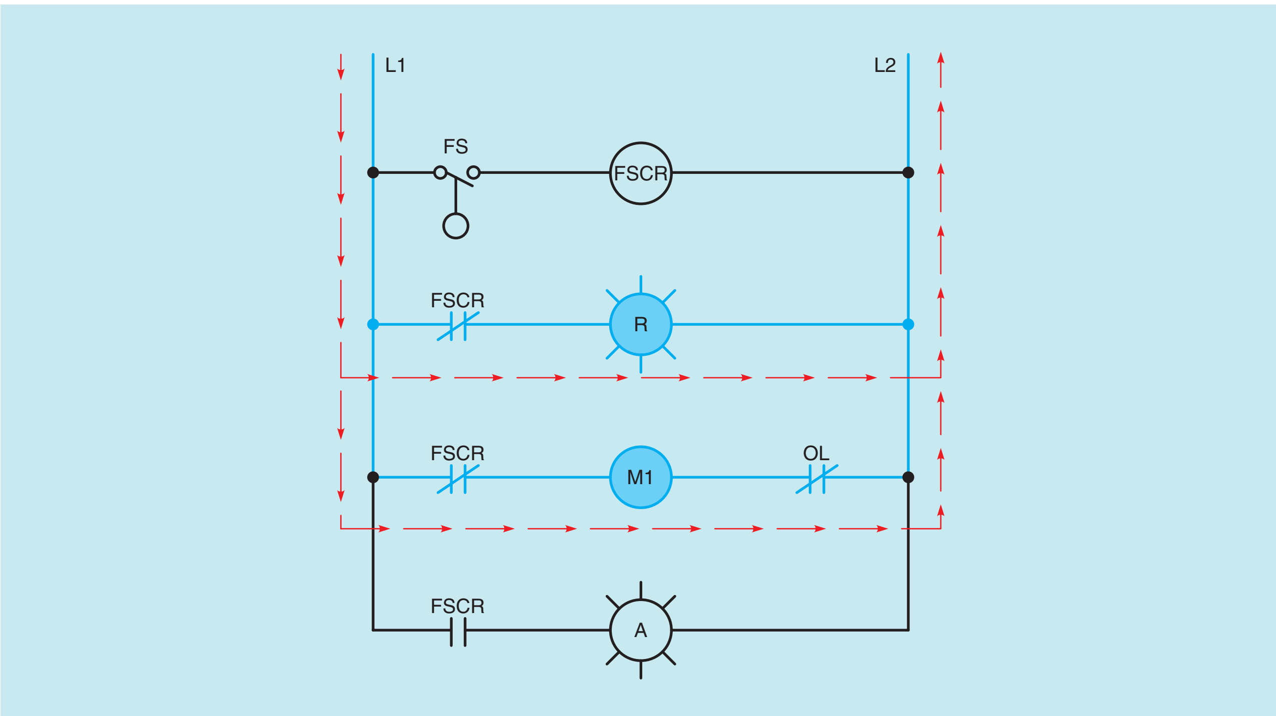


Figure 32–2 Warning light and pump motor have energized.

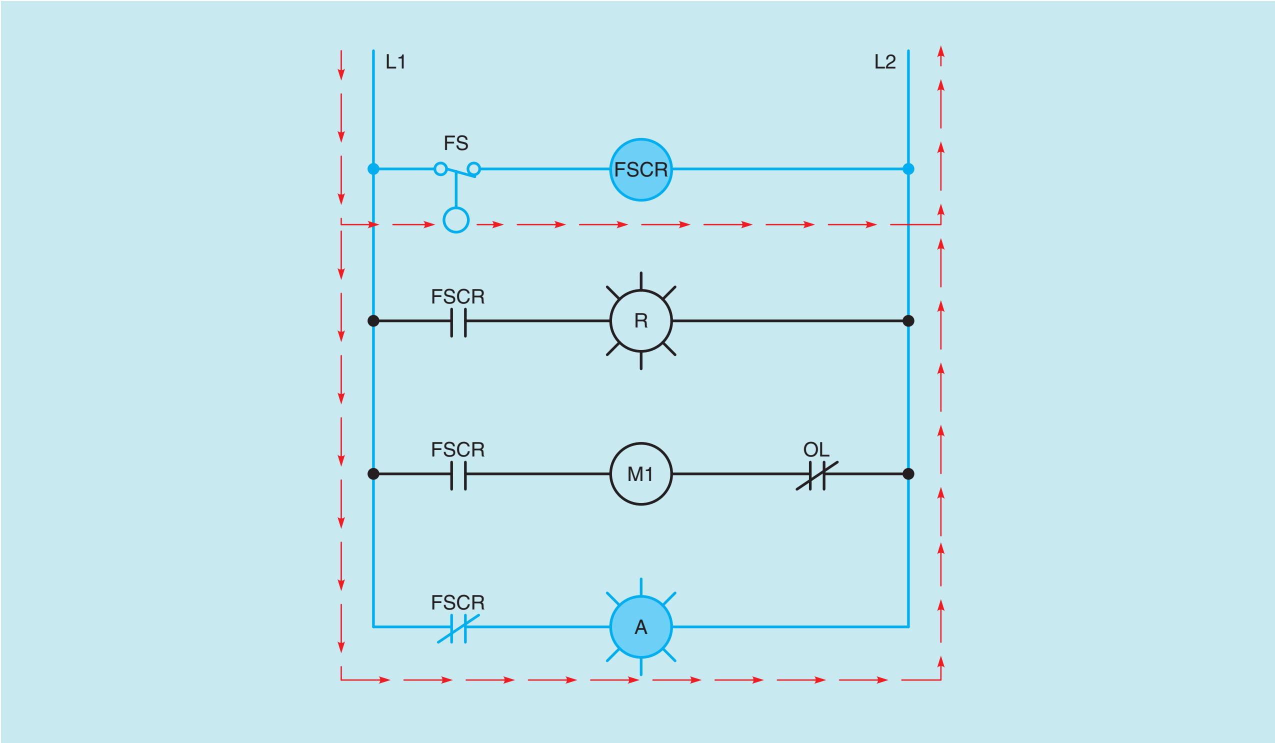


Figure 32–3 Float switch energized FSCR relay.

closed contacts open, the circuits to the red pilot light and to coil M1 are broken. When motor starter M1 de-energizes, the pump motor stops. When the normally open FSCR contact closes, current flows to the amber pilot light. When the pump motor turns off, the water level begins to drop in the tank. When the water level drops low enough, the float switch opens and de-energizes relay coil FSCR. When relay FSCR de-energizes, all FSCR contacts return to their normal positions as shown in Figure 32–1. If the pump motor is operating and the overload relay opens the overload contact, only the motor starter will be de-energized. The pilot lights will continue to operate.

Review Questions

(Refer to circuit 32–1.)

1. Explain the operation of circuit 32–1 if float switch FS were connected normally closed instead of normally open.
2. Explain the operation of circuit 32–1 if relay coil M1 were burned out.

UNIT 33

DEVELOPING A WIRING DIAGRAM (CIRCUIT #1)

OBJECTIVES

After studying this unit, the student will be able to:

- Interpret a wiring diagram.
- Develop a wiring diagram from a schematic diagram.
- Connect a control circuit using a wiring circuit diagram.

Wiring diagrams will now be developed for the three circuits just discussed. The method used for developing wiring diagrams is the same as the method used for installing new equipment. To illustrate this principle, the components of the system will be placed on paper and connections will be made to the various contacts and coils. Using a little imagination, it will be possible to visualize actual relays and contacts mounted in a panel, and wires connecting the various components.

Figure 33–1 shows the schematic for the alarm silencing circuit, and Figure 33–2 shows the components of the system. The connection of the circuit is more easily understood with the aid of a simple numbering system. The rules for this system are as follows:

A. Each time a component is crossed the number must change.

B. Number all connected components with the same number.

C. Never use a number set more than once.

Figure 33–3 shows the schematic of the alarm silencing circuit with numbers placed beside each component. Notice that a 1 has been placed beside L1 and one side of the pressure switch. The pressure switch is a component. Therefore, the number must change when the pressure switch is crossed. The other side of the pressure switch is numbered with a 2. A 2 is also placed on one side of the normally closed S contact, one side of the red warning light, one side of the normally open reset push button, and one side of the normally open S contact. All of these components are connected electrically; therefore, each has the same number.

When the normally closed S contact is crossed, the number is changed. The other side of the normally closed S contact is now a 3, and one side of the horn is a 3. The other side of the horn is connected to L2. The other side of the red warning light and one side of relay

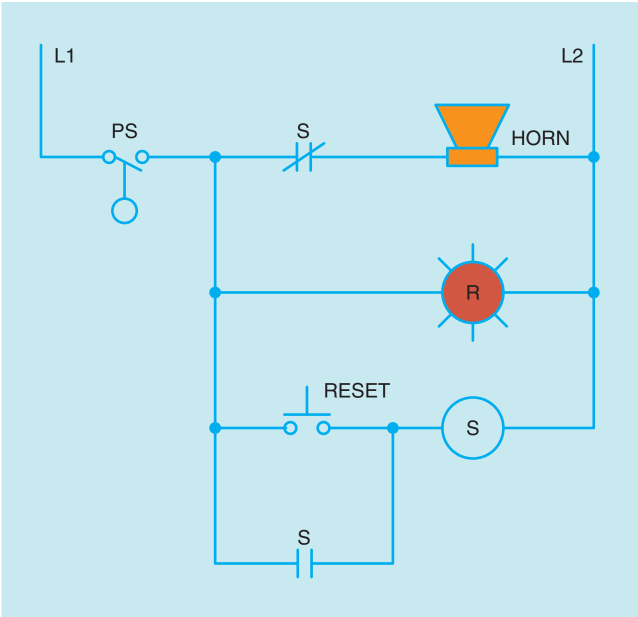


Figure 33–1 Alarm silencing circuit.

coil S is also connected to L2. All of these points are labeled with a 4. The other side of the normally open reset button, the other side of the normally open S contact, and the other side of relay coil S are numbered with a 5.

The same numbers that are used to label the schematic in Figure 33–3 are used to label the components shown in Figure 33–4. L1 in the schematic is labeled with a 1; therefore, 1 is used to label L1 on the wiring diagram in Figure 33–4. One side of the pressure switch in the schematic is labeled with a 1 and the other side is labeled with a 2. The pressure switch in the wiring diagram is shown with three terminals. One terminal is labeled C for common, one is labeled NO for normally open, and one is labeled NC for normally closed. This is a common contact arrangement used on many pilot devices and control relays (see Figure 15–1). In the schematic the pressure switch is connected as a normally open device; therefore, terminals C and NO will be used. A 1 is placed by terminal C and a 2 is placed beside terminal NO. Notice that a 2 has also been placed beside

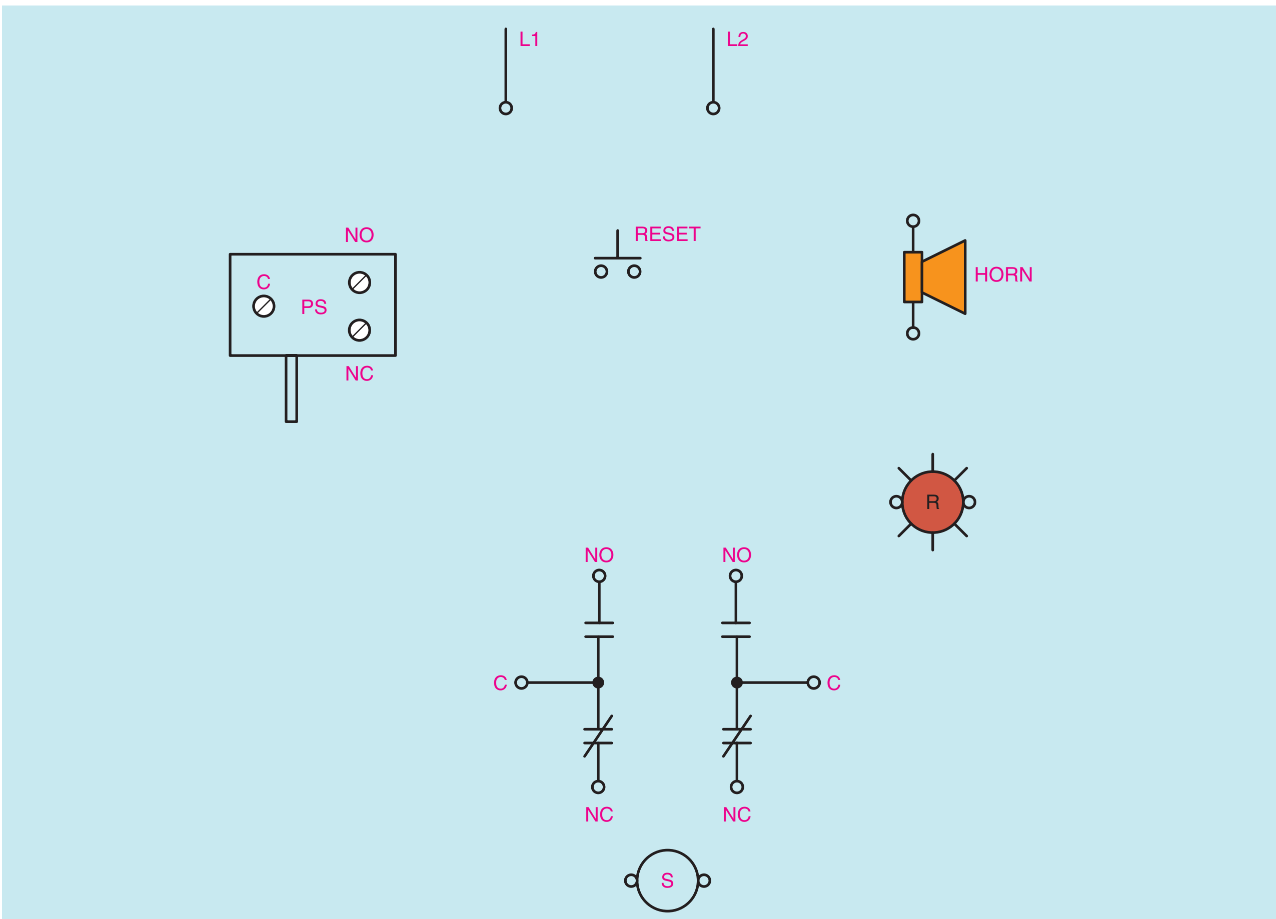


Figure 33–2 Circuit components.

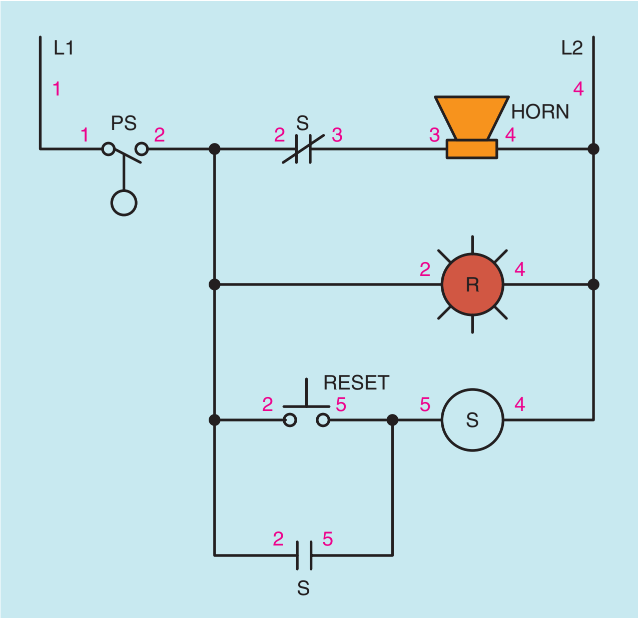


Figure 33–3 Numbers aid in circuit connection.

one side of the normally open reset button, one side of the normally closed contact located on relay S, one side of the normally open contact located on relay S, and one side of the red warning light. A 3 is placed beside the common terminal of relay contact S which is used to produce a normally closed contact, and beside one of the terminal connections of the horn. A 4 is placed beside L2, the other terminal of the horn, the other side of the red warning light, and one side of relay coil S. A 5 is placed on the other side of relay coil S, the other side of the normally open reset button, and on the common terminal of relay contact S which is used as a normally open contact.

Notice that the numbers used to label the components of the wiring diagram are the same as the numbers used to label the components of the schematic. For instance, the pressure switch in the schematic is shown as being normally open and is labeled with a 1 and a 2. The pressure switch in the wiring diagram is labeled with a 1 beside the common terminal and a 2 beside the NO terminal. The normally closed S contact in the schematic is labeled with a 2 and a 3. Relay S in the wiring

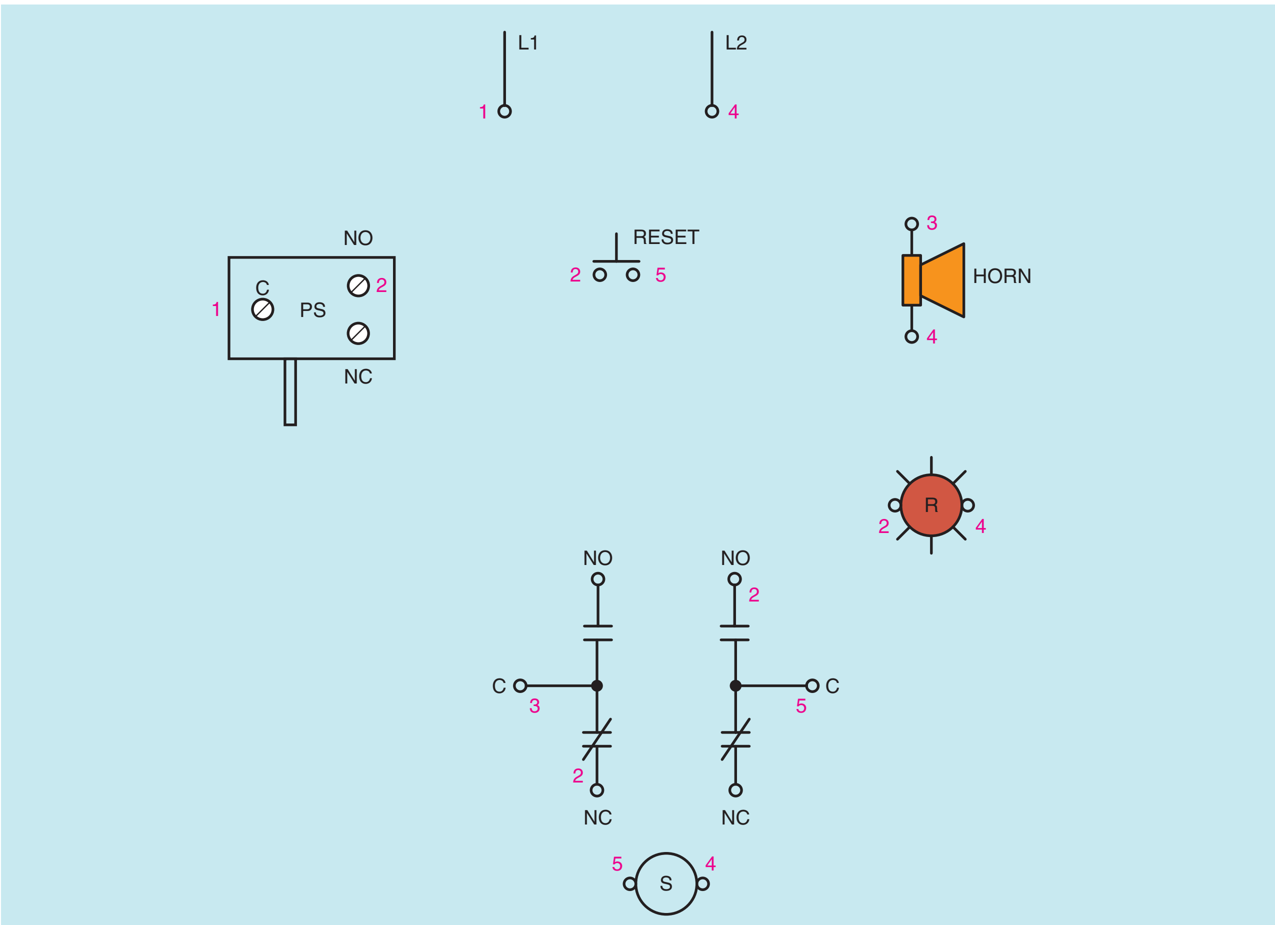


Figure 33–4 Circuit components have been numbered to match the schematic.

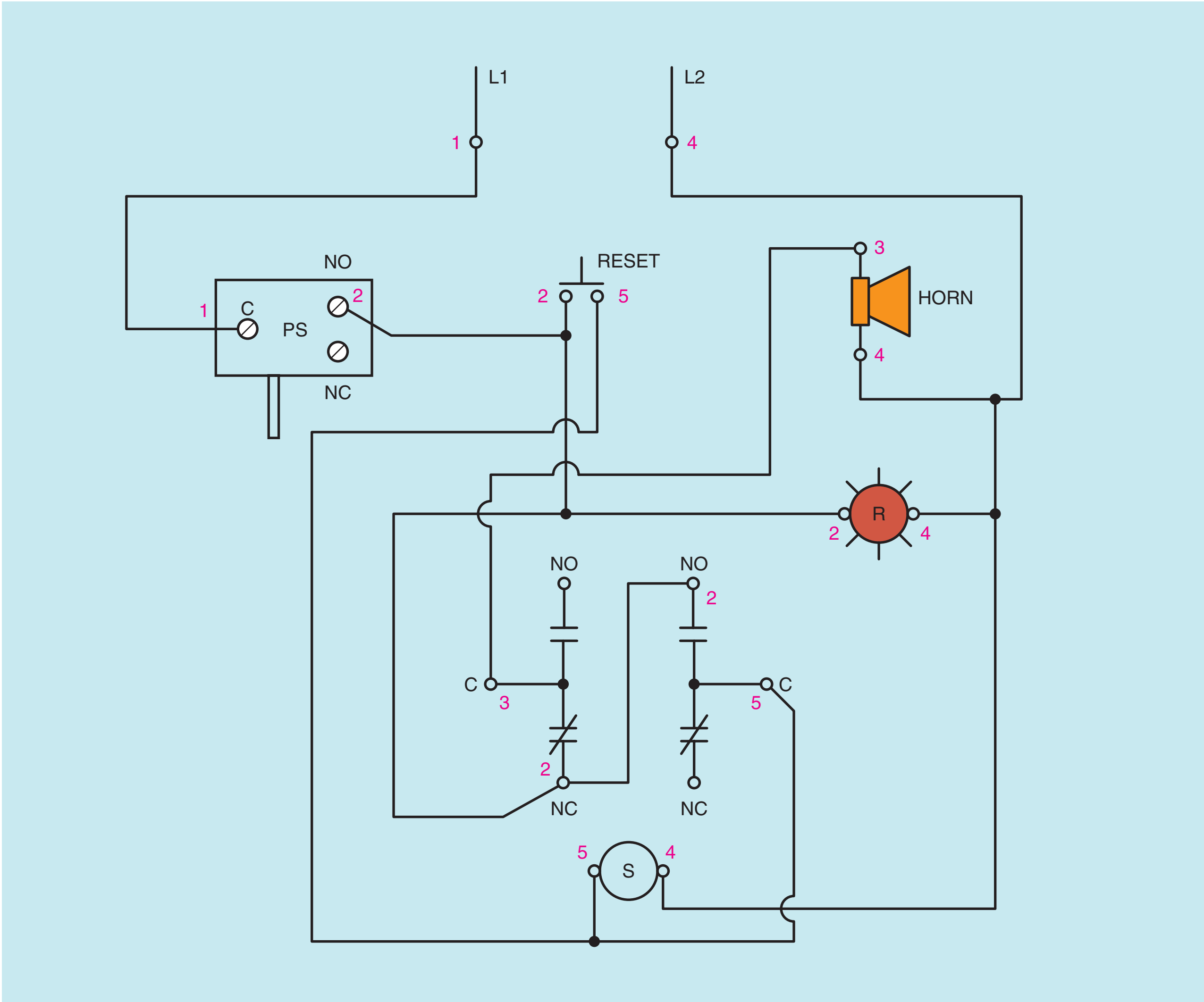


Figure 33–5 Final wiring is done by connecting numbers.

diagram has a normally closed contact labeled with a 2 and a 3. The numbers used to label the components in the wiring diagram correspond to the number used to label the same components in the schematic.

After labeling the components in the wiring diagram with the proper numbers, it is simple to connect the circuit (Figure 33–5). Connection of the circuit is made by connecting like numbers. For example, all of the components labeled with a 1 are connected, all of those labeled with a 2 are connected, all of the 3s are connected, all of the 4s are connected, and all of the 5s are connected.

Review Questions

1. Why are numbers used when developing a wiring diagram from a schematic diagram?
2. The float switch in Figure 33–1 is:
   a. Normally closed
   b. Normally open
   c. Normally closed held open
   d. Normally open held closed
3. The circuit in Figure 33–1 is designed to sound an alarm if the liquid level rises to a high enough level. What change would have to be made in the circuit so that it would sound an alarm if the liquid level dropped below a certain point?

UNIT 34

DEVELOPING A WIRING DIAGRAM (CIRCUIT #2)

OBJECTIVES

After studying this unit, the student will be able to:

- Develop a wiring diagram using this schematic.
- Connect this circuit.

The circuit shown in Figure 34–1 is the same as the schematic shown in Figure 31–1, except the schematic in 34–1 has been labeled with numbers. Figure 34–2 shows the components of the wiring diagram. The numbers used to label the components in the wiring diagram correspond to the numbers in the schematic. For instance, the schematic shows the numbers 1 and 8 beside normally open contact TR1. The wiring diagram also shows the numbers 1 and 8 beside normally open contact TR1. The numbers used with each component shown on the schematic have been placed beside the proper component shown in the wiring diagram.

Figure 34–3 shows the wiring diagram with connected wires. Notice that the wiring diagram shows motor connections while the schematic does not. Although it is a common practice to omit motor connections in control schematics, wiring diagrams do show the motor connections.

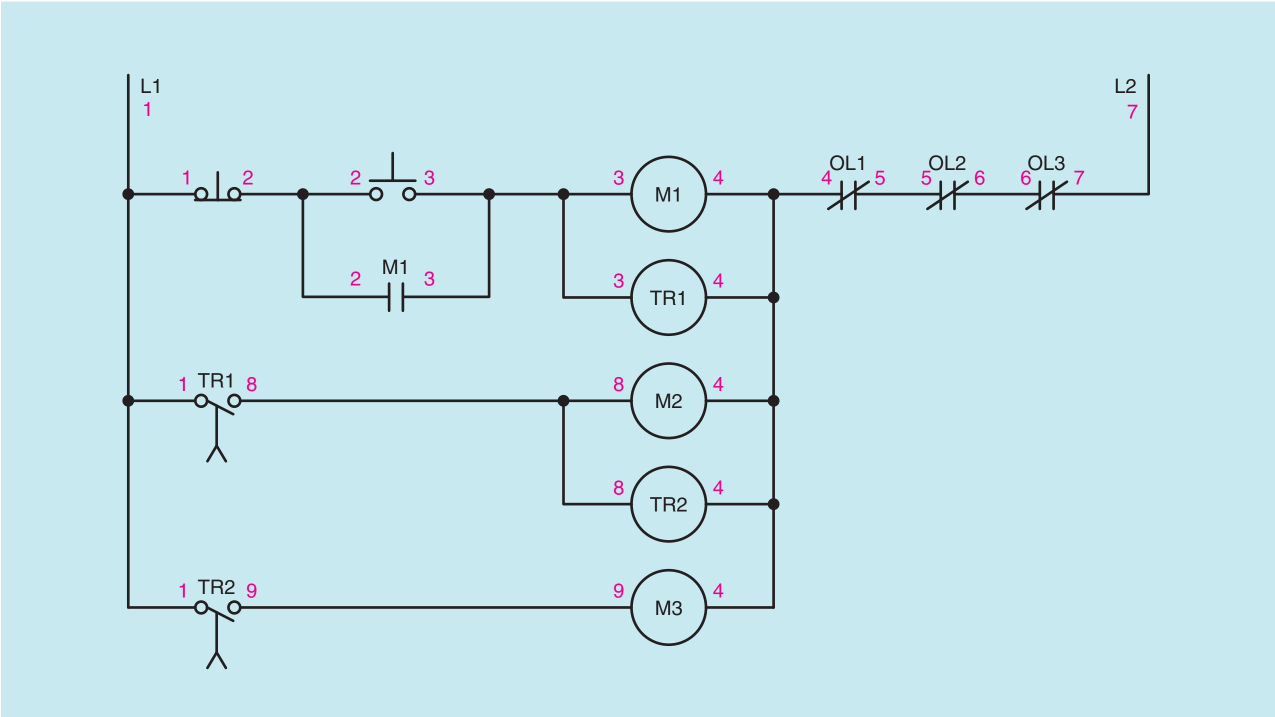


Figure 34–1 Schematic with components numbered.

Review Question

1. Referring to circuit 34–1, would it be possible to change the components that have been numbered with an 8 to a number 9, and the components that have been numbered with a 9 to a number 8 without affecting the operation of the circuit?

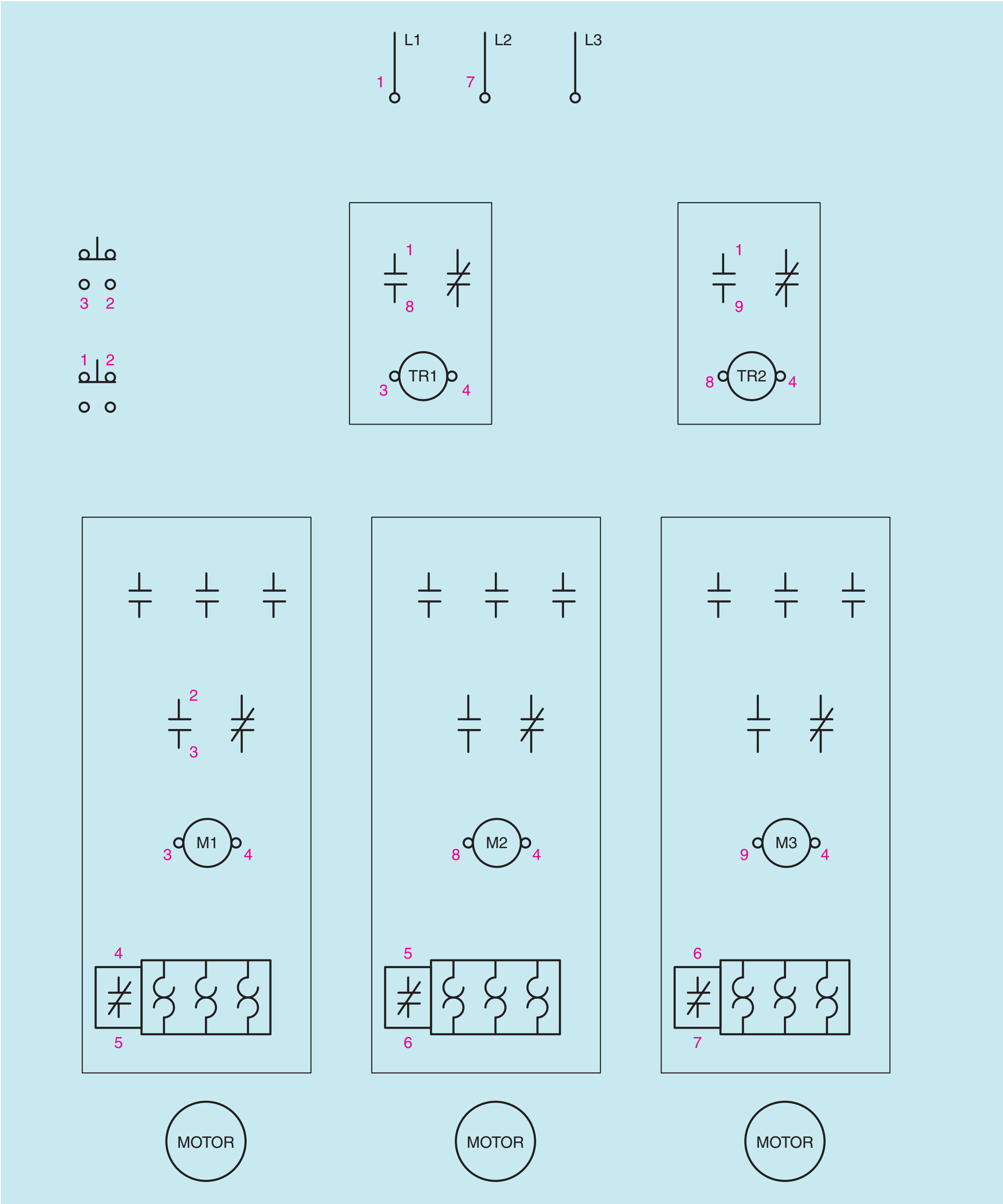


Figure 34–2 Components have been numbered to match the schematic.

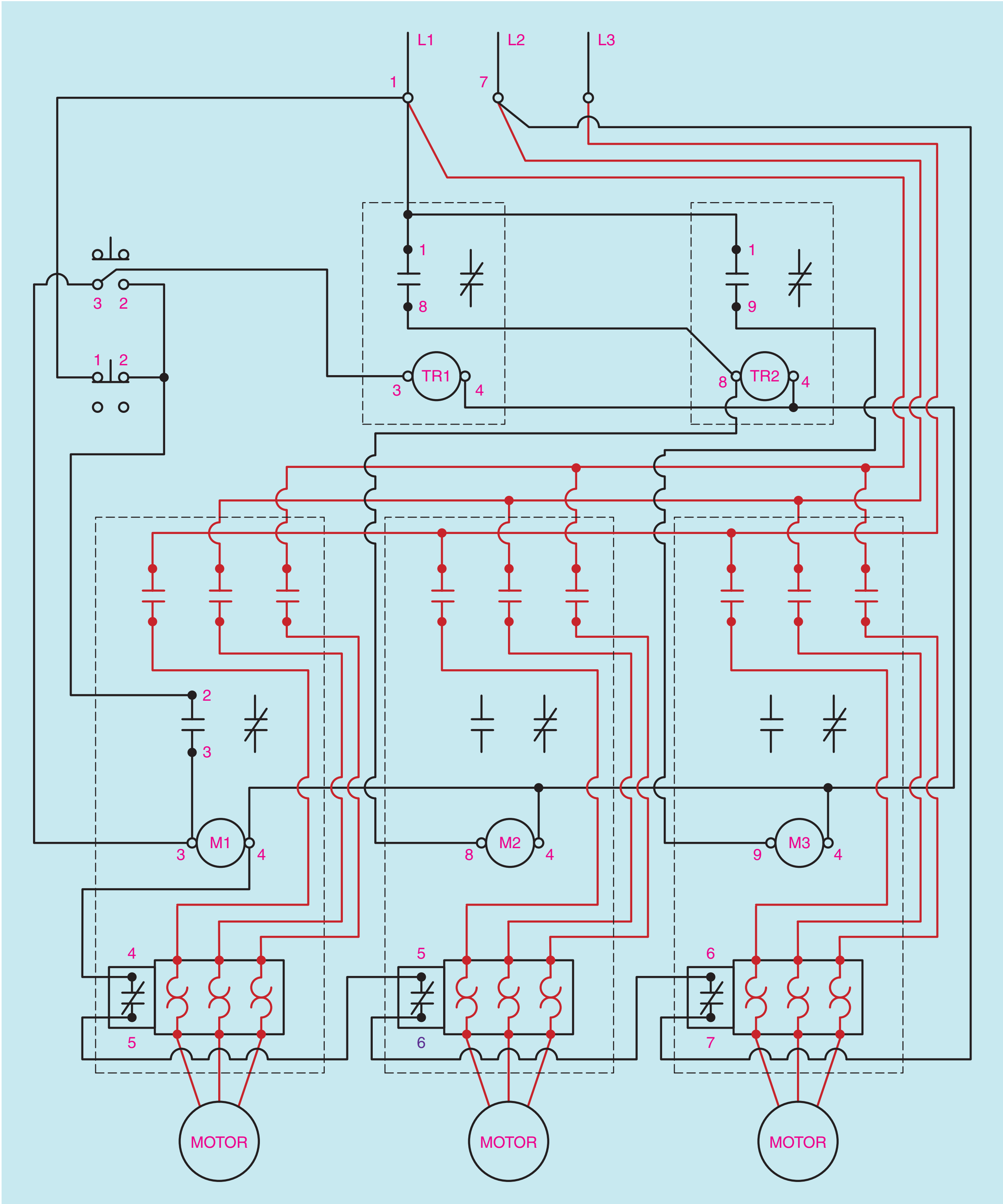


Figure 34–3 Wire connections are made by connecting like numbers.

UNIT 35

DEVELOPING A WIRING DIAGRAM (CIRCUIT #3)

OBJECTIVES

After studying this unit, the student will be able to:

- Develop a wiring diagram using this schematic.
- Connect this circuit.

Figure 35–1 shows the same schematic as Figure 32–1, except that Figure 35–1 has been labeled with numbers in the same manner as the two previous circuits. Figure 35–2 shows the components of the wiring diagram labeled with numbers that correspond to the numbered components shown in the schematic. Figure 35–3 shows the wiring diagram with connected wires.

The same method has been used to number the circuits in the last few units. Although most control schematics are numbered to aid the electrician in troubleshooting, several methods are used. Regardless of the method used, all numbering systems use the same principles. An electrician who learns this method of numbering a schematic will have little difficulty understanding a different method.

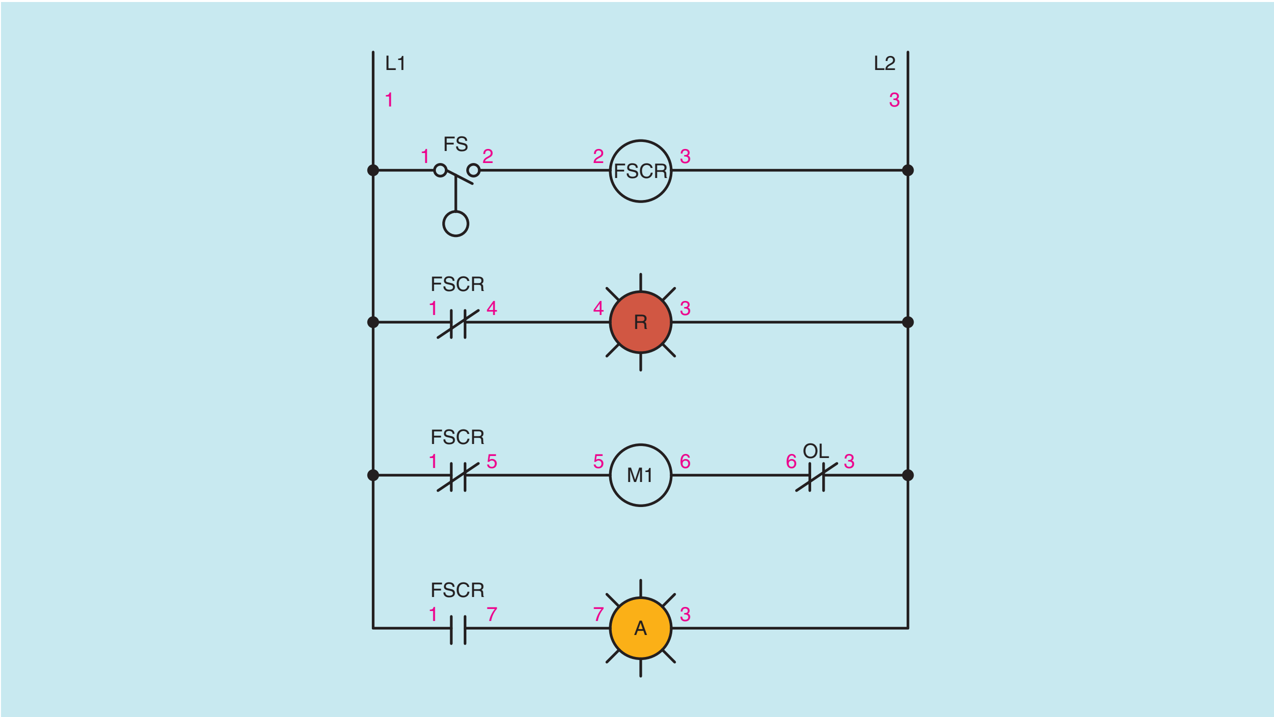


Figure 35–1 Schematic with components numbered.

Review Question

1. Are numbering systems other than the one described in this text used to develop wiring diagrams from schematic diagrams?

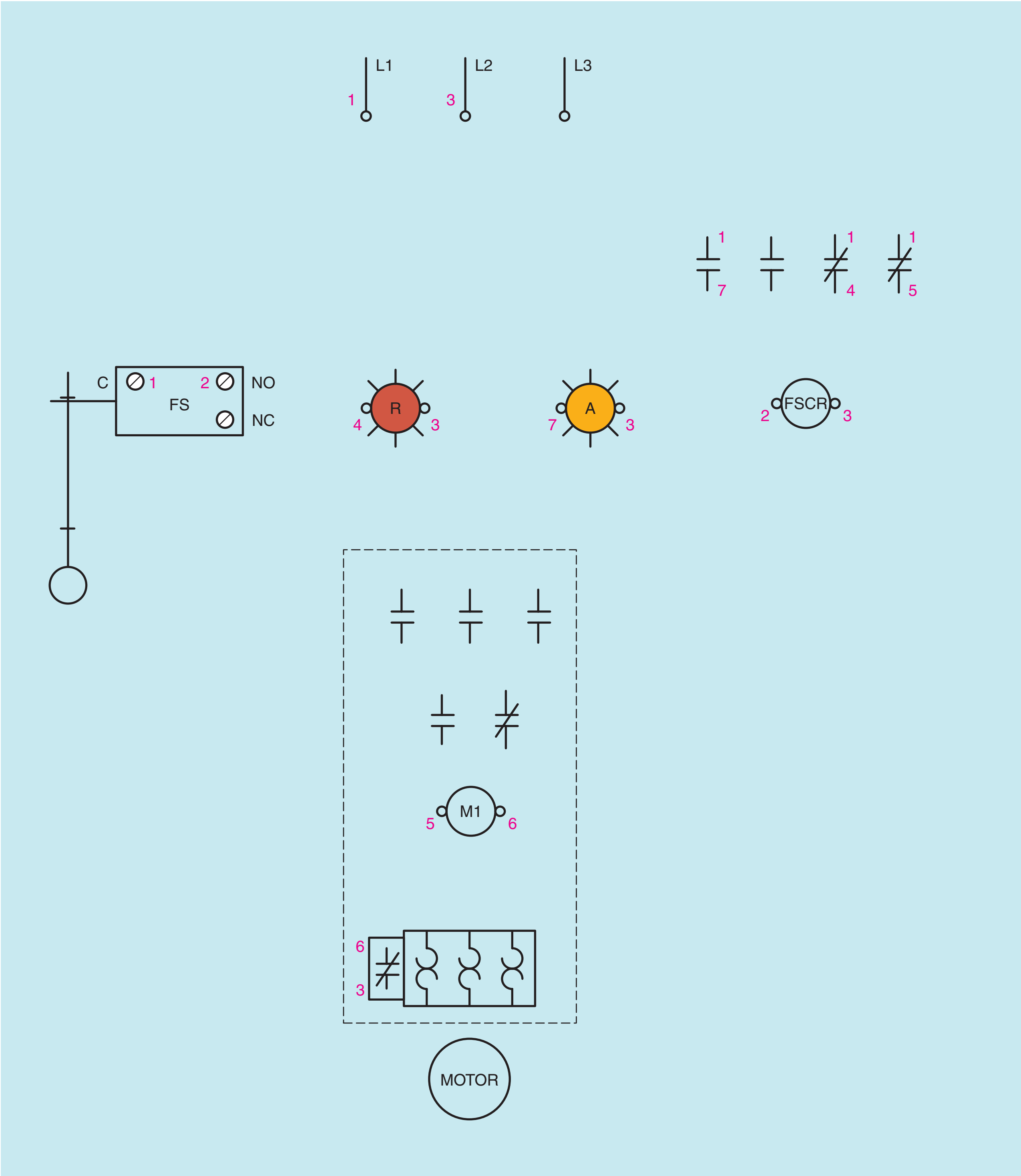


Figure 35–2 Components have been numbered to correspond with the schematic.

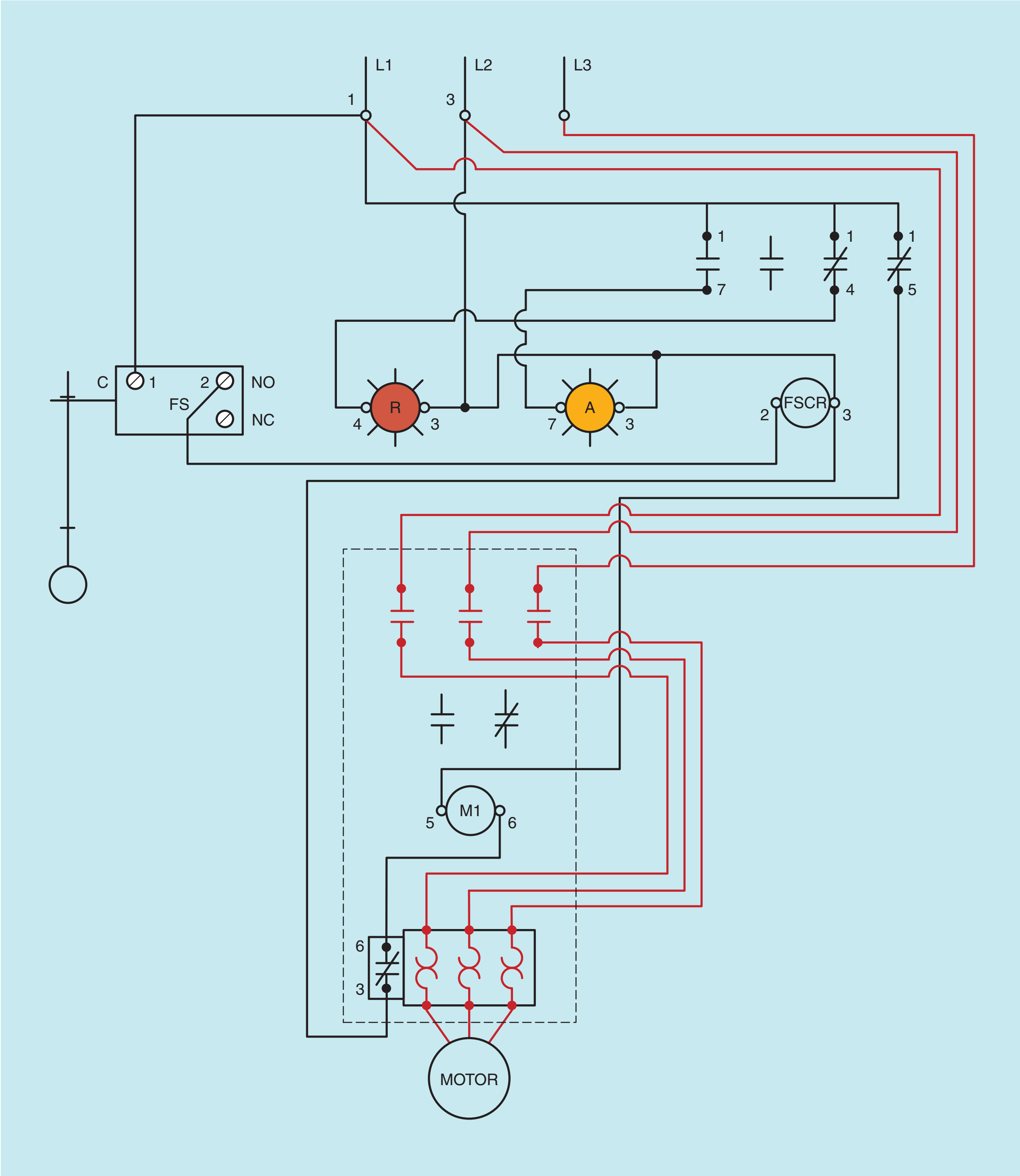


Figure 35–3 Wire connections are made by connecting like numbers.

UNIT 36

READING LARGE SCHEMATIC DIAGRAMS

OBJECTIVES

After studying this unit, the student will be able to:

- Discuss notations written on large schematics.
- Find contacts that are controlled by specific coils on different lines.
- Find contacts that are controlled by specific coils on different electrical prints.

The schematics presented in this text so far have been small and intended to teach circuit logic and how basic control systems operate. Schematics in industry, however, are often much more complicated and may contain several pages. Notation is generally used to help the electrician interpret the meaning of certain components and find contacts that are controlled by coils. The schematic shown in Figure 36–1 is part of a typical industrial control schematic. Refer to this schematic to locate the following information provided about the control system.

1. At the top left-hand side find the notation: (2300V 3θ 60 Hz). This indicates that the motor is connected to a 2300-V, three-phase, 60-Hz power line (Figure 36–2).
2. To the right of the first notation, locate the notation: (200A 5000V DISCONNECT SWITCH). This indicates that there is a 200 A disconnect switch, rated at 5000 V, that can be used to disconnect the motor from the power line. Also notice that there are six contacts for this switch, two in each line. This is common for high-voltage disconnect switches.
3. At the top of the schematic, locate the two current transformers, 1CT and 2CT. These two current transformers are used to detect the amount of motor current. Current transformers produce an output current of 5 A under a short circuit condition. The notation beside each CT indicates that it has a ratio of 150 to 5. The secondary of 1CT is connected to 1OL and 3OL. The secondary of 2CT is connected to 2OL and 4OL. Overload coils 1OL and 3OL are connected in series, which forces each to have the same current flow. Also note that coil symbols (not heater symbols) are used for the overloads. This indicates that these overload relays are magnetic, rather than thermal.

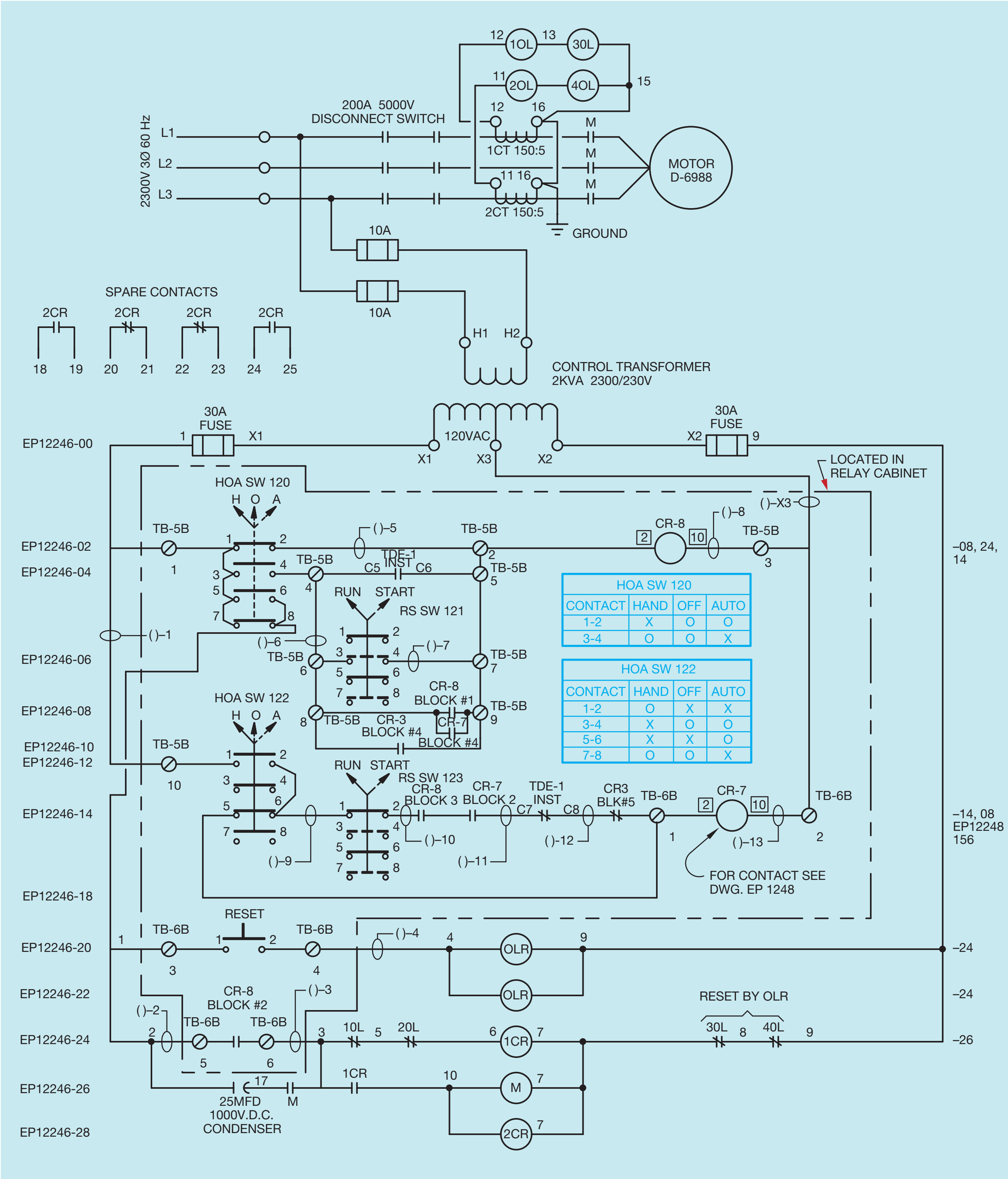


Figure 36–1 Typical industrial schematic diagram.

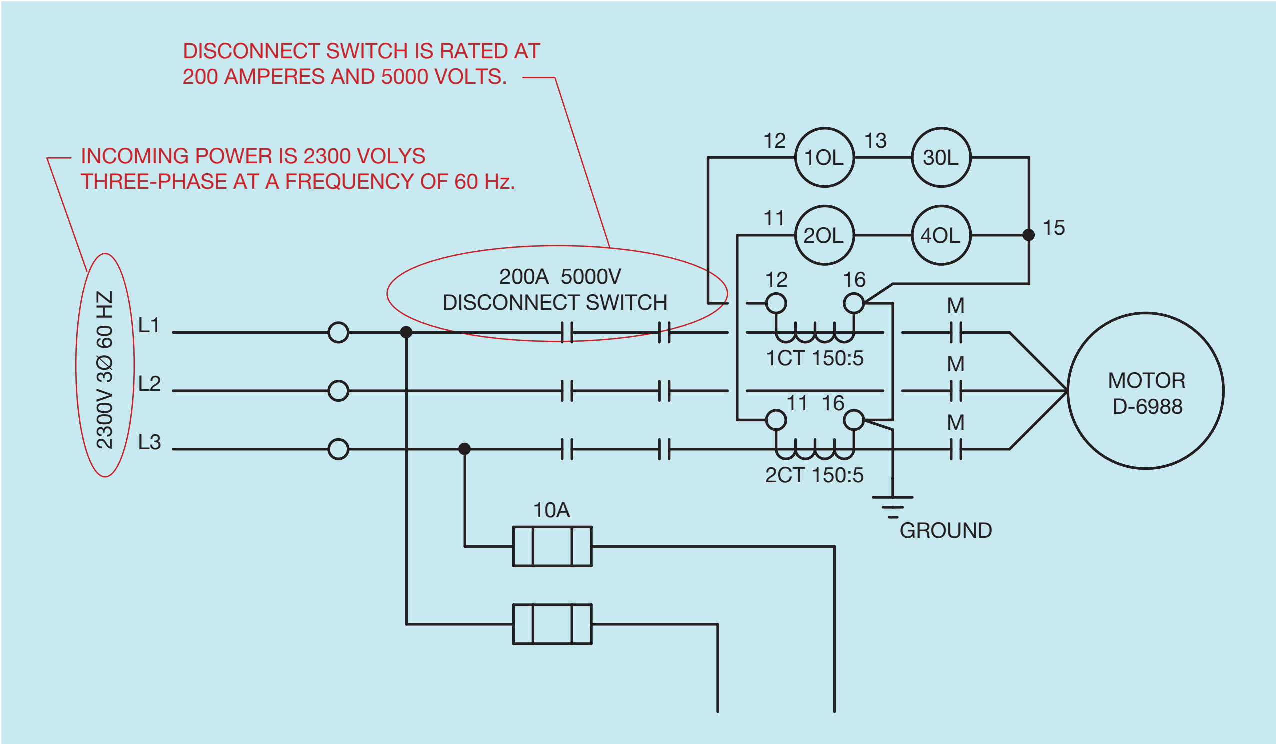


Figure 36–2

4. Locate the two 10 A fuses connected to the primary of the control transformer (Figure 36–3). The control transformer is rated at 2 kVA (2000 VA). The high voltage winding is rated at 2300 V and the secondary winding is rated at 230 V. Also note that the secondary winding contains a center tap (X3). The center tap can be used to provide 120 V from either of the other X terminals. Terminals X1 and X2 are connected to 30 A fuses.

5. To the left of the 30 A fuse connected to terminal X1, locate the notation (EP12246-00) (Figure 36–4). This notation indicates that you are looking at Electrical Print 12246, and line 00. Most multi-page schematics will use some form of notation similar to this to indicate the page and line number you are viewing.

6. On line number EP12246-02, locate the Hand-Off-Automatic switch labeled (HOA SW 120). Also locate the contact chart for this switch just to the right of the center of the schematic. The chart indicates connection between specific terminals for different settings of the switch. The X indicates connection between terminals and 0 indicates no connection. Notice that in the hand position, there is connection between terminals 1 and 2. There is no connection between terminals 3 and 4. In the OFF position, there is no connection between any of the terminals. In the AUTO position, there is connection between terminals 3 and 4 but no connection between terminals 1 and 2. Referring back to the switch itself, notice that there are three arrows drawn at the top of the switch. One arrow points to H, one points to O, and one points to A. The line connected to the arrowhead pointed at H is shown as a solid line. The lines connected to the other two arrowheads are shown as broken or dashed. The solid line represents the position the switch is set in for the contact arrangement shown on the schematic. The schematic indicates that at the present time there is a connection between terminals 1 and 2, and no connection between terminals 3 and 4. This is consistent with the contact chart for this switch.

7. Locate the RUN-START switch (RS SW 121) to the right and below (HOA SW 120). A contact chart is not shown for this switch. Since there are only two positions for this switch, a different

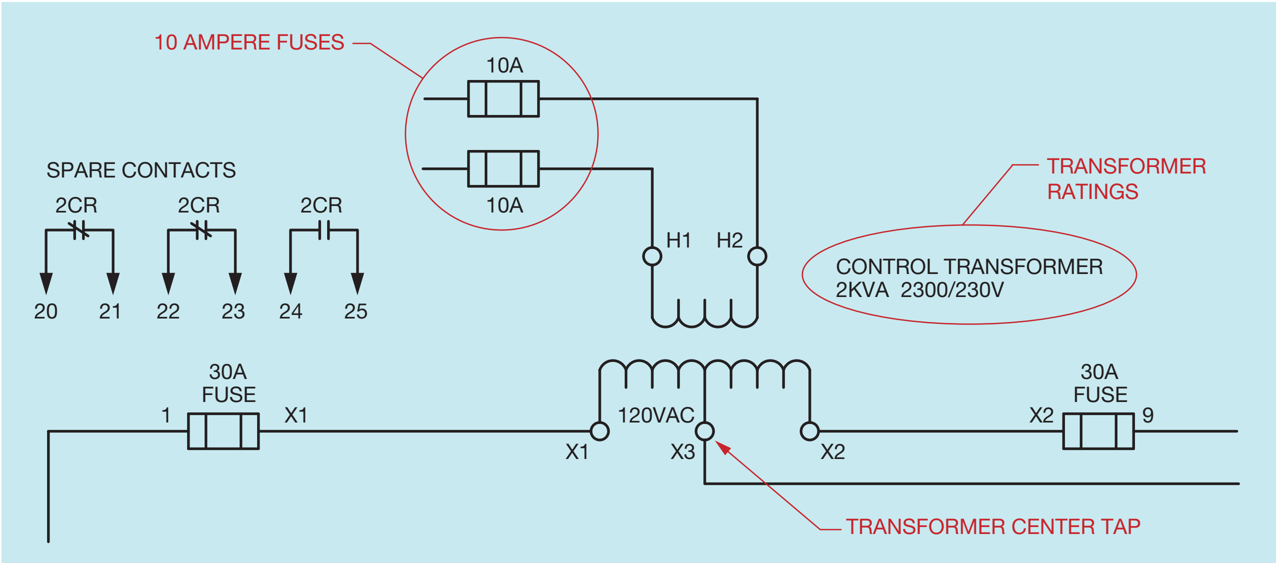


Figure 36–3

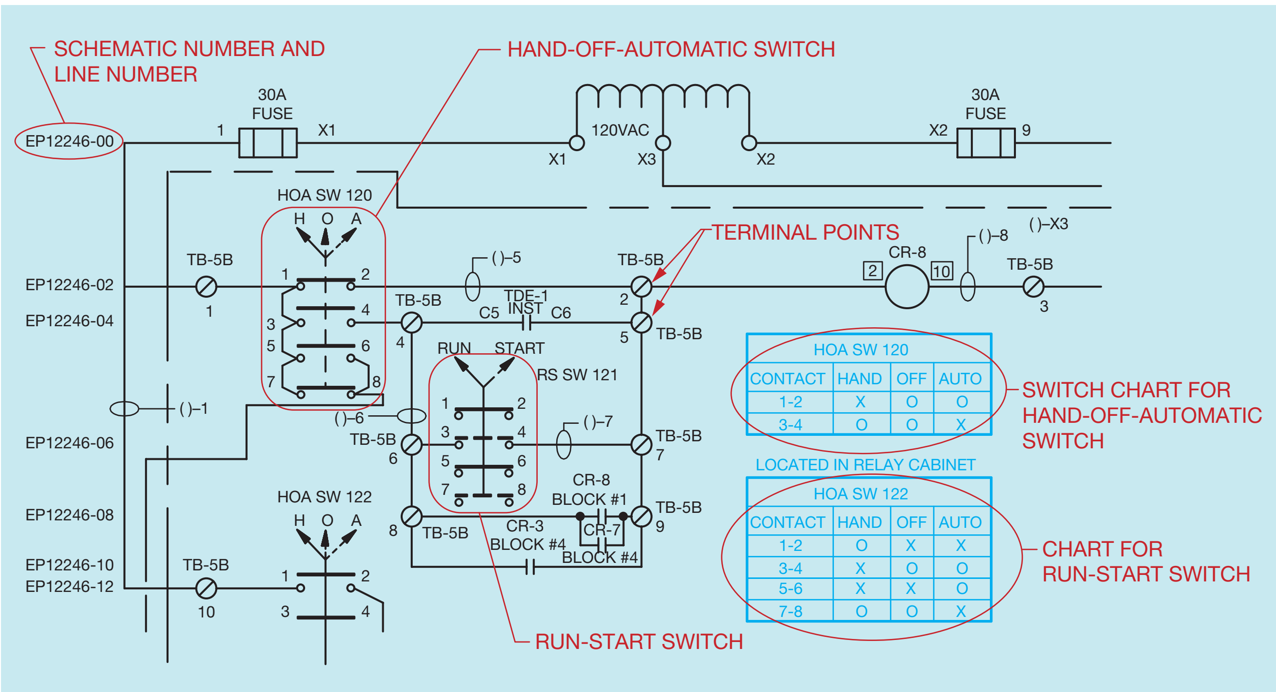


Figure 36–4

method is employed to indicate contact position for the different switch positions. Notice that arrowheads at the top of the switch are pointing at the RUN and START positions. The line drawn to the RUN position is solid and the line drawn to the START position is shown as broken or dashed. The schematic shows a solid line between switch terminals 1 and 2, and 5 and 6. Dashed lines are shown between terminals 3 and 4, and 7 and 8. When the switch is set in the RUN position, there

is a connection between terminals 1 and 2, and 5 and 6. When the switch is in the START position, there is a connection between terminals 3 and 4, and 7 and 8.

8. On line 02, there are three terminals marked TB-5B. These indicate terminal block points. Locate the terminal with 2 drawn beside it. This wire position is located on screw terminal #2 of terminal block 5B. Another terminal block point is shown below it. This terminal location is screw terminal #5 of terminal block 5B.

9. Find relay coil CR-8 on line 02 (Figure 36–5). CR stands for Control Relay. Notice that the numbers 2 and 10 on each side of the coil are shown inside a square box. The square box indicates that these are terminal numbers for the relay and should not be confused with wire numbers. Terminals 2 and 10 are standard coil connections for relays designed to fit into an 11-pin tube socket. If you were trying to physically locate this relay, the pin numbers would be a strong hint as to what you are trying to find.

10. Beside pin number 10 of relay coil CR-8 is a circle with a line connected to it. The line goes to a symbol that looks like ()-8. This indicates a test point. Test points are often placed at strategic points to aid in troubleshooting when it becomes necessary.

11. At the far right-hand side of line 02 is the notation (-08, 24, 14). These numbers indicate the lines on the schematic where contacts controlled by relay coil CR-8 can be found. Find the contacts labeled CR-8 on these lines of the schematic.

12. Locate coil CR-7 on line 14 (Figure 36–6). At the far right-hand side, find the notation (-14, 08, EP12248 156). This notation again indicates the places where contacts controlled by coil CR-7 can be found. CR-7 contacts are located on lines 14 and 08 in this schematic and on line 156 of Electrical Print #12248.

13. At the right side of the schematic between lines 00 and 02 is the notation (LOCATED IN RELAY CABINET). An arrow is pointing at a dashed line.

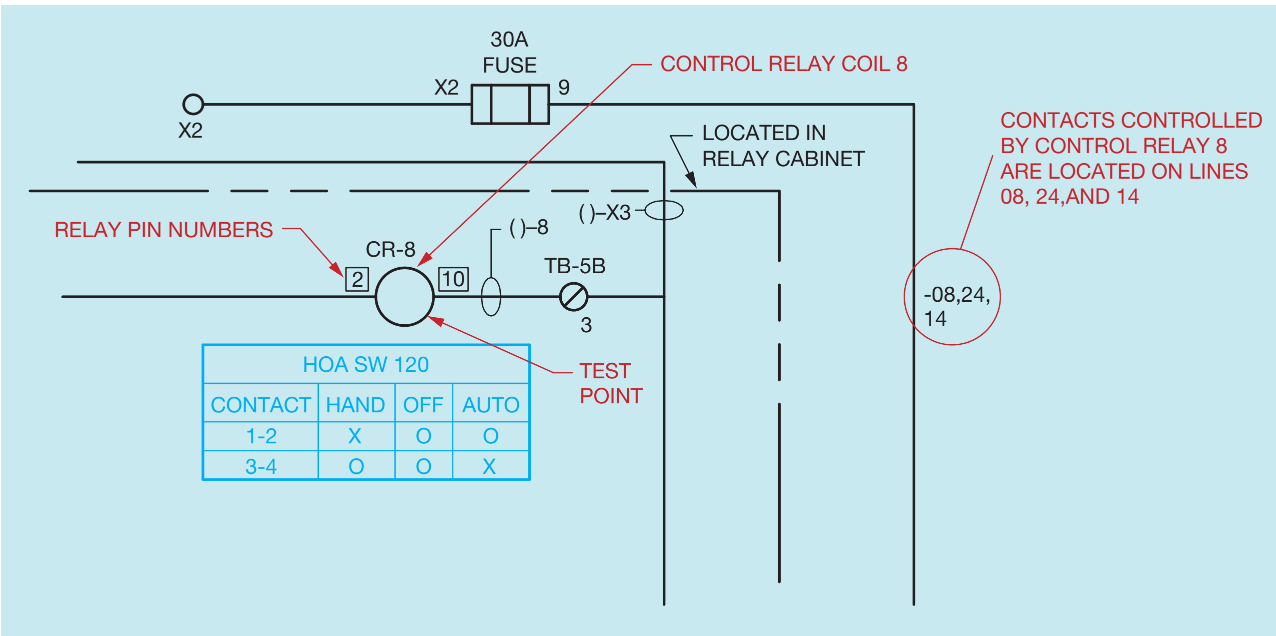


Figure 36–5

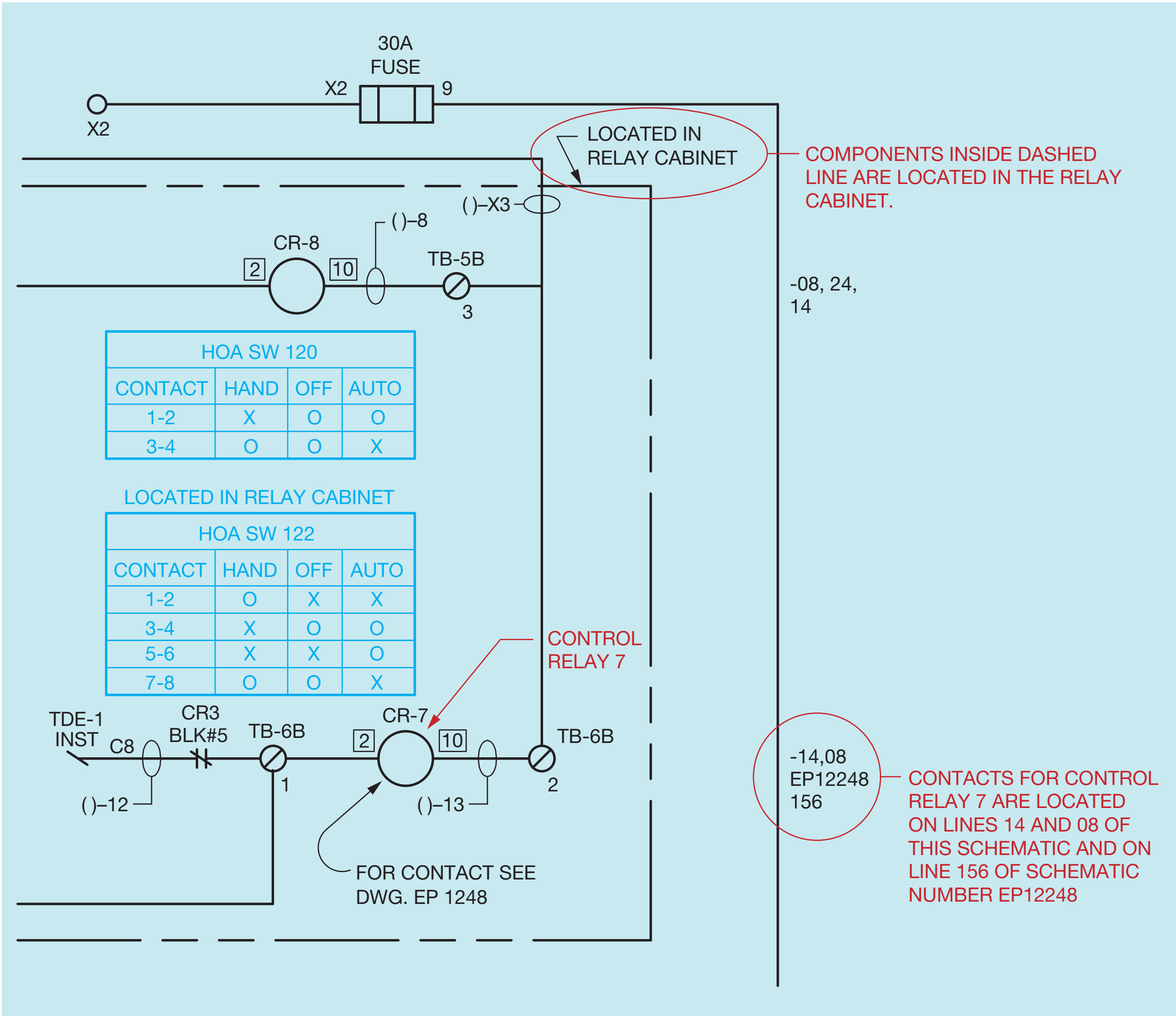


Figure 36–6

This gives the physical location of such control components as starters, relays, and terminal blocks. Push buttons, HOA switches, pilot lights, etc. are generally located on a control terminal where an operator has access to them.

These are notations that are common to many industrial control schematics. Nothing is standard, however. Many manufacturers use their own numbering and notation system, which is specific to their company. Some use the NEMA symbols that are discussed in this text and others do not. With practice and an understanding of basic control logic and schematics, most electricians can determine what these different symbols mean and the way they are used in a circuit. The old saying "Practice makes perfect" certainly applies to reading schematic diagrams.

Review Questions

Refer to Figure 36–1 to answer the following questions.

1. When switch HOA SW 122 is in the OFF position, which contacts have connection between them?
2. How much voltage will be applied to coil 1CR when it is energized?
3. Referring to switch (RS SW 123), in what position must the switch be set to make connection between terminals 3 and 4?
4. What are the terminal numbers for the two normally open spare contacts controlled by coil 2CR?
5. How much voltage is applied to coil CR-7 when it is energized?
6. What contact(s) is/are located between screw numbers 8 and 9 of terminal block 5B?
7. Between which terminal block and screw numbers is relay coil CR-7 located?
8. Assume that HOA SW 120 has been set in the AUTO position. List four ways by which coil CR-8 could be energized.
9. In what position must switch HOA SW 123 be set to make connection between terminals 3 and 4?
10. If one of the magnetic overload relays opens its contact, how can it be reset?

UNIT 37
INSTALLING CONTROL SYSTEMS

OBJECTIVES

After studying this unit, the student will be able to:

- Discuss the installation of control circuits.
- Use the number system on a schematic diagram to troubleshoot a circuit.

Wiring diagrams can be misleading in that they show all components grouped together. In actual practice, the control relays and motor starters may be located in one cabinet, the push buttons and pilot lights in a control panel, and pilot devices, such as limit switches, and pressure switches, may be located on the machine itself (Figure 37–1). Most control systems use a relay cabinet to house the control relays and motor starters. Wiring is brought to the relay cabinet from the push buttons and pilot lights located in the control panel, and from the pilot devices located on the machine. All of the connections are made inside the relay cabinet.

Relay cabinets generally contain rows of terminal strips. These terminal strips are used as connection points between the control wiring inside the cabinet and inputs or outputs to the machine or control panel. Most terminal strips are designed so that connection points can be numbered. This type of system can be more costly to install, but it will more than pay for the extra cost in the time saved when troubleshooting. For example, assume that an electrician desires to check limit switch LS15 to see if its contacts are open or closed. Limit switch LS15 is located on the machine, but assume that in the schematic one side of the limit switch is number 25 and the other side of the limit switch is number 26. If numbers 25 and 26 can be located on the terminal strip, the electrician can check the limit switch from the relay cabinet without having to go to the machine and remove the cover from the limit switch. The electrician will only have to connect the probes of a voltmeter across terminals 25 and 26. If the voltmeter indicates the control voltage of the circuit, the limit switch contacts are open. If the voltmeter indicates 0 volts, the limit switch contacts are closed.

Part of a typical ladder diagram is shown in Figure 37–2. Wire numbers have been placed on the schematic. Connections to the components using a terminal strip are shown in Figure 37–3. An industrial diagram showing terminal block connections is shown in Figure 37–4.

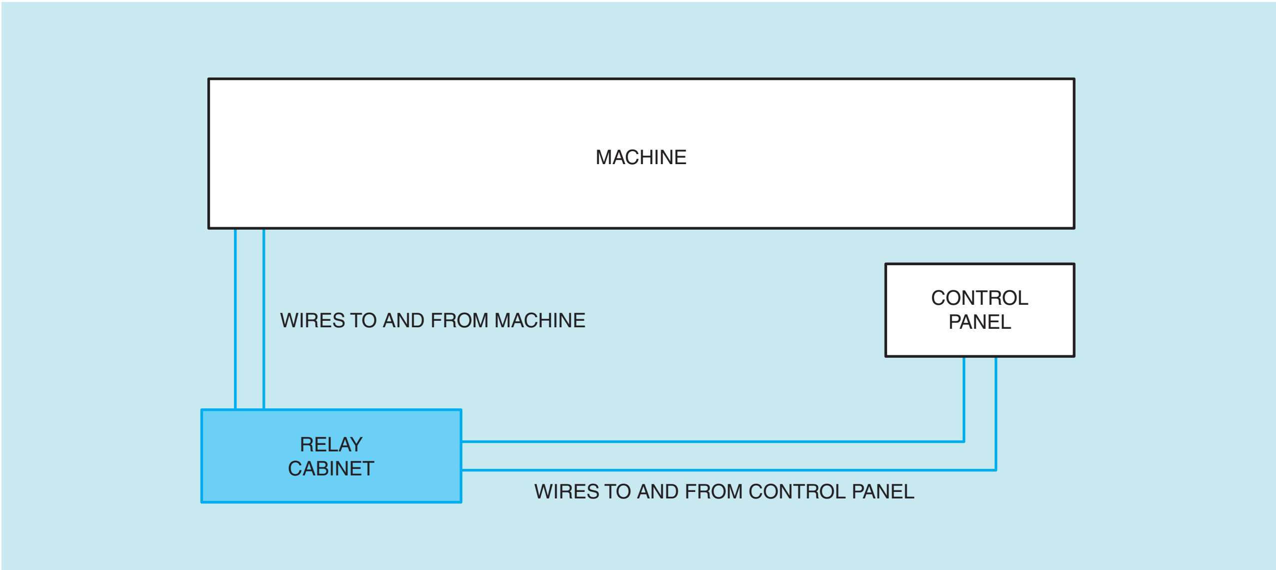


Figure 37–1 Most wire connections are made inside the relay cabinet.

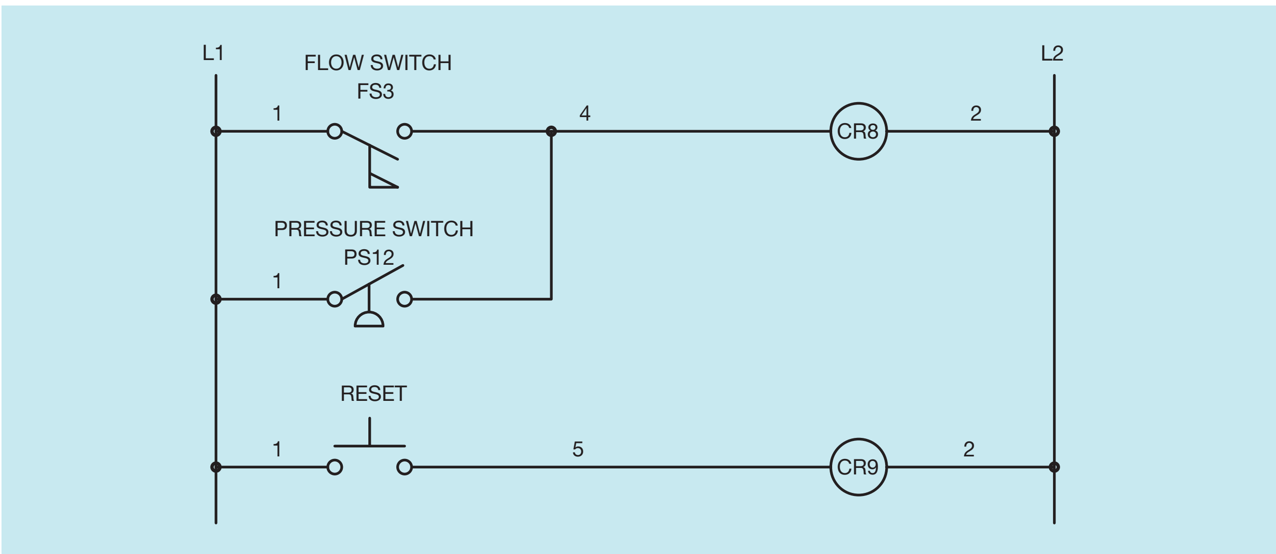


Figure 37–2 Part of a typical ladder or schematic diagram.

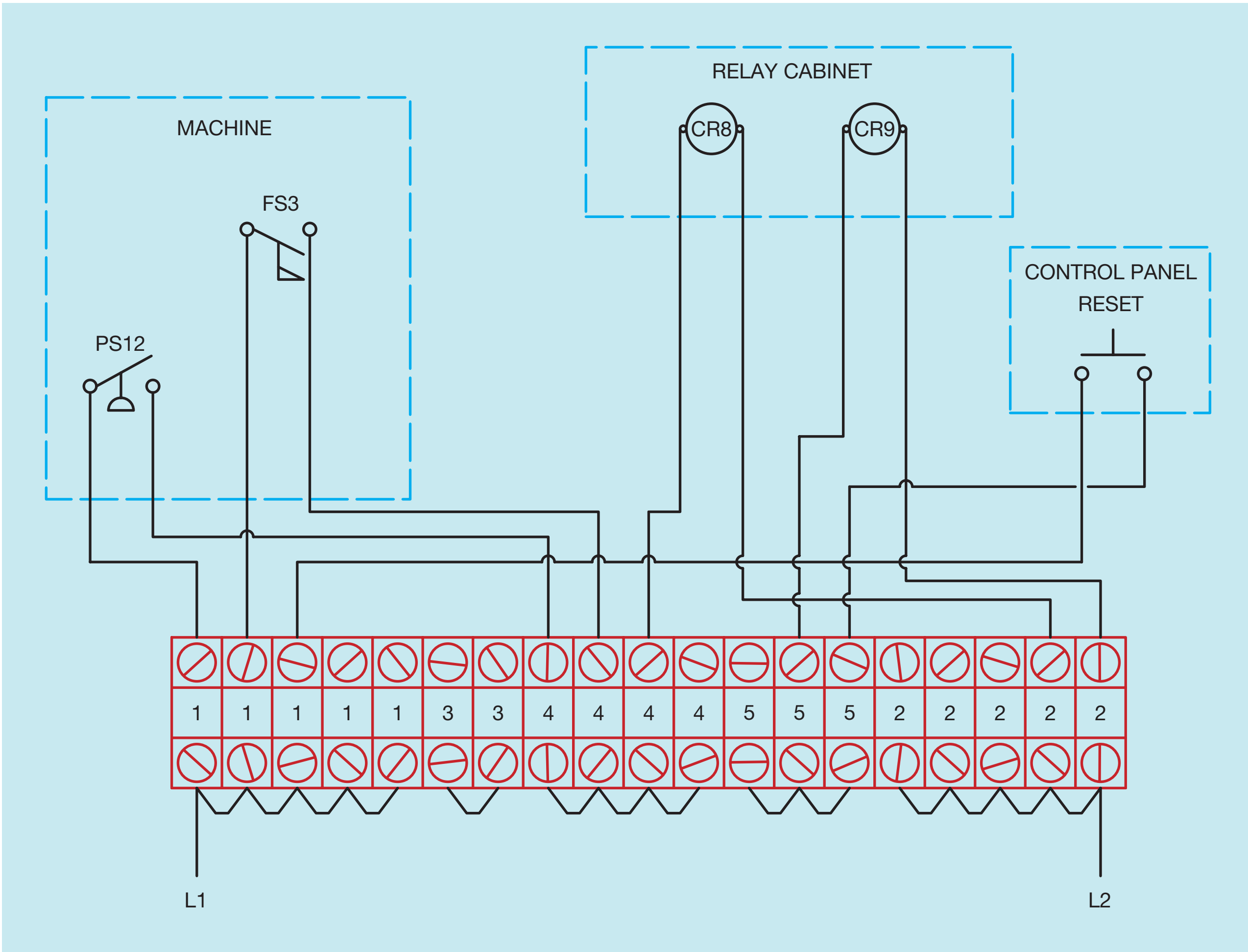


Figure 37–3 Typical connections using a terminal strip.

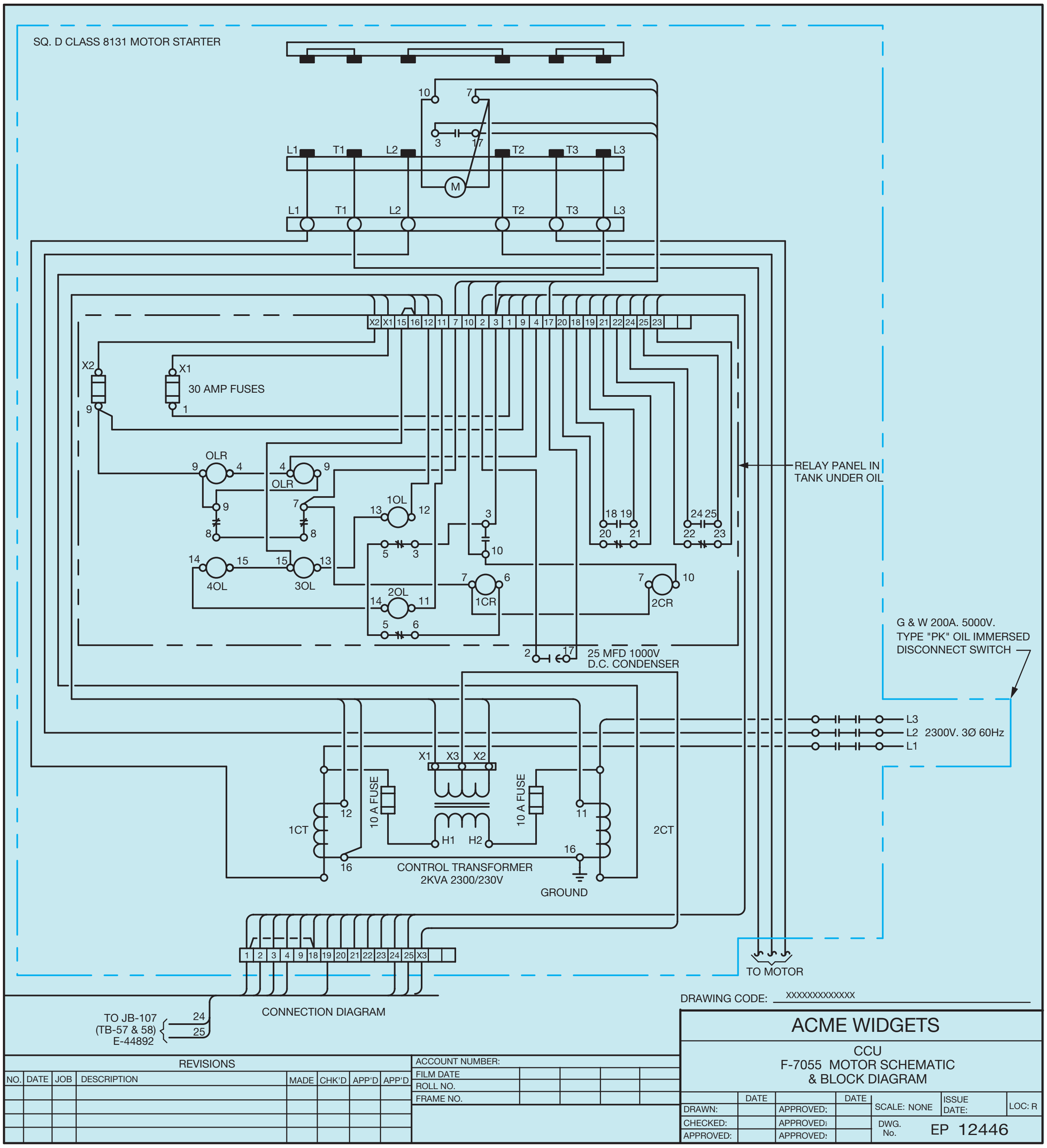


Figure 37–4 Industrial diagram showing terminal block connections.

Review Questions

1. Define a schematic diagram.
2. Define a wiring diagram.
3. Are symbols in a schematic shown in their energized or de-energized condition?
4. Draw the standard NEMA symbol for the following components.
   A. Float switch (NO)
   B. Limit switch (NC)
   C. Normally open push button
   D. Relay coil
   E. Overload contact
5. You are an electrician working in an industrial plant. Your job is to connect the components shown in Figure 37–3 to the terminal strip. Should switch FS3 be connected normally open or normally closed? Explain your answer.
6. Should switch PS12 be connected normally open or normally closed? Explain your answer.

Section 4

BASIC CONTROL CIRCUITS

UNIT 38
HAND-OFF AUTOMATIC CONTROLS

OBJECTIVES

After studying this unit, the student will be able to:

- State the purpose of hand-off-automatic controls.
- Connect hand-off-automatic controls.
- Read and draw diagrams using hand-off-automatic controls.

Hand-off-automatic switches are used to select the function of a motor controller either manually or automatically. This selector switch may be a separate unit or built into the starter enclosure cover. A typical control circuit using a single-break selector switch is shown in Figure 38–1.

With the switch turned to the HAND (manual) position, coil (M) is energized all the time and the motor runs continuously. In the OFF position, the motor does not run at all. In the AUTOMATIC position, the motor runs whenever the two-wire control device is closed. An operator does not need to be present. The control device may be a pressure switch, limit switch, thermostat, or other two-wire control pilot device.

The heavy-duty, three-position double-break selector switch shown in Figure 38–2 is also used for manual and automatic control. When the switch is turned to "hand," the coil is energized, by-passing the automatic control device in the "auto" position.

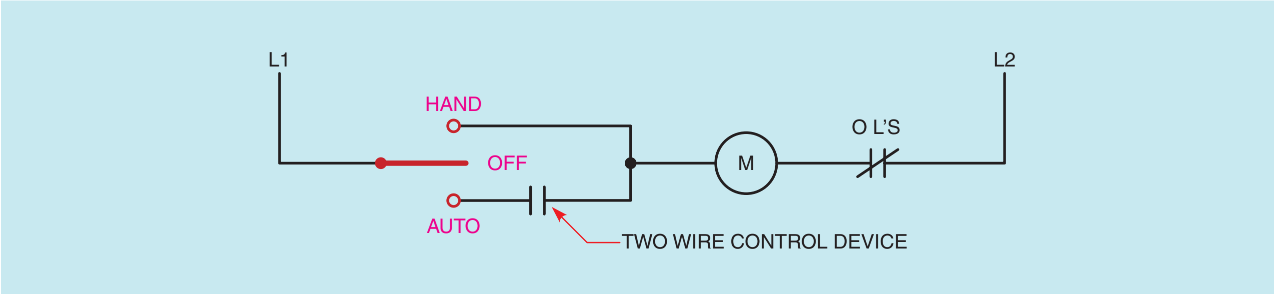


Figure 38–1 Standard duty, three-position selector switch in control circuit.

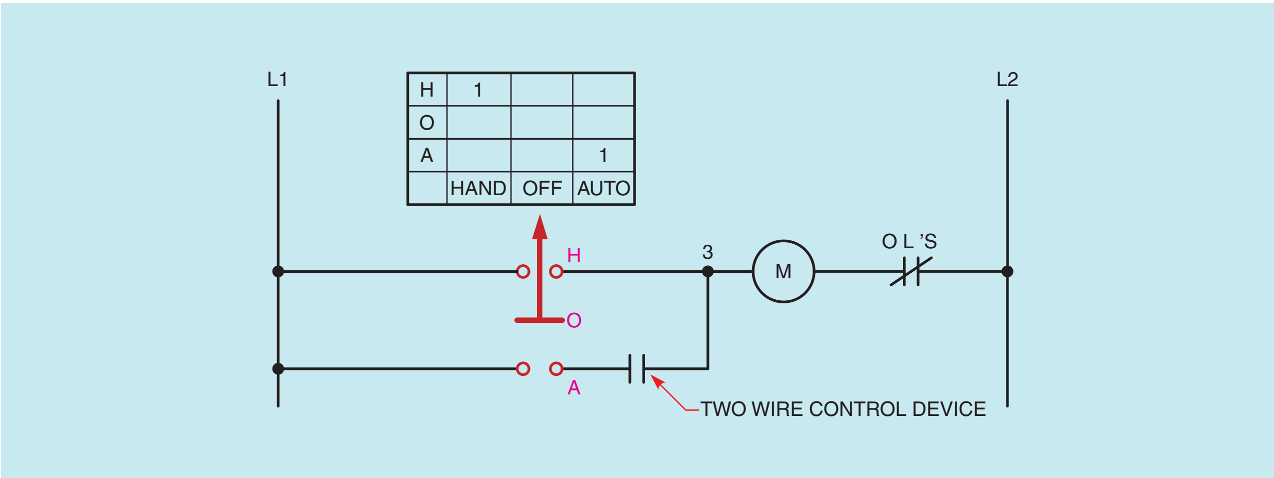


Figure 38–2 Diagram of a heavy duty, three-position selector switch in control circuit.

Review Questions

1. A selector switch and two-wire pilot device cannot be used to control a large motor directly, but rather must be connected to a magnetic starter. Explain why this is true.
2. Determine the minimum number of wires in each conduit shown in Figure 38–3.
3. Complete Figure 38–4 to show the wiring diagram of the hand-off-automatic selector switch, pull box, pressure switch and L1 and coil M.

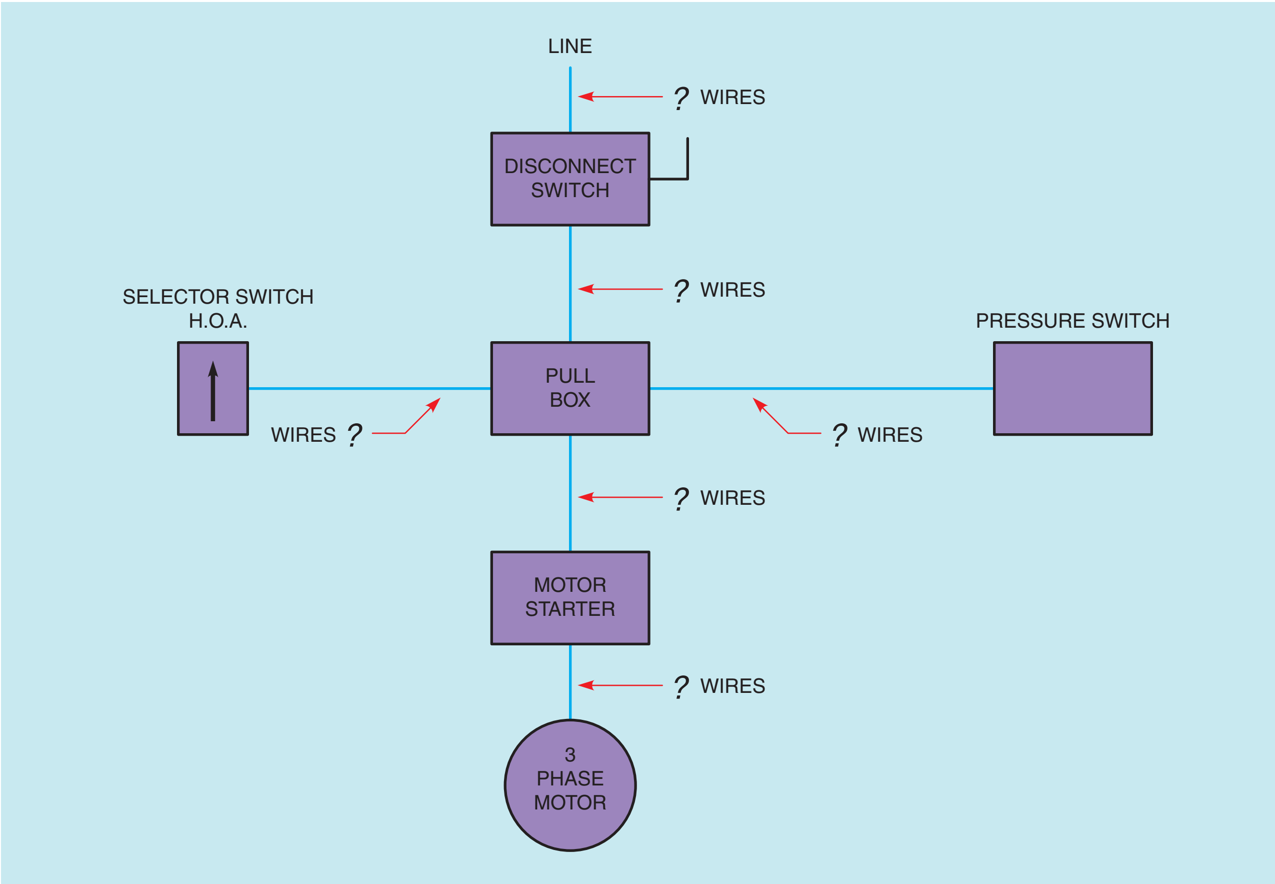


Figure 38–3

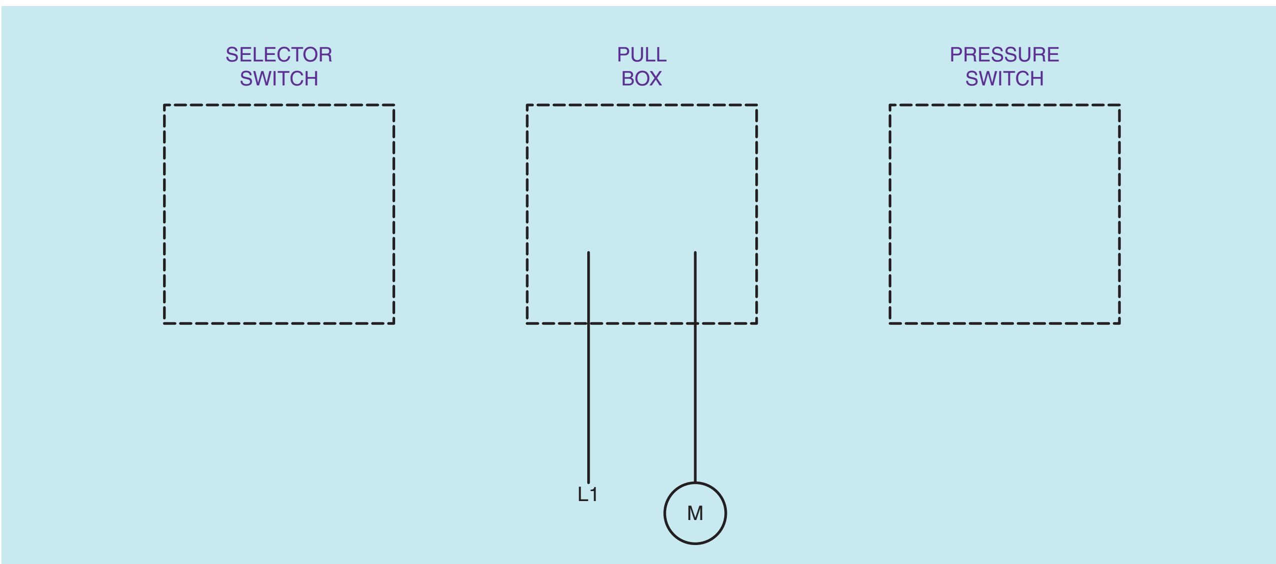


Figure 38–4

UNIT 39

MULTIPLE PUSH-BUTTON STATIONS

OBJECTIVES

After studying this unit, the student will be able to:

- Read and interpret diagrams using multiple push-button stations.
- Draw diagrams using multiple push-button stations.
- Connect multiple push-button stations.

The conventional three-wire, push-button control circuit may be extended by the addition of one or more push-button control stations. The motor may be started or stopped from a number of separate stations by connecting all start buttons in parallel and all stop buttons in series. The operation of each station is the same as that of the single push-button control in the basic three-wire circuit covered in unit 29. Note in Figure 39–1 that pressing any stop button de-energizes the coil. Pressing any start button energizes the coil.

When a motor must be started and stopped from more than one location, any number of start and stop buttons may be connected. Another possible arrangement is to use only one start-stop station and several stop buttons at different locations to serve as emergency stops.

Multiple push-button stations are used to control conveyor motors on large shipping and receiving freight docks.

Review Questions

1. Using the line diagram in Figure 39–2, determine the number of wires controlling the three-phase motor. The conduit layout plan indicates the sections of conduit for which the quantity of wires is to be determined.
2. Referring to Figure 39–2, select the proper wire size for the motor and conduit size for each run. The control wiring is 14 AWG stranded copper. Although local codes supersede the *National Electrical Code*® (*NEC*®), the calculations in this problem are to be done with the *National Electrical Code*®. The motor in this example is 30 hp, operates on 480 V 3θ, and has a NEMA code B. The conductors are copper with type THHW insulation. They are used in an area with an ambient temperature of 30°C or 86°F. The raceway is to be EMT (Electrical Metallic Tubing).

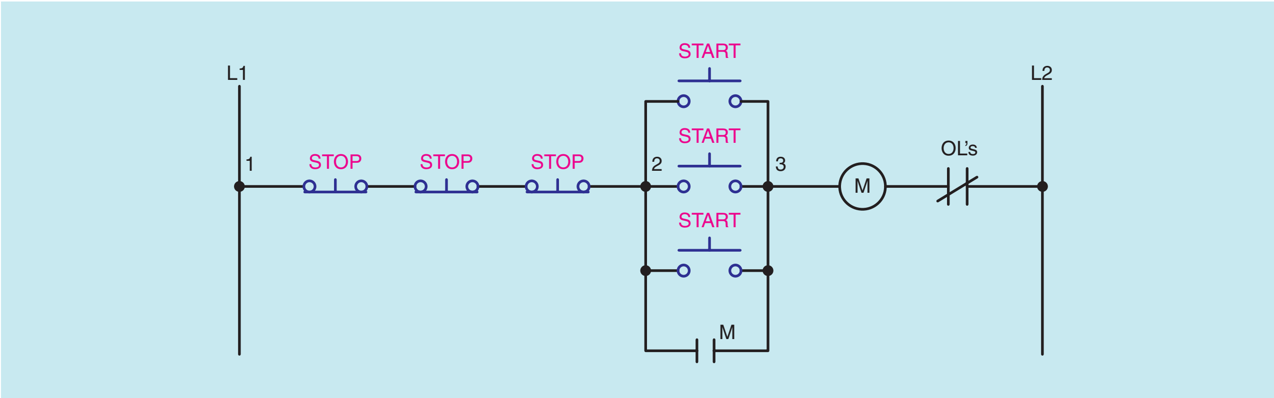


Figure 39–1 Three-wire control using a momentary contact, multiple push-button station.

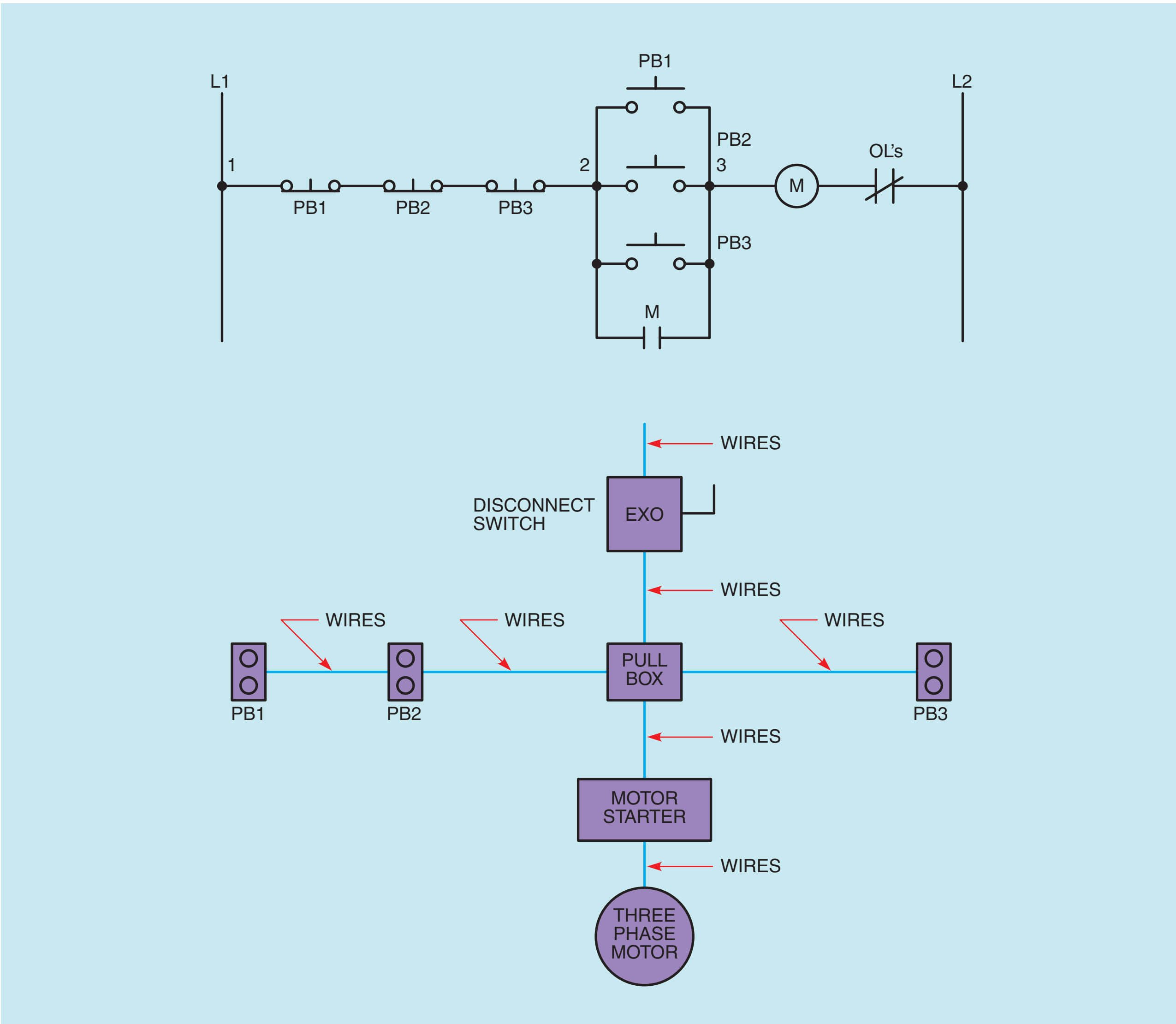


Figure 39–2

UNIT 40

INTERLOCKING METHODS FOR REVERSING CONTROL

OBJECTIVES

After studying this unit, the student will be able to:

- Explain the purpose of the various interlocking methods.
- Read and interpret wiring and line diagrams of reversing controls.
- Read and interpret wiring and line diagrams of interlocking controls.
- Wire and troubleshoot reversing and interlocking controls.

The direction of rotation of three-phase motors can be reversed by interchanging any two motor leads to the line. If magnetic control devices are to be used, then reversing starters accomplish the reversal of the motor direction (Figure 40–1A). Reversing starters wired to NEMA standards interchange lines L1 and L3 (Figure 40–1B). To do this, two contactors for the starter assembly are required—one for the forward direction and one for the reverse direction (Figure 40–1C). A technique called *interlocking* is used to prevent the contactors from being energized simultaneously or closing together and causing a short circuit. There are three basic methods of interlocking.

Mechanical Interlock

A mechanical interlocking device is assembled at the factory between the forward and reverse contactors. This interlock locks out one contactor at the beginning of the stroke of either contactor to prevent short circuits and burnouts.

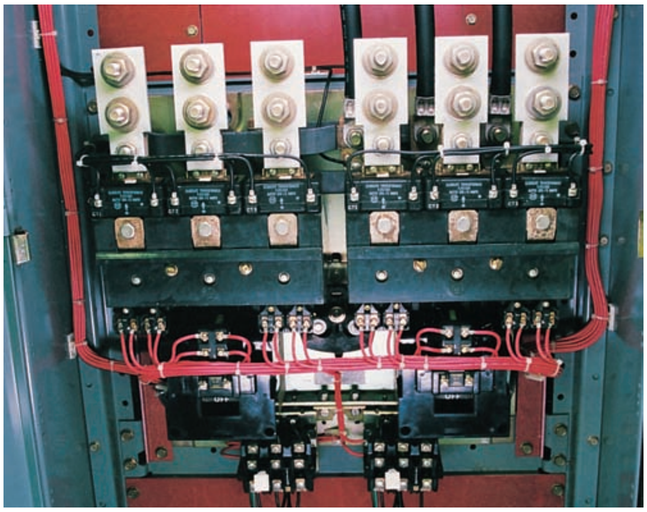


Figure 40–1A Horizontal mount size 5 reversing starter. Note the use of current transformers on each starter. The output of the transformers are connected to the overload heaters.

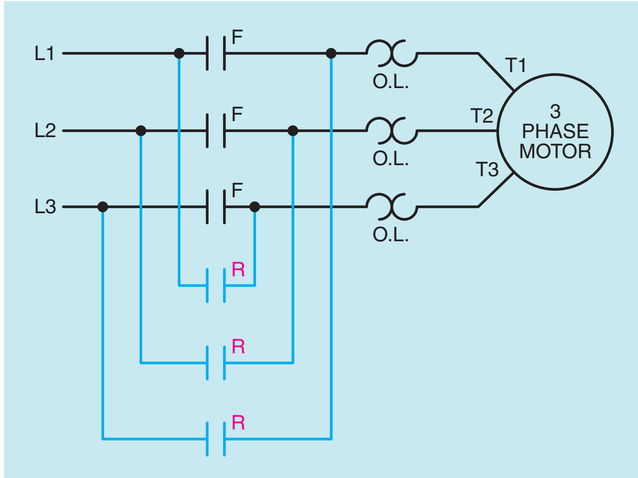


Figure 40–1C Elementary diagram of a reversing starter power circuit.

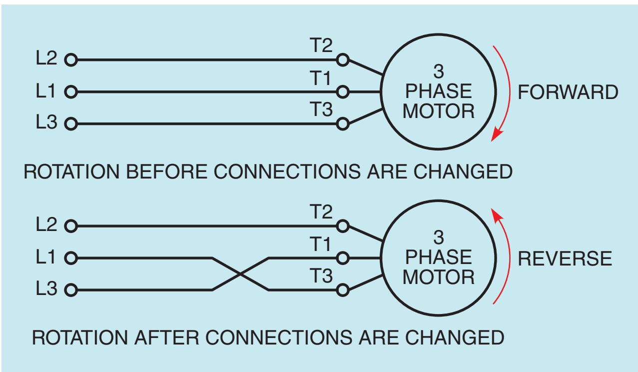


Figure 40–1B Reversing rotation of an induction motor.

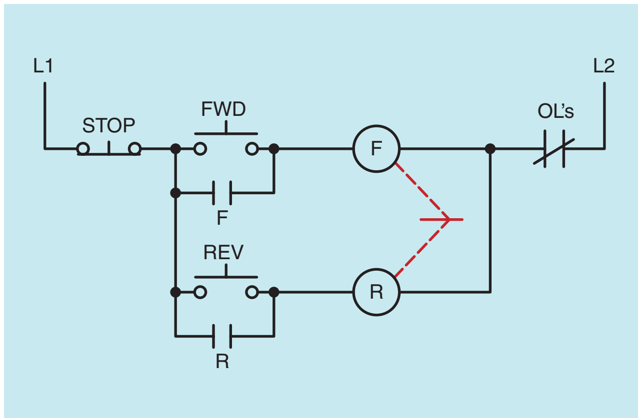


Figure 40–2 Mechanical interlock between the coils prevents the starter from closing all contacts simultaneously. Only one contactor can close at a time.

The mechanical interlock between the contactors is represented in the elementary diagram of Figure 40–2 by the broken line between the coils. The broken line indicates that coils F and R cannot close contacts simultaneously because of the mechanical interlocking action of the device.

When the forward contactor coil (F) is energized and closed through the forward push button, the

mechanical interlock prevents the accidental closing of coil R. Starter F is blocked by coil R in the same manner. The first coil to close moves a lever to a position that prevents the other coil from closing its contacts when it is energized. If an oversight allows the second coil to remain energized without closing its contacts, the excess current in the coil due to the lack of the proper inductive reactance will damage the coil.

Note in the elementary diagram of Figure 40–2 that the stop button must be pushed before the motor can be reversed.

Reversing starters are available in horizontal and vertical construction (Figure 40–3A).

A mechanical interlock is installed on the majority of reversing starters in addition to the use of one or both of the following electrical methods: push-button interlock and auxiliary contact interlock.

Push-Button Interlock

Push-button interlocking is an *electrical method* of preventing both starter coils from being energized simultaneously.

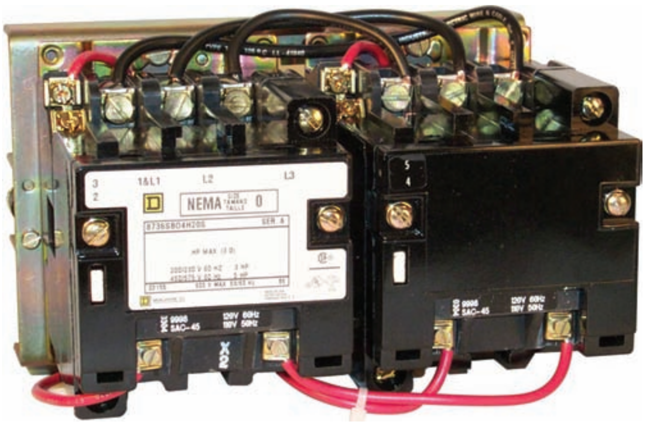


Figure 40–3A Horizontally mounted reversing starters without overload relay. (Courtesy Square D Company.)

When the forward button in Figure 40–3B is pressed, coil F is energized and the normally open (NO) contact F closes to hold in the forward contactor. Because the normally closed (NC) contacts are used in the forward and reverse push-button units, there is no need to press the stop button before changing the direction of rotation. If the reverse button is pressed while the motor is running in the forward direction, the forward control circuit is de-energized and the reverse contactor is energized and held closed.

Repeated reversals of the direction of motor rotation are not recommended. Such reversals may cause the overload relays and starting fuses to overheat; this disconnects the motor from the circuit. The driven machine may be damaged also. It may be necessary to wait until the motor has coasted to a standstill.

NEMA specifications call for a starter to be derated. That is, the next size larger starter must be selected when it is to be used for "plugging" to stop, or "reversing" at a rate of more than five times per minute.

Reversing starters consisting of mechanical and electrical interlocked devices are preferred for maximum safety.

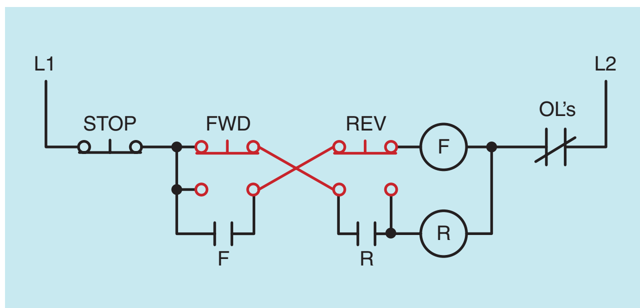


Figure 40–3B Double-circuit push buttons are used for push-button interlocking.

Auxiliary Contact Interlock

Another method of electrical interlock consists of normally closed auxiliary contacts on the forward and reverse contactors of a reversing starter (Figure 40–4).

When the motor is running forward, an NC contact (F) on the forward contactor opens and prevents the reverse contactor from being energized by mistake and by closing. The same operation occurs if the motor is running in reverse.

The term *interlocking* is also used generally when referring to motor controllers and control stations that are interconnected to provide control of production operations.

To reverse the direction of rotation of single-phase motors, *either* the starting *or* running winding motor leads are interchanged, but not both. Figure 40–5A completes the wiring diagram for the single-phase, four-wire, split phase induction motor; Figure 40–5B is a wiring diagram for a single-phase vertical starter; and Figure 40–5C is a line diagram of the connections.

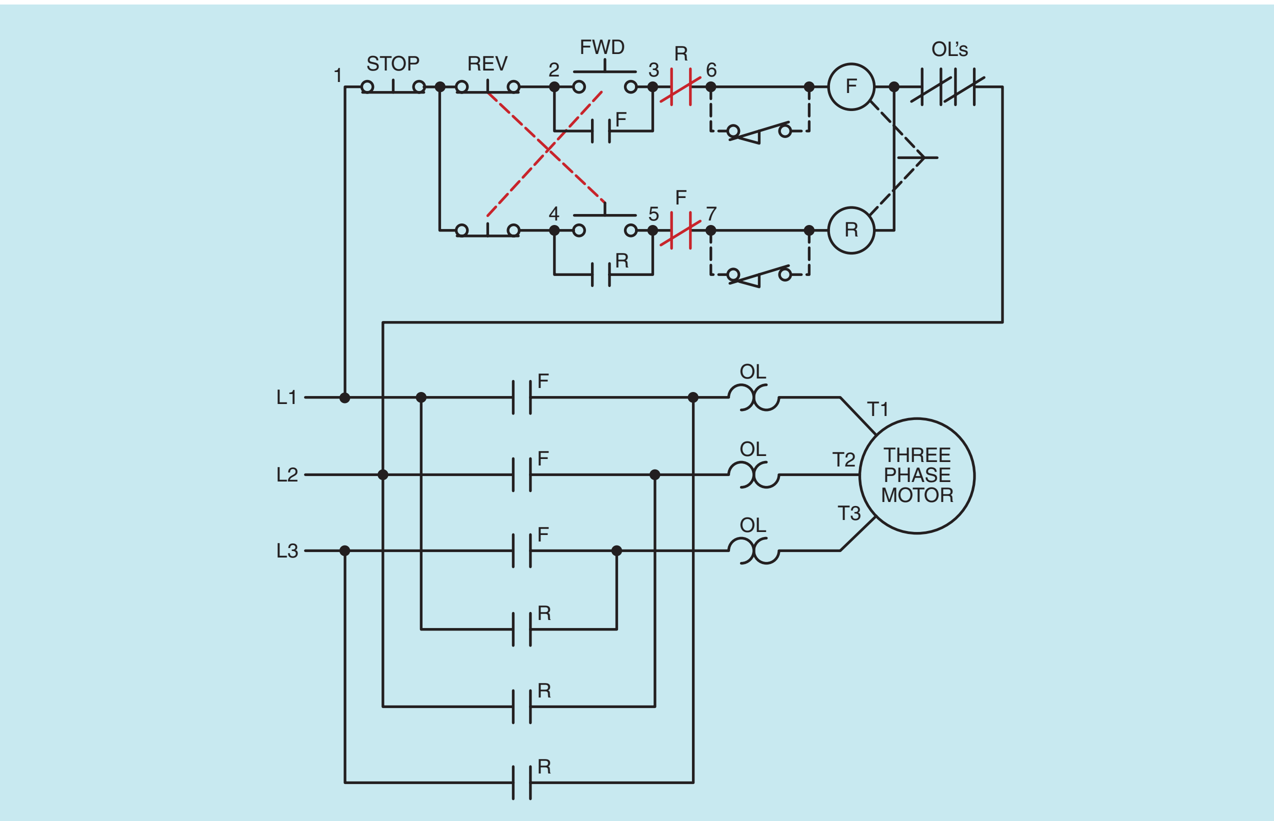


Figure 40–4 Elementary diagram of the reversing starter shown in Figure 40–1A. The mechanical push button and auxiliary contact interlocks are indicated.

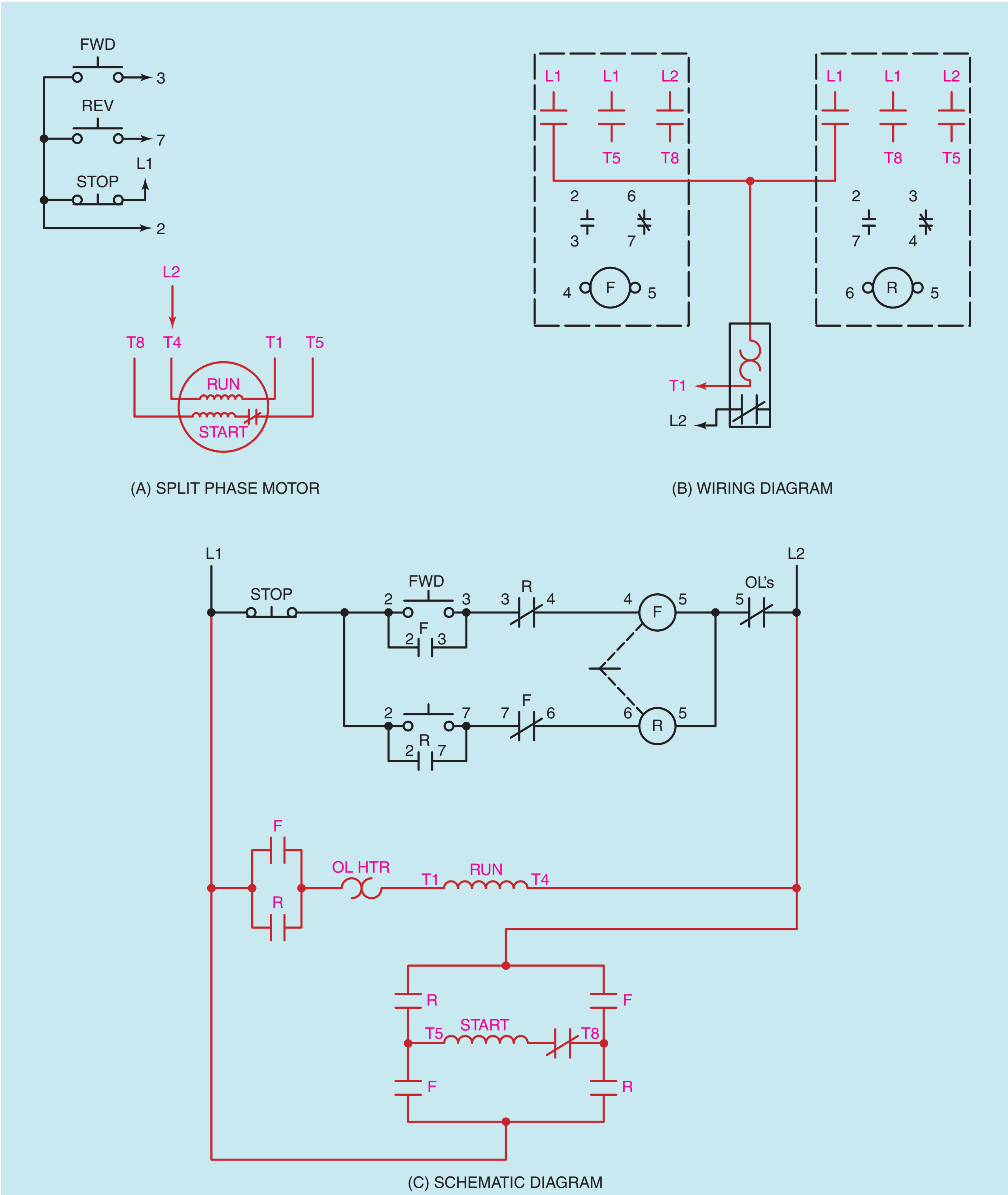


Figure 40–5 Sizes 0 and 1 reversing starters used with single split-phase induction motors.

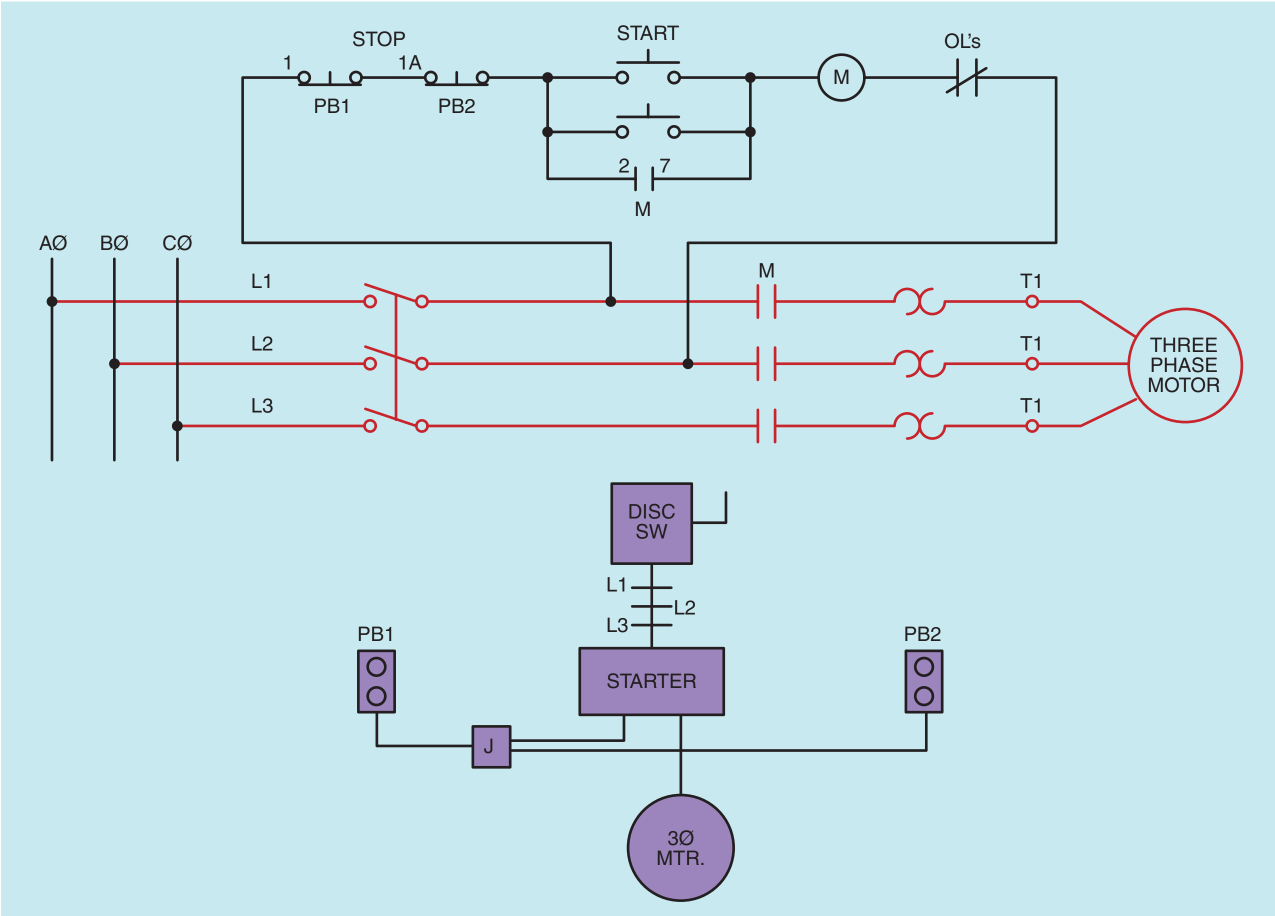
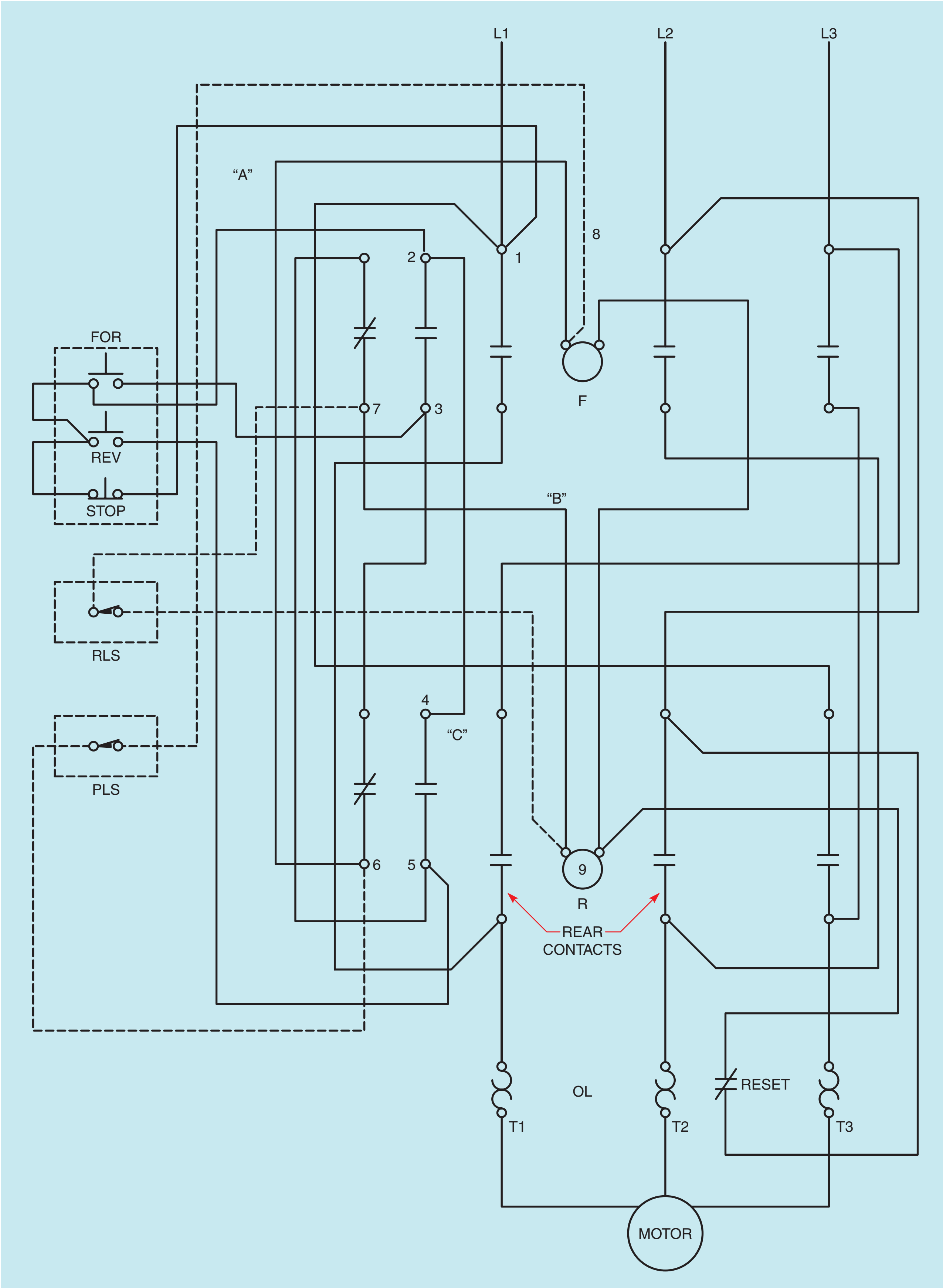


Figure 40–6

Review Questions

1. How is a change in the direction of rotation of a three-phase motor accomplished?
2. What is the purpose of interlocking?
3. What will happen if both start buttons are pushed in a control with push-button interlocking? Why?
4. How is auxiliary contact interlocking obtained on a reversing starter?
5. When the forward coil is energized, in what position is the forward interlock (F)?
6. If a mechanical interlock is the only means of interlocking used, describe the operation that must be followed to reverse the direction of rotation of the motor while running.
7. If pilot lights are to indicate the direction of rotation of a motor, where should the devices be connected so as not to add any contacts?
8. What is the sequence of the operations if limit switches are used in Figure 40–4?
9. What will happen in Figure 40–4 if limit switches are installed and the jumpers from terminals 6 and 7 to the coils are not removed?
10. In place of the push buttons in Figure 40–2, draw a selector switch for forward-reverse-stop control. Show the target table for this selector switch.
11. From the elementary drawing in Figure 40–6, determine the number and terminal identification of the wiring in each conduit in the conduit layout. Indicate your solutions in the same manner as the example given below the disconnect switch.
12. Convert the control circuit only (Figure 40–7) from the wiring diagram to an elementary diagram. Include the limit switches (RLS, FLS) as operating in the control circuit.



L1
L2
L3
"A"
8
2
1
FOR
7
3
F
REV
STOP
"B"
RLS
PLS
4
"C"
6
5
9
R
REAR
CONTACTS
OL
RESET
T1
T2
T3
MOTOR

Figure 40–7

UNIT 41
SEQUENCE CONTROL

OBJECTIVES

After studying this unit, the student will be able to:

- Describe the purpose of starting motors in sequence.
- Read and interpret sequence control diagrams.
- Make the proper connections to operate motors in sequence.
- Troubleshoot sequence motor control circuits.

Sequence control is the method by which starters are connected so that one cannot be started until the other is energized. This type of control is required whenever the auxiliary equipment associated with a machine, such as high-pressure lubricating and hydraulic pumps, must be operating before the machine itself can be operated safely. Another application of sequence control is in main or subassembly line conveyors.

The proper push-button station connections for sequence control are shown in Figure 41–1. Note that the control circuit of the second starter is wired through the maintaining contacts of the first starter. As a result, the second starter is prevented from starting until after the first starter is energized. If standard starters are used, the connection wire (X) must be removed from one of the starters.

If sequence control is to be provided for a series of motors, the control circuits of the additional starters can be connected in the manner shown in Figure 41–2. That is, M3 will be connected to M2 in the same step arrangement by which M2 is connected to M1.

The stop button or an overload on any motor will stop all motors with this method.

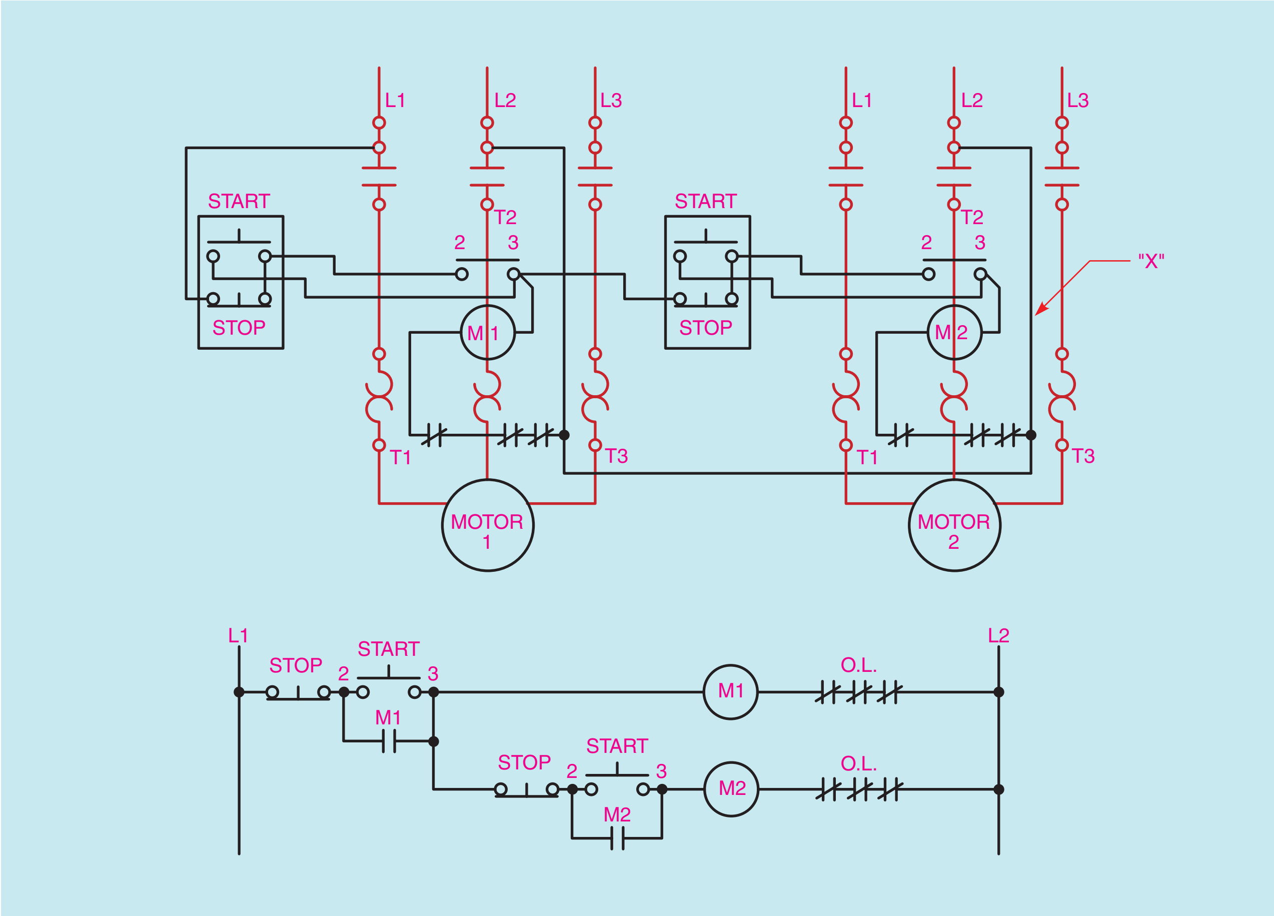


Figure 41–1 Standard starters wired for sequence control. (Courtesy Allen-Bradley Co.)

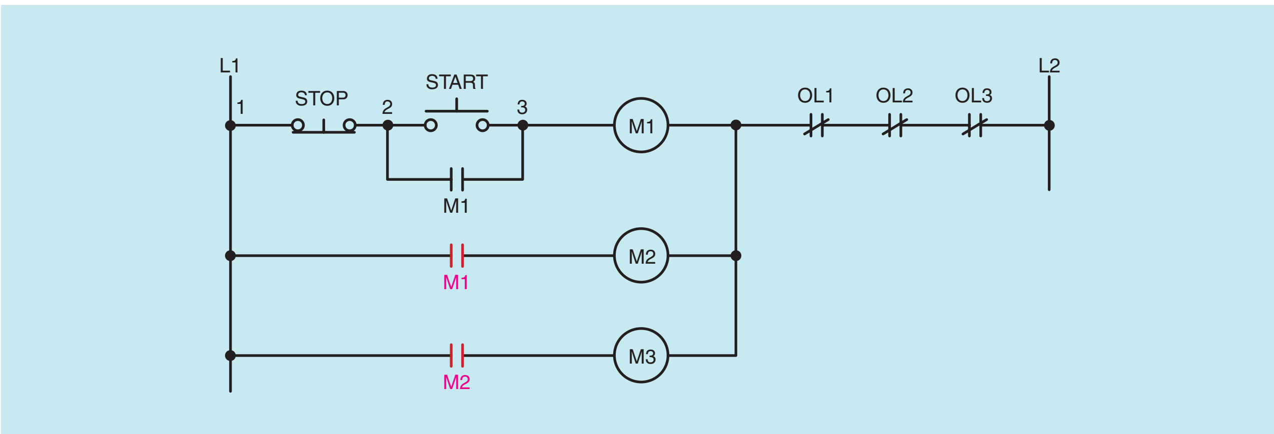


Figure 41–2 Auxiliary contacts (or interlocks) used for automatic sequence control. Contact M1 energizes coil M2; contact M1 energizes coil M3.

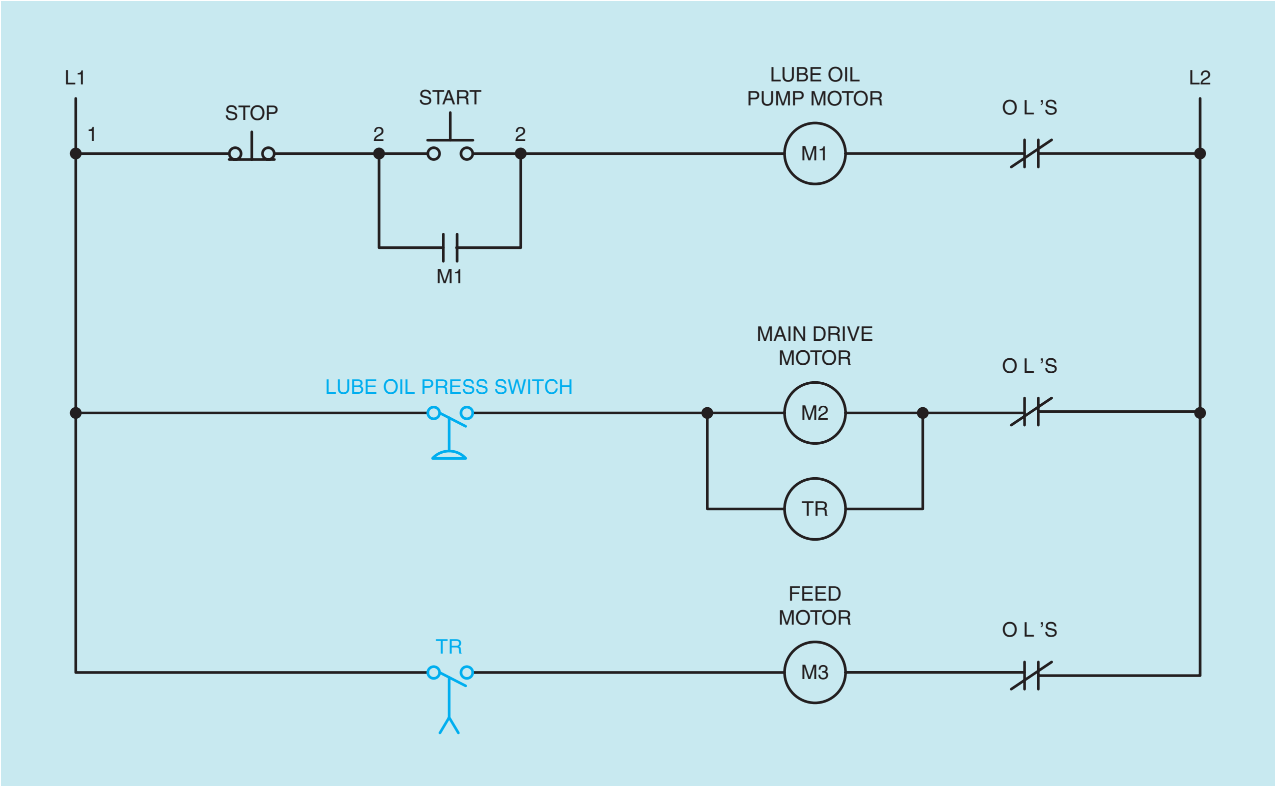


Figure 41–3 Pilot devices used in an automatic sequence control scheme.

Automatic Sequence Control

A series of motors can be started automatically with only one start-stop control station as shown in Figures 41–2 and 41–3. When the lube oil pump, (M1) in Figure 41–3, is started by pressing the start button, the pressure must be built up enough to close the pressure switch before the main drive motor (M2) will start. The pressure switch also energizes a timing relay (TR). After a preset time delay, the contact (TR) will close and energize the feed motor starter coil (M3).

If the main drive motor (M2) becomes overloaded, the starter and timing relay (TR) will open. As a result, the feed motor circuit (M3) will be de-energized due to the opening of the contact (TR). If the lube oil pump motor (M1) becomes overloaded, all the motors will stop. Practically any desired overload control arrangement is possible. A motor starter with an overload relay is shown in Figure 41–4.

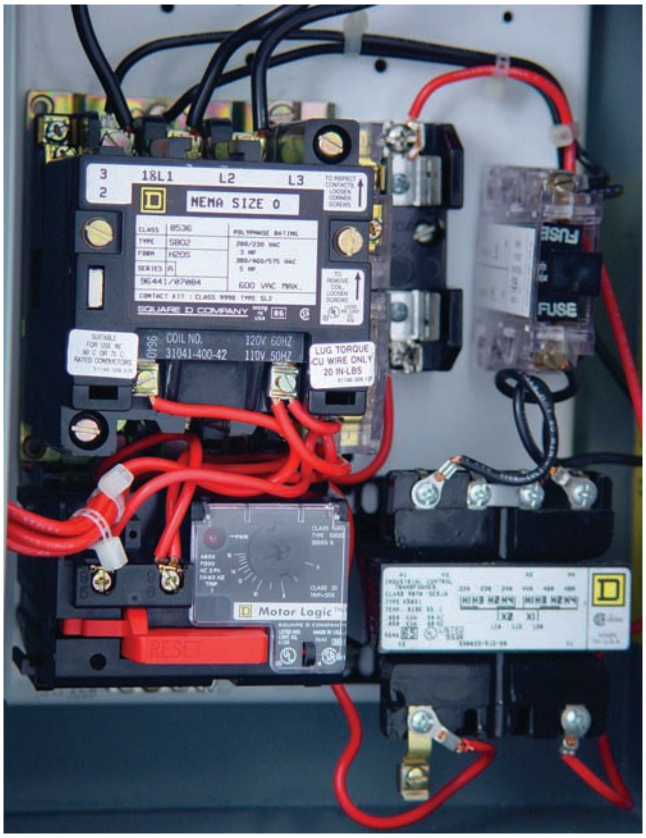


Figure 41–4 Motor starter with overload relay. (Courtesy Square D Company.)

Review Questions

1. Describe what is meant by sequence control.
2. Referring to the diagram in Figure 41–2, explain what will happen if the motor controlled by coil (M1) becomes overloaded.
3. In Figure 41–2, what will happen if there is an overload on the motor controlled by starter (M2)?
4. What is the sequence of operation in Figure 41–2?
5. Redraw Figure 41–3 so that if the feed motor (M3) is tripped out because of overload, it will also stop the main drive motor (M2).

UNIT 42

JOGGING (INCHING) CONTROL CIRCUITS

OBJECTIVES

After studying this unit, the student will be able to:

- Define the process of jogging control.
- State the purpose of jogging controllers.
- Describe the operation of a jogging control circuit using a control relay.
- Describe the operation of a jogging control using a control relay on a reversing starter.
- Describe the operation of a jogging control using a selector switch.
- Connect jogging controllers and circuits.
- Recommend solutions for troubleshooting jogging controllers.

Jogging, or *inching,* is defined by the National Electrical Manufacturers' Association (NEMA) as "the quickly repeated closure of a circuit to start a motor from rest for the purpose of accomplishing small movements of the driven machine." The term *jogging* is often used when referring to across-the-line starters; the term *inching* can be used to refer to reduced voltage starters. Generally, the terms are used interchangeably because they both prevent a holding circuit.

Jogging Control Circuits

The control circuits covered in this unit are representative of the various methods that are used to obtain jogging.

Figure 42–1 is a line diagram of a very simple jogging control circuit. The STOP button is held open mechanically, Figure 42–2. With the STOP button

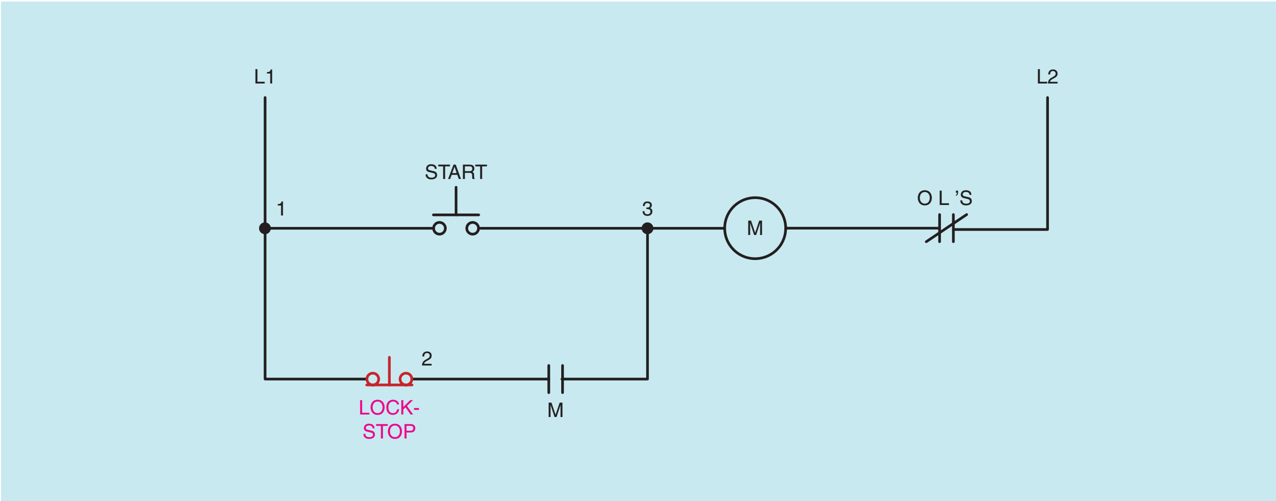


Figure 42–1 LOCK-STOP push button in jogging circuit.

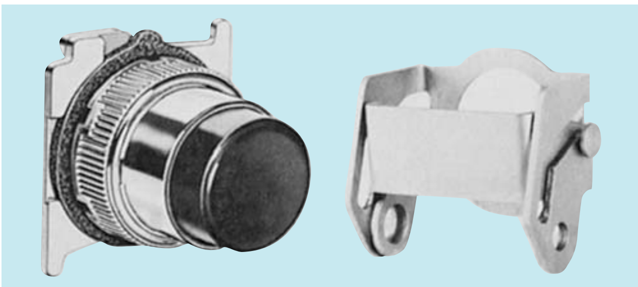


Figure 42–2 Oiltight push-button operator with extra long button to accept padlock attachment (on right) to provide lockout-on-stop feature. (Courtesy Eaton Corp., Cutler-Hammer Products.)

held open, maintaining contact M cannot hold the coil energized after the start button is closed. The disadvantage of a circuit connected in this manner is the loss of the lock-stop safety feature. This circuit can be mistaken for a conventional three-wire control circuit, locked off for safety reasons, such as to keep a circuit or machine from being energized. A padlock should be installed for safety purposes. If the LOCK-STOP push button is used for jogging, it should be clearly marked for this purpose.

Figure 42–3 illustrates other simple schemes for jogging circuits. The normally closed push-button contacts on the JOG button in Figure 42–3B are connected in series with the holding circuit contact on the magnetic starter. When the JOG button is pressed, the normally open contacts energize the starter magnet. At the same time, the normally closed contacts disconnect the holding circuit. When the button is released, therefore, the starter immediately opens to disconnect the motor from the line. The action is similar in Figure 42–3A. A *jogging attachment can be used to prevent the reclosing of the normally closed contacts of the JOG button.* This device assures that the starter holding circuit is not re-established if the JOG button is released too rapidly. Jogging can be repeated by reclosing the JOG button; it can be continued until the jogging attachment is removed.

CAUTION: If the circuits shown in Figure 42–4 are used without the jogging attachment mentioned, they are hazardous. A control station using such a circuit, less a jogging attachment, can maintain the circuit when the operator's finger is quickly removed from the button. This could injure production workers, equipment, and machinery. This circuit should not be used by responsible people committed to safety in the electrical industry.

Jogging Using a Control Relay

When a jogging circuit is used, the starter can be energized only as long as the JOG button is depressed. This

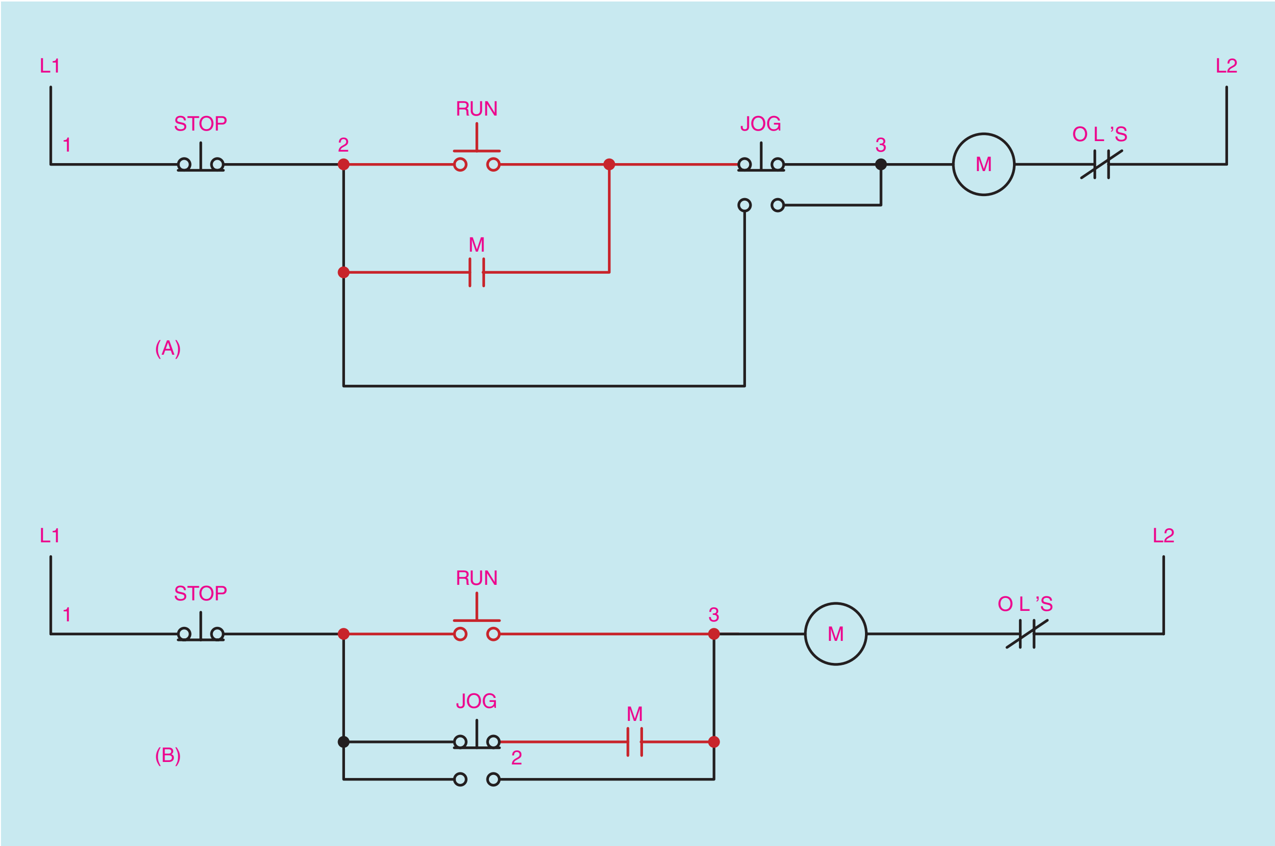


Figure 42–3 Line diagrams of simple jogging control circuits.

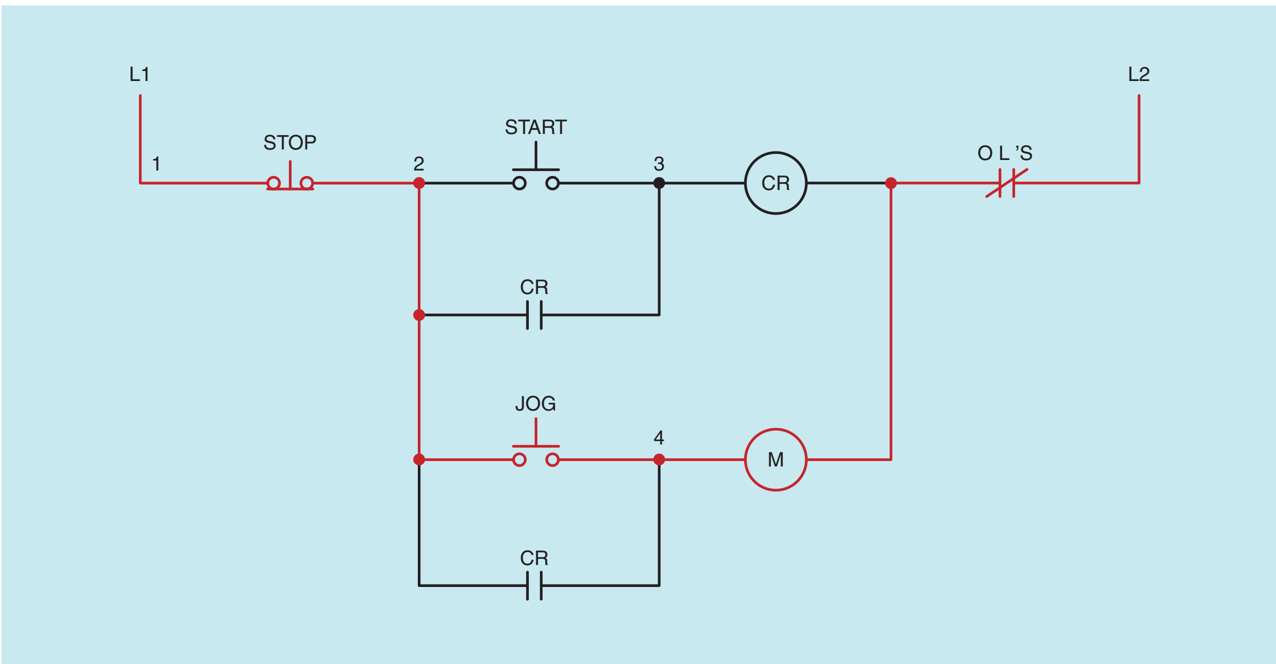


Figure 42–4 Jogging is achieved with added use of control relay.

means the machine operator has instantaneous control of the motor drive.

The addition of a control relay to a jogging circuit provides even greater control of the motor drive. A control relay jogging circuit is shown in Figure 42–4. When the START button is pressed, the control relay is energized and a holding circuit is formed for the control relay and the starter magnet. The motor will now run. The JOG button is connected to form a circuit to the starter magnet. This circuit is independent of the control relay. As a result, the JOG button can be pressed to obtain the jogging or inching action.

Other typical jogging circuits using control relays are shown in Figure 42–5. In Figure 42–5A,

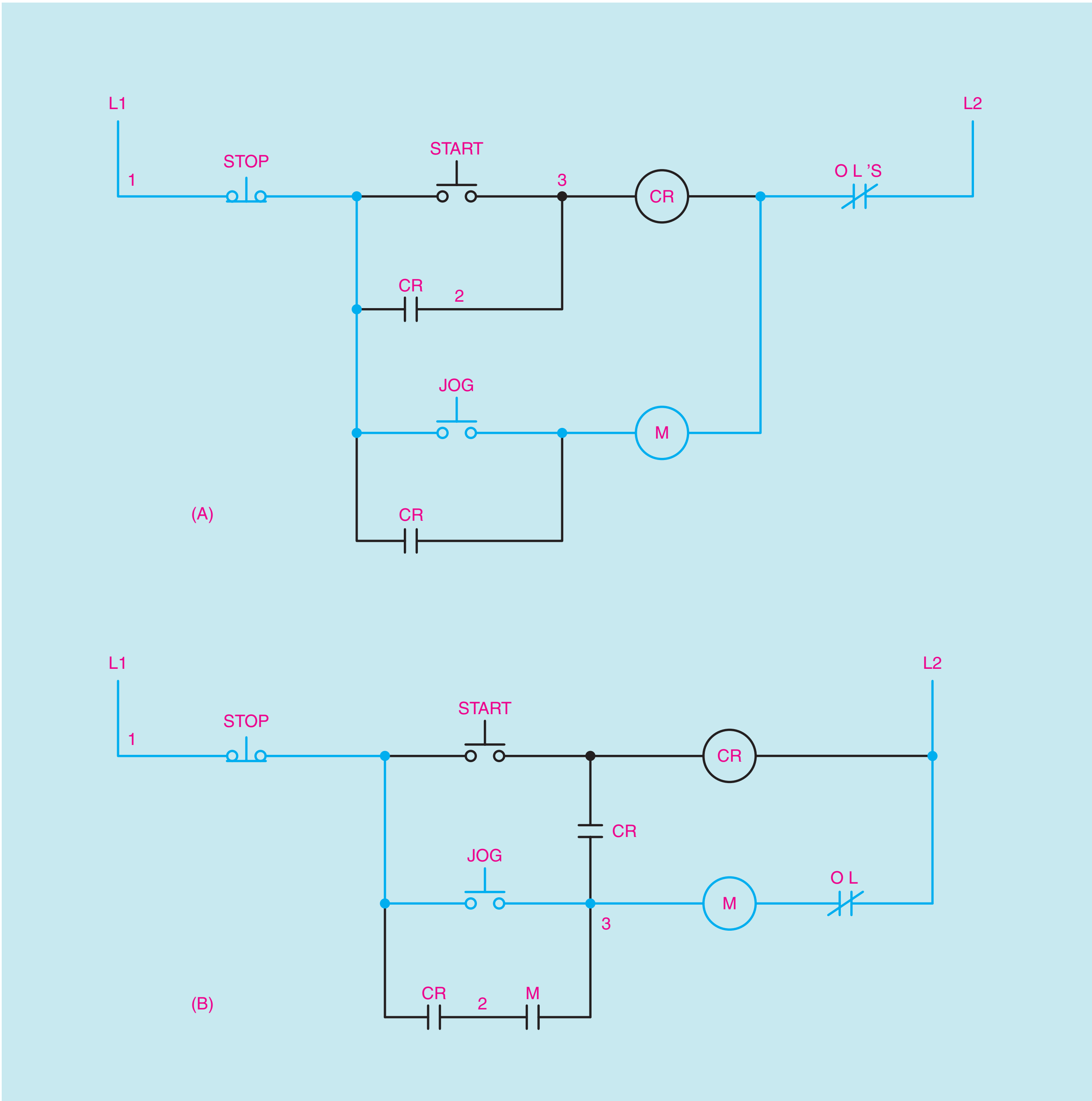


Figure 42–5 Line diagrams using control relays in typical installations.

pressing the START button energizes the control relay. In turn, the relay energizes the starter coil. The normally open starter interlock and relay contact then form a holding circuit around the START button. When the JOG button is pressed, the starter coil is energized independently of the relay and a holding circuit does not form. As a result, a jogging action can be obtained.

Jogging with a Control Relay on a Reversing Starter

The control circuit shown in Figure 42–6 permits the motor to be jogged in either the forward or the reverse direction while the motor is at standstill or is rotating in either direction. Pressing either the START-FORWARD button or the START-REVERSE button causes the corresponding starter coil to be energized. The coil then closes the circuit to the control relay, which picks up and completes the holding circuit around the START button. While the relay is energized, either the forward or the reverse starter will also remain energized. If either JOG button is pressed, the relay is de-energized and the closed starter is released. Continued pressing of either JOG button results in a jogging action in the desired direction.

Jogging with a Selector Switch

The use of a selector switch in the control circuit to obtain jogging requires a three-element control station with start and stop controls and a selector switch. A standard duty, two-position selector switch is shown connected in the circuit in Figure 42–7. The starter maintaining circuit is disconnected when the selector switch is placed in the JOG position. The motor is then inched with the start button. Figure 42–8 is the same

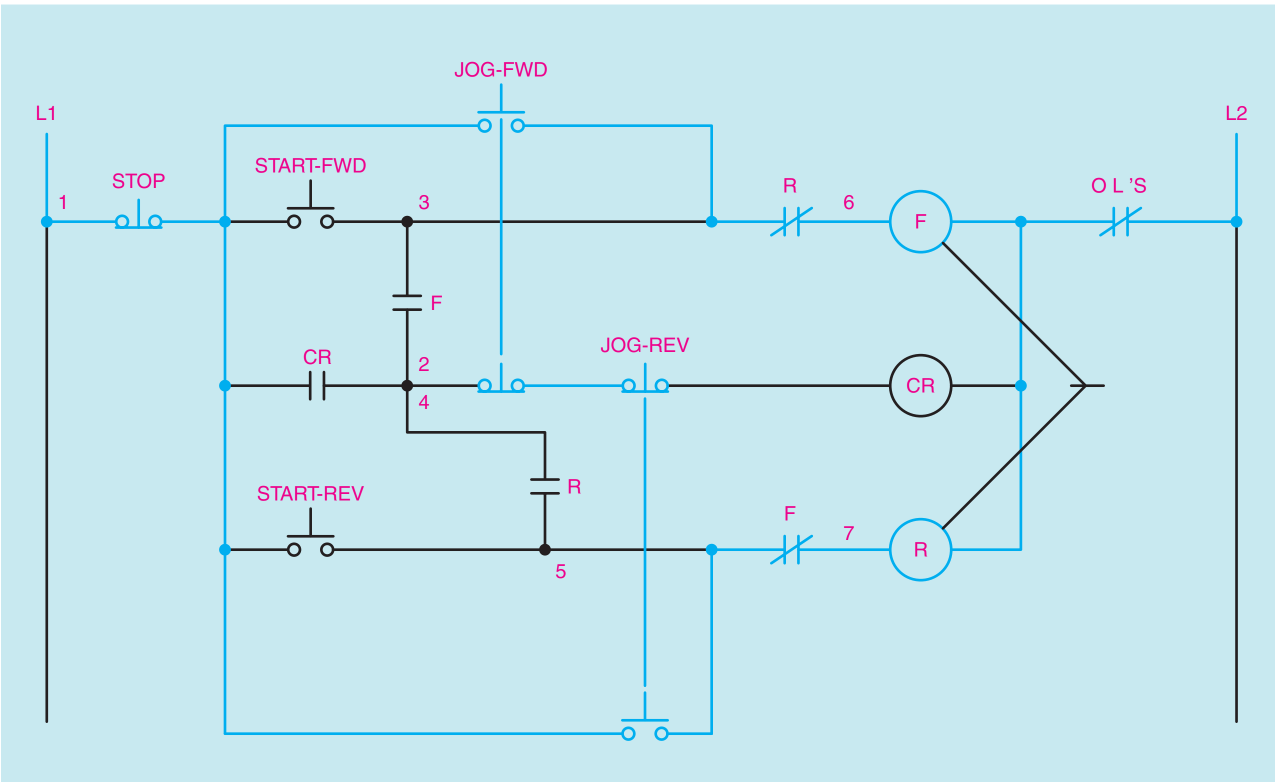


Figure 42–6 Jogging using control relay on a reversing starter.

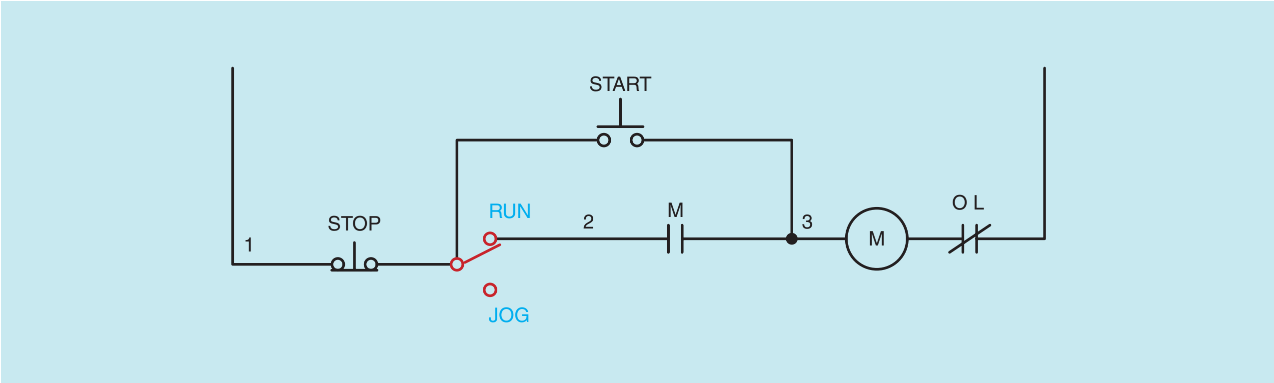


Figure 42–7 Jogging using a standard duty, two-position selector switch.

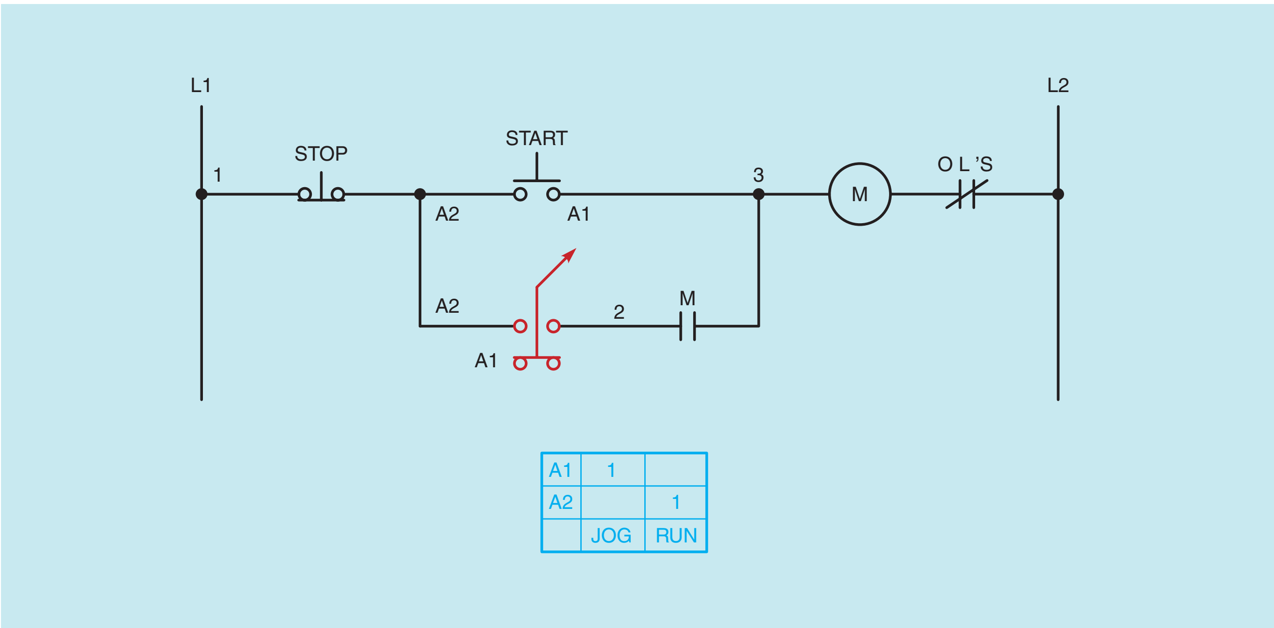


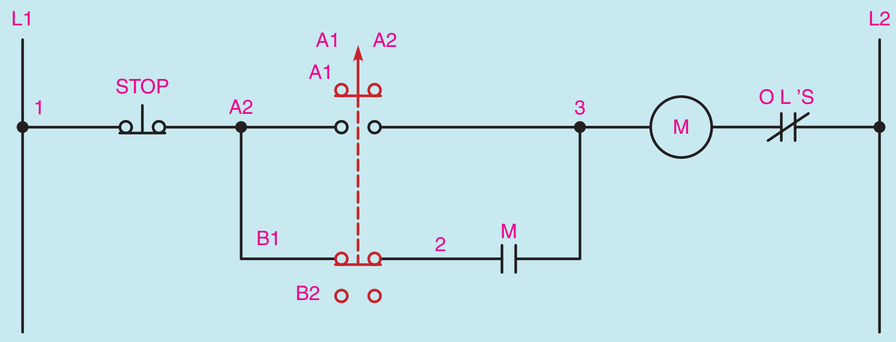
Figure 42–8 Jogging using a selector-switch jog with start button.

circuit as that shown in Figure 42–7 with the substitution of a heavy-duty, two-position selector switch.

The use of a selector push button to obtain jogging is shown in Figure 42–9. In the JOG position, the holding circuit is broken, and jogging is accomplished by depressing the push button.

Jogging with a Push-Pull Operator

Another type of jog-run control can be connected using a push-pull operator. The push-pull operator used in this circuit contains two normally open momentary contacts (Figure 42–10). When the control is pulled



A1	1			
A2		1		1
B1	1	1		
B2				1
	FREE	DEPRESSED	FREE	DEPRESSED
	RUN		JOG	

Figure 42–9 Jogging using selector push button.

outward, contact A completes a circuit to coil CR. When coil CR energizes, both CR contacts close. Contact CR1 completes a circuit to the coil of motor starter M. When motor starter M energizes, contact M closes. Since contacts CR2 and M are closed, a circuit is maintained to coil M when the push-pull operator is released and movable contact A returns to its normally open position. The circuit will remain in this condition until the STOP button is pushed and coils CR and M de-energize.

When the push-pull operator is pressed, movable contact B completes a circuit to coil M. When coil M energizes, auxiliary contact M closes. Contact CR2, however, is open and there is no complete circuit to maintain current flow to coil M. When the push button is released and movable contact B returns to its open position, the circuit to coil M is broken and the motor starter de-energizes.

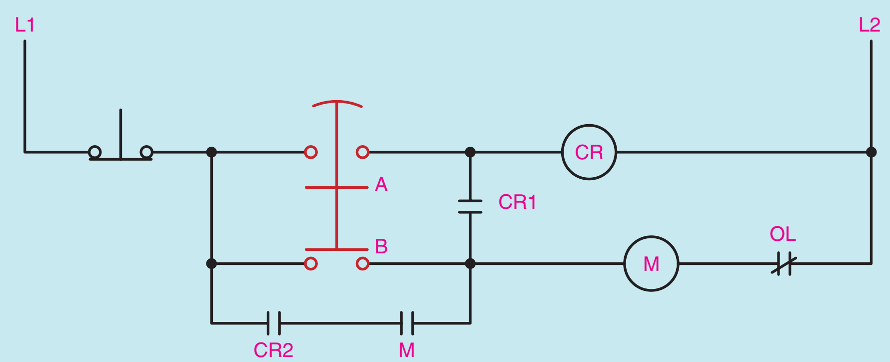


Figure 42–10 Jog-run control using a push-pull operator.

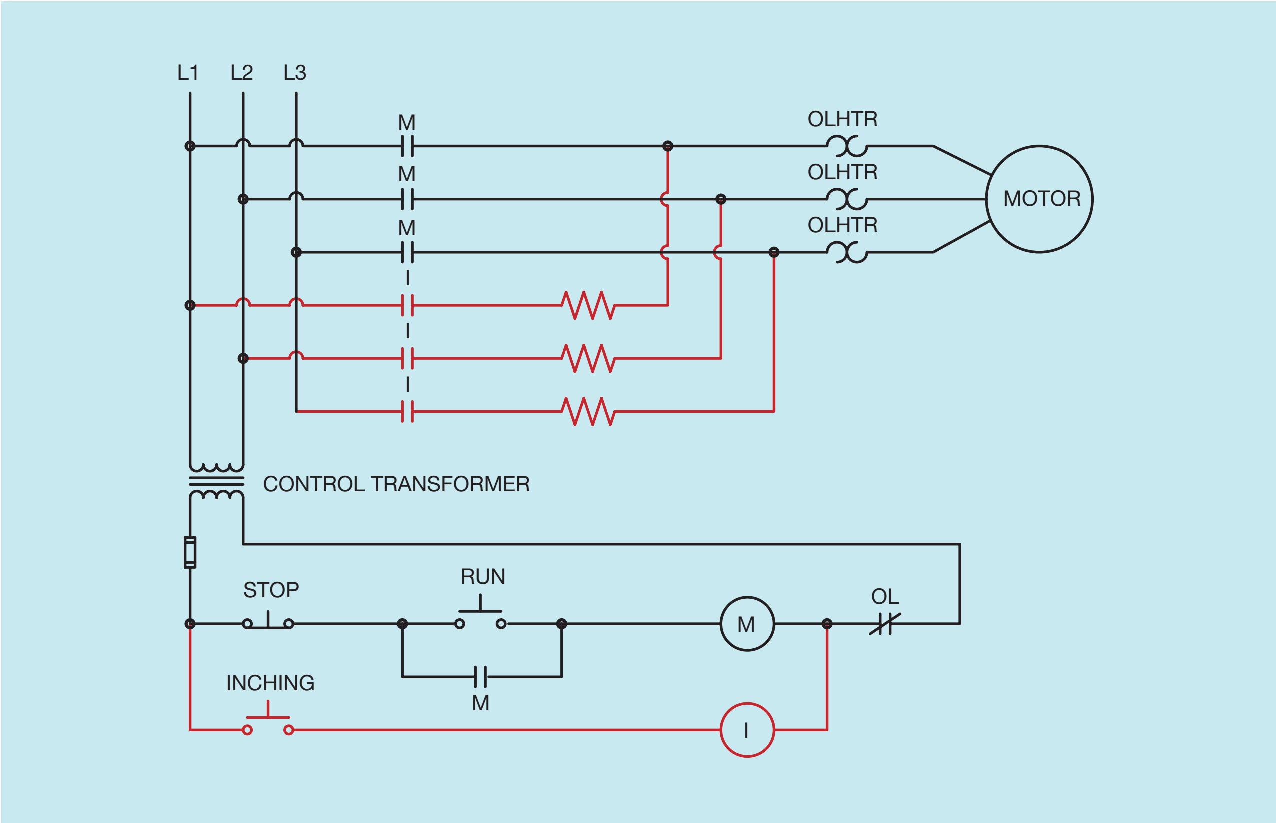


Figure 42–11 Inching circuit using resistors to reduce the amount of voltage applied to the motor.

Inching

As stated at the beginning of this unit, inching differs from jogging in that inching is accomplished by reducing the voltage applied to the motor. Although different methods can be employed to accomplish the voltage reduction, one of the most common methods of providing inching is to connect resistors in series with the motor as shown in Figure 42–11. A separate contactor is used to connect the motor to power when inching. Since the voltage and current applied to the motor has been reduced, the size of the inching contactor can be smaller than the one used for the starter.

Review Questions

1. Why is jogging (inching) included in this section on “Methods of Deceleration”?
2. What is the safety feature of a LOCK-STOP push button?
3. In (A) of Figure 42–3, what will happen if both the RUN and JOG push buttons are closed?
4. What will happen if the START and JOG push buttons of the circuit shown in Figure 42–4 are pushed at the same time?
5. In Figure 42–6, what will happen if both JOG push buttons are pushed momentarily?
6. Draw an elementary control diagram of a reversing starter. Use a standard duty selector switch with FORWARD, REVERSE, and STOP push buttons with three methods of interlocking.
7. Describe the contact arrangement of the push-pull operator used for a jog-run control.

UNIT 43
PLUGGING

OBJECTIVES

After studying this unit, the student will be able to:

- Define what is meant by the plugging of a motor.
- Describe how a control circuit using a zero-speed switch operates to stop a motor.
- Describe the action of a time-delay relay in a plugging circuit.
- Describe briefly the action of the several alternate circuits which use the zero-speed switch.
- Connect plugging control circuits.
- Recommend troubleshooting solutions for plugging problems.

Plugging is defined by NEMA as a system of braking, in which the motor connections are reversed so that the motor develops a counter torque which acts as a retarding force. Plugging controls provide for the rapid stop and quick reversal of motor rotation.

Motor connections can be reversed while the motor is running unless the control circuits are designed to prevent this type of connection. Any standard reversing controller can be plugged, either manually or with electromagnetic controls. Before the plugging operation is attempted, however, several factors must be considered including:

1. the need to determine if methods of limiting the maximum permissible currents are necessary, especially with repeated operations and dc motors.
2. the need to examine the driven machine to insure that repeated plugging will not cause damage to the machine.

Plugging Switches and Applications

Plugging switches, or zero-speed switches, are designed to be added to control circuits as pilot devices to provide quick, automatic stopping of machines. In most cases, the machines will be driven by squirrel cage motors. If the switches are adjusted properly, they will prevent the direction reversal of rotation of the controlled drive after it reaches a standstill following the reversal of the motor connections. One typical use of plugging

switches is for machine tools which must stop suddenly at some point in their cycle of operation to prevent inaccuracies in the work or damage to the machine. Another use is for processes in which the machine must stop completely before the next step of work begins. In this case, the reduced stopping time means that more time can be applied to production to achieve a greater total output.

Typical plugging switches are shown in Figure 43–1. The shaft of a plugging switch is connected mechanically to the motor shaft or to a shaft on the driven machine. The rotating motion of the motor is transmitted to the plugging switch contacts either by a centrifugal mechanism or by a magnetic induction arrangement (eddy current disc) within the switch. The switch contacts are wired to the reversing starter which controls the motor. The switch acts as a link between the motor and the reversing starter. The starter applies just enough power in the reverse direction to bring the motor to a quick stop.

Figure 43–1 Plugging (zero-speed) switch.

Plugging a Motor to a Stop from One Direction Only

The forward rotation of the motor in Figure 43–2 closes the normally open plugging switch contact. When the stop button is pushed, the forward contactor

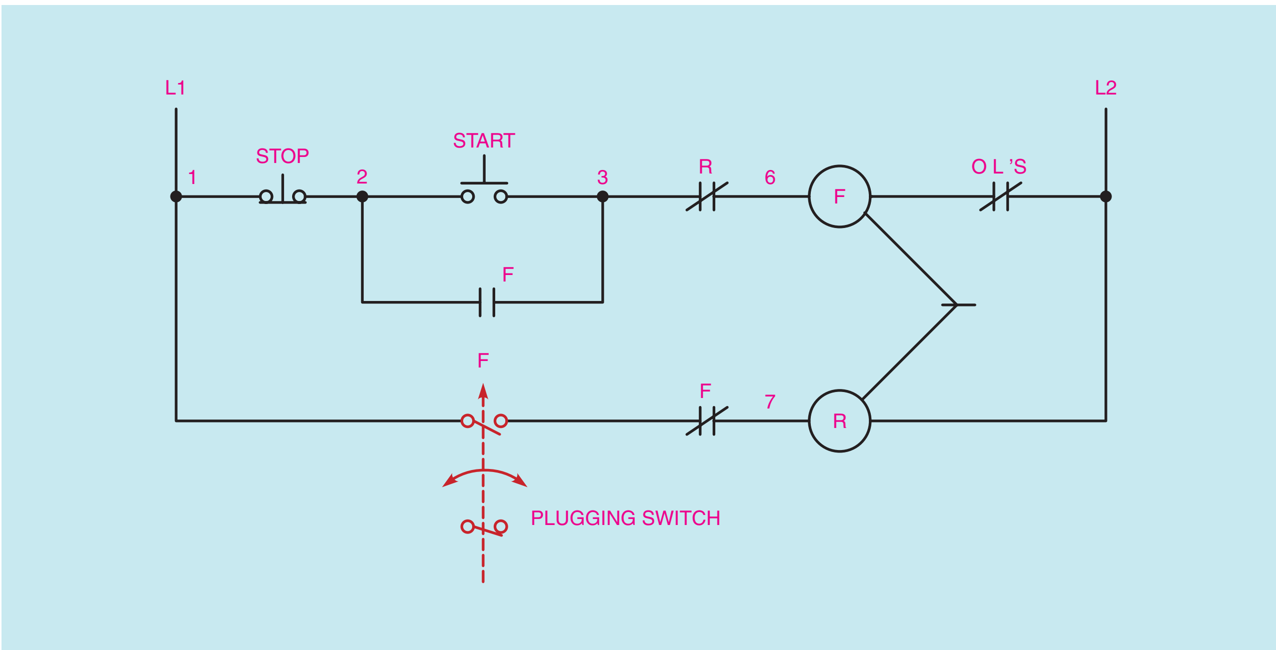


Figure 43–2 Plugging motor to stop from one direction only.

drops out. At the same time, the reverse contactor is energized through the plugging switch and the normally closed forward interlock. Thus, the motor connections are reversed and the motor is braked to a stop. When the motor is stopped, the plugging switch opens to disconnect the reverse contactor. This contactor is used only to stop the motor using the plugging operation; it is not used to run the motor in reverse.

Adjustment

The torque that operates the plugging switch contacts will vary according to the speed of the motor. An adjustable contact spring is used to oppose the torque to insure that the contacts open and close at the proper time regardless of the motor speed. To operate the contacts, the motor must produce a torque that will overcome the spring pressure. The spring adjustment is generally made with screws that are readily accessible when the switch cover is removed.

Care must be exercised to prevent the entry of chips, filings, and hardware into the housing when it is opened. Such material may be attracted to the magnets or hamper spring action. The housing must be carefully cleaned before the cover is removed for maintenance or inspection.

Installation

To obtain the greatest possible accuracy in braking, the switch should be driven from the shaft with the highest available speed that is within the operating speed range of the switch.

The plugging switch may be driven by gears, by a chain drive, or a direct flexible coupling. The preferred method of driving the switch is to connect a direct flexible coupling to a suitable shaft on the driven machine. The coupling must be flexible since the centerline of the motor or machine shaft and the centerline of the plugging switch shaft are difficult to align accurately enough to use a rigid coupling. The switch must be driven by a positive means. Thus, a belt drive should not be used. In addition, a positive drive must be used between the various parts of the machine being controlled, especially where these parts have large amounts of inertia.

The starter used for this type of circuit is a reversing starter that interchanges two of the three motor leads for a three-phase motor, reverses the direction of current through the armature for a dc motor, and reverses the relationship of the running and starting windings for a single-phase motor.

Motor Rotation

Experience shows that there is little way of predetermining the direction of the rotation of motors when the phases are connected externally in proper sequence. This is an important consideration for the electrician and the electrical contractor when the applicable electrical code or specifications require that each phase wire of a distribution system be color coded.

If the shaft end of a motor runs counterclockwise rather than in the desired clockwise direction, the electrician must reconnect the motor leads at the motor. For example, assume that many three-phase motors are to be connected and the direction of rotation of all the motors must be the same. If counterclockwise rotation is desired, the supply phase should be connected to the motor terminals in the proper sequence, T_1, T_2, and T_3. If the motor does not rotate in the desired counterclockwise direction using these connections, the leads may be interchanged at the motor. Once the proper direction of rotation is established, the remaining motors can be connected in a similar manner if they are from the same manufacturer. If the motors are from different manufacturers, they may rotate in different directions even when all the connections are similar and the supply lines have been phased out for the proper phase sequence and color coded. The process of correcting the rotation may be difficult if the motors are located in a place that is difficult to reach.

Lockout Relay

The zero-speed switch can be equipped with a lockout relay or a safety latch relay. This type of relay provides a mechanical means of preventing the switch contacts from closing unless the motor starting circuit is energized. The safety feature insures that if the motor shaft is turned accidentally, the plugging switch contacts do not close and start the motor. The relay coil

generally is connected to the T1 and T2 terminals of the motor. The lockout relay should be a standard requirement for circuits to protect people, machines, and production processes.

Plugging with the Use of a Timing Relay

A time-delay relay may be used in a motor plugging circuit (Figure 43–3). Unlike the zero-speed switch, this control circuit does not compensate for a change in the load conditions on the motor. The circuit shown in Figure 43–3 can be used for a constant load condition once the timer is preset. If the EMERGENCY STOP button in Figure 43–3A is pushed *momentarily* and the normally open circuit is *not* completed, the motor will coast to a standstill. (This action is also true of the normal double contact STOP button.) If the EMERGENCY STOP button is pushed to *complete* the normally open circuit of the push button, contactor S is energized through the closed contacts (TD and R). Contactor S closes and reconnects the motor leads, causing a reverse torque to be applied. When the relay coil is de-energized, the opening of contact TD can be retarded. The time lag is set so that contact TD opens at or near the point at which motor shaft speed reaches 0 r/min.

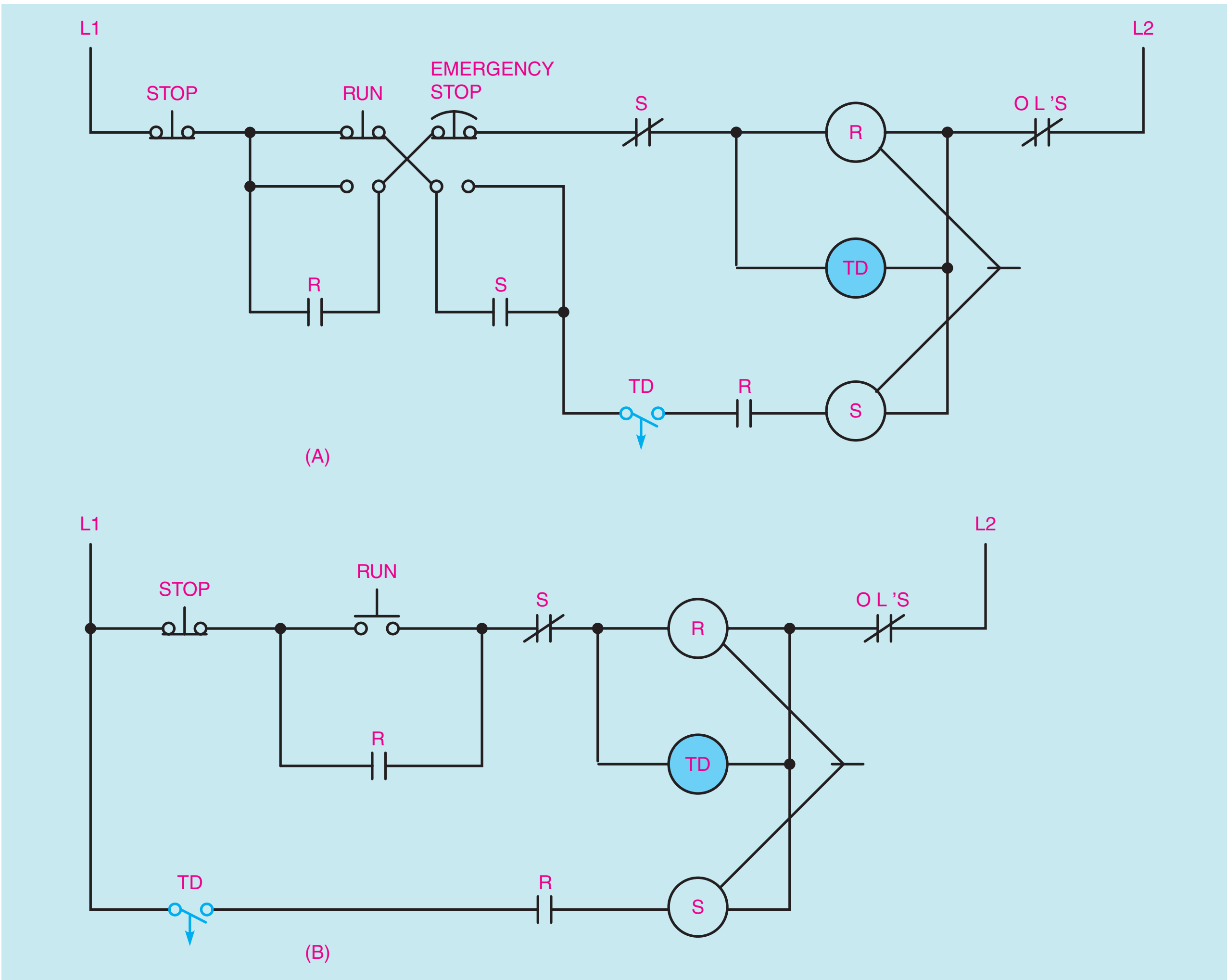


Figure 43–3 Plugging with time-delay relay.

Alternate Circuits for Plugging Switch

The circuit in Figure 43–4 is used for operation in one direction only. When the STOP push button is pressed and immediately released, the motor and the driven machine coast to a standstill. If the STOP button is held down, the motor is plugged to a stop.

Using the circuit shown in Figure 43–5, the motor may be started in either direction. When the STOP button is pressed, the motor can be plugged to a stop from either direction.

The circuit shown in Figure 43–6 provides operation in one direction. The motor is plugged to a stop when the STOP button is pressed. Jogging is possible with the use of a control relay.

Figure 43–7 shows a circuit for controlling the direction of rotation of a motor in either direction. Jogging in either the forward or reverse direction is possible if control jogging relays are used. The motor can

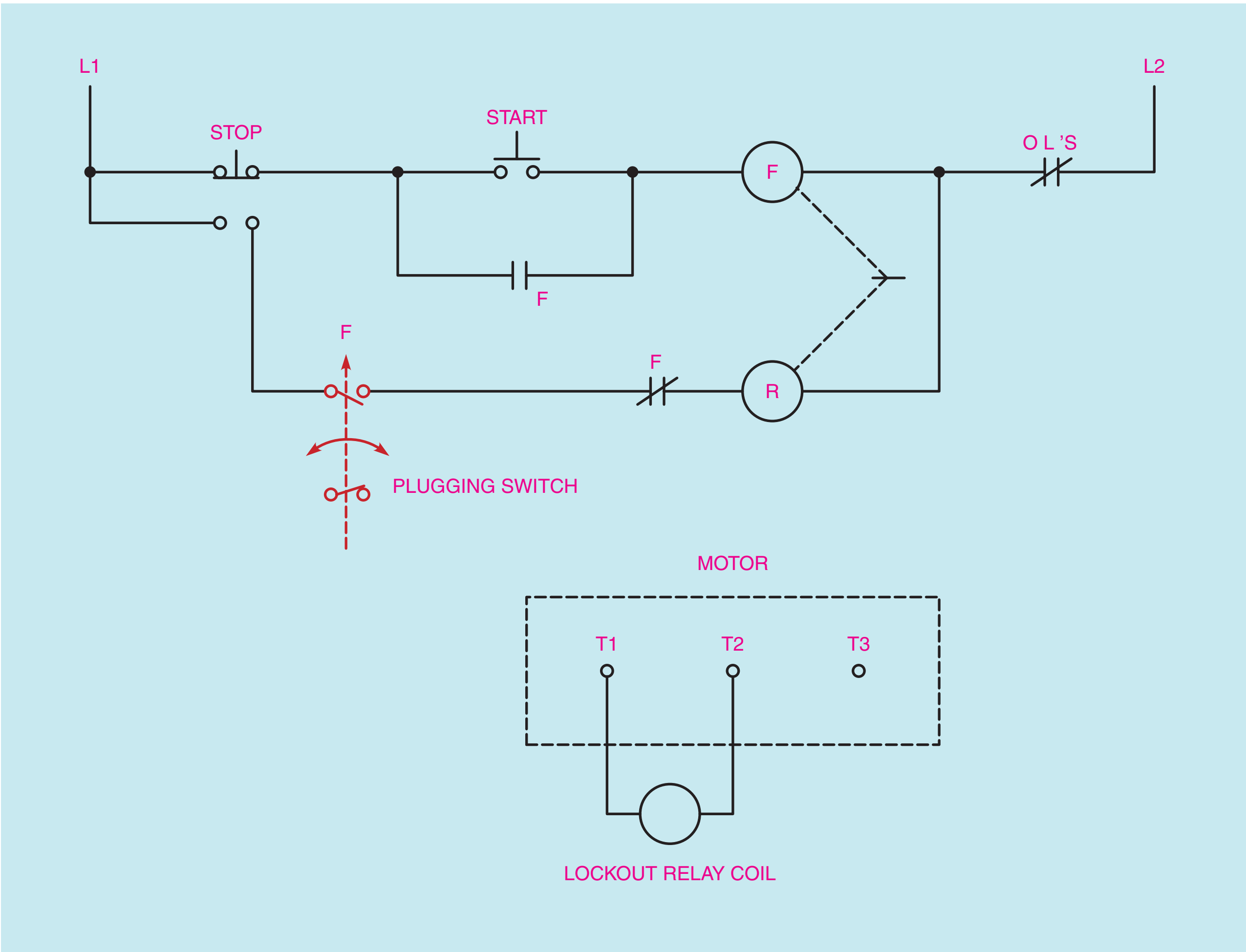


Figure 43–4 Holding STOP button will stop motor in one direction.

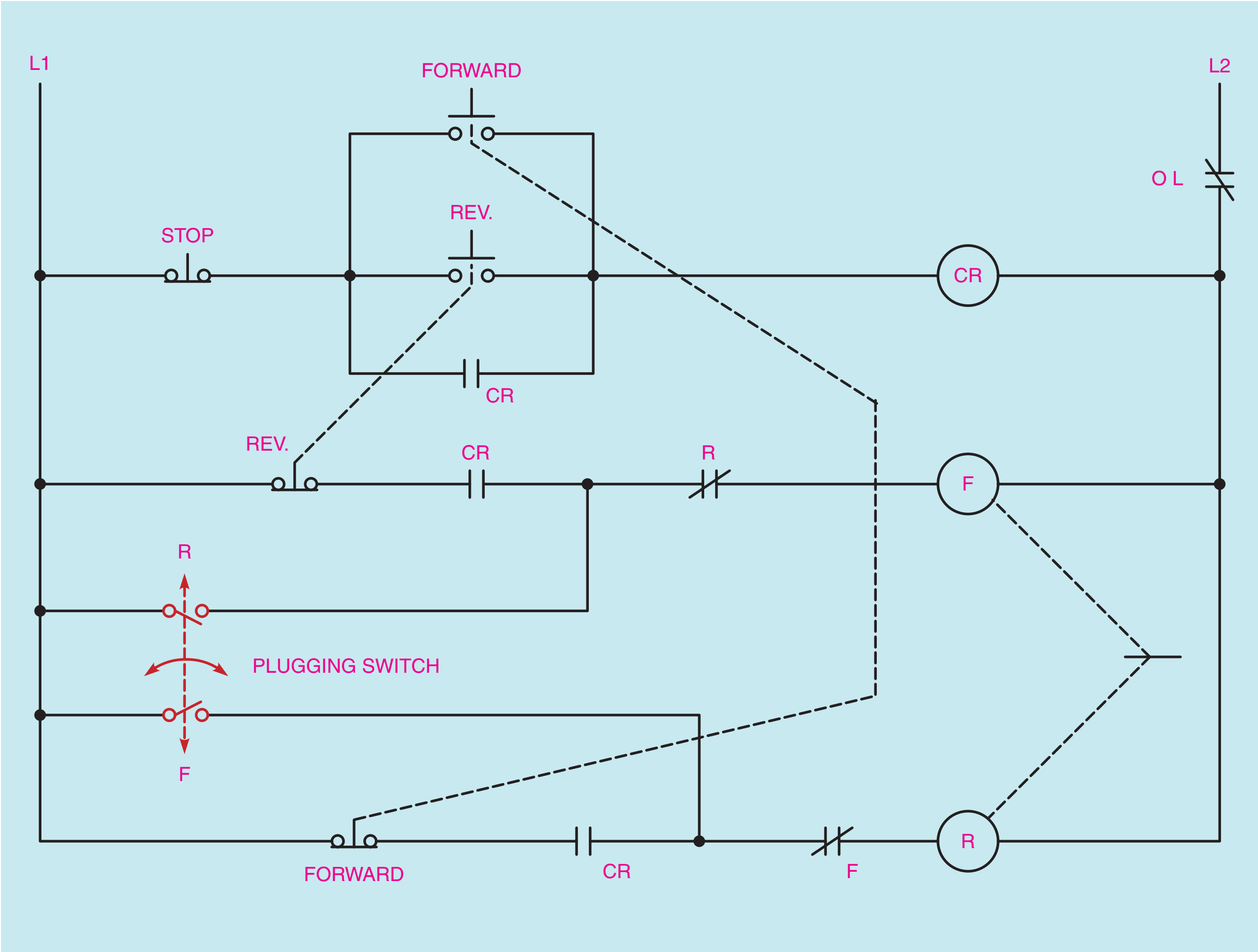


Figure 43–5 In this circuit, pressing STOP button stops motor in either direction.

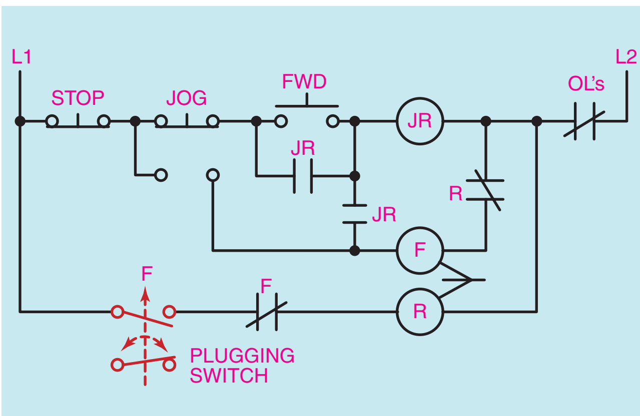


Figure 43–6 Pressing STOP button will stop motor in one direction.

be plugged to a stop from either direction by pressing the STOP button.

The circuit in Figure 43–8 provides control in either direction using a maintained contact selector switch with FORWARD, OFF, and REVERSE positions. The plugging action is available from either direction of rotation when the switch is turned to the OFF position. Low-voltage protection is not provided with this circuit.

The circuit in Figure 43–9 allows motor operation in one direction. The plugging switch is used as a speed interlock. The solenoid, or coil F, will not operate until the main motor reaches its running speed. A typical application of this circuit is to provide an interlock for a conveyor system. The feeder conveyor motor cannot be started until the main conveyor is operating.

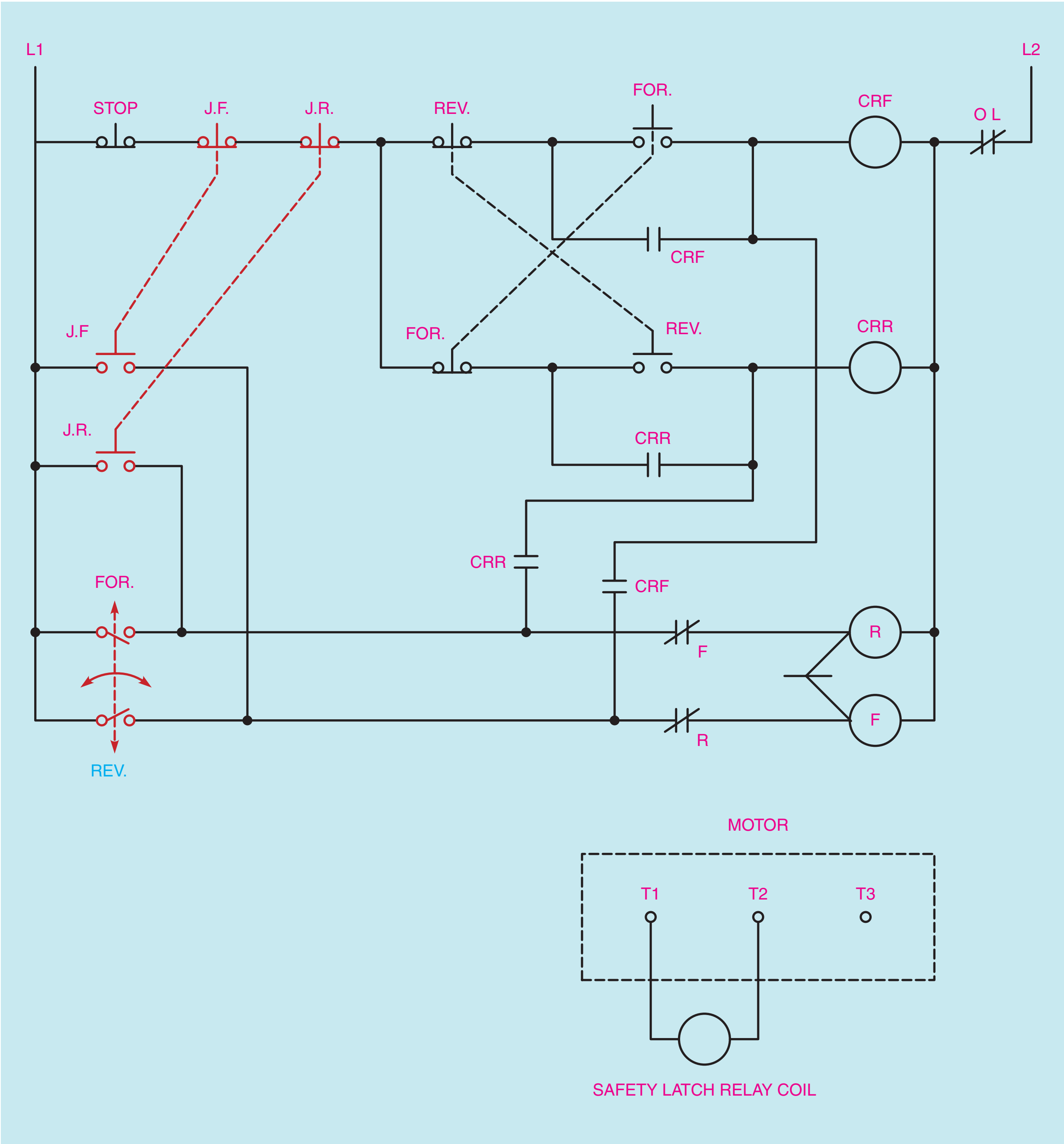


Figure 43–7 Use of control jogging relays will stop motor in either direction.

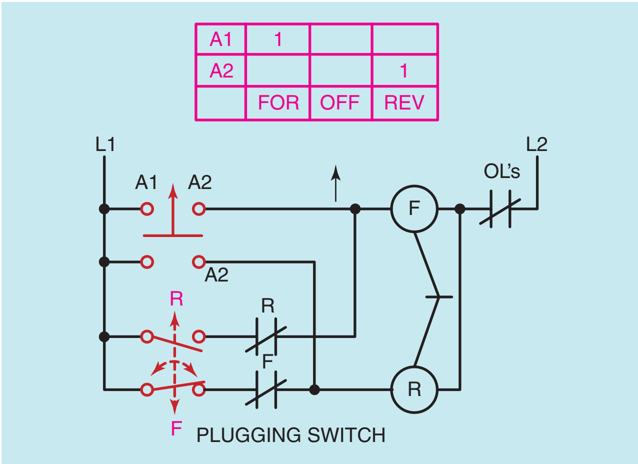


Figure 43–8 Using the maintained contact selector switch.

Antiplugging Protection

Antiplugging protection, according to NEMA, is obtained when a device prevents the application of a counter torque until the motor speed is reduced to an acceptable value. An antiplugging circuit is shown in Figure 43–10. With the motor operating in one direction, a contact on the antiplugging switch opens the control circuit of the contactor used to achieve rotation in the opposite direction. This contact will not close until the motor speed is reduced. Then the other contactors can be energized.

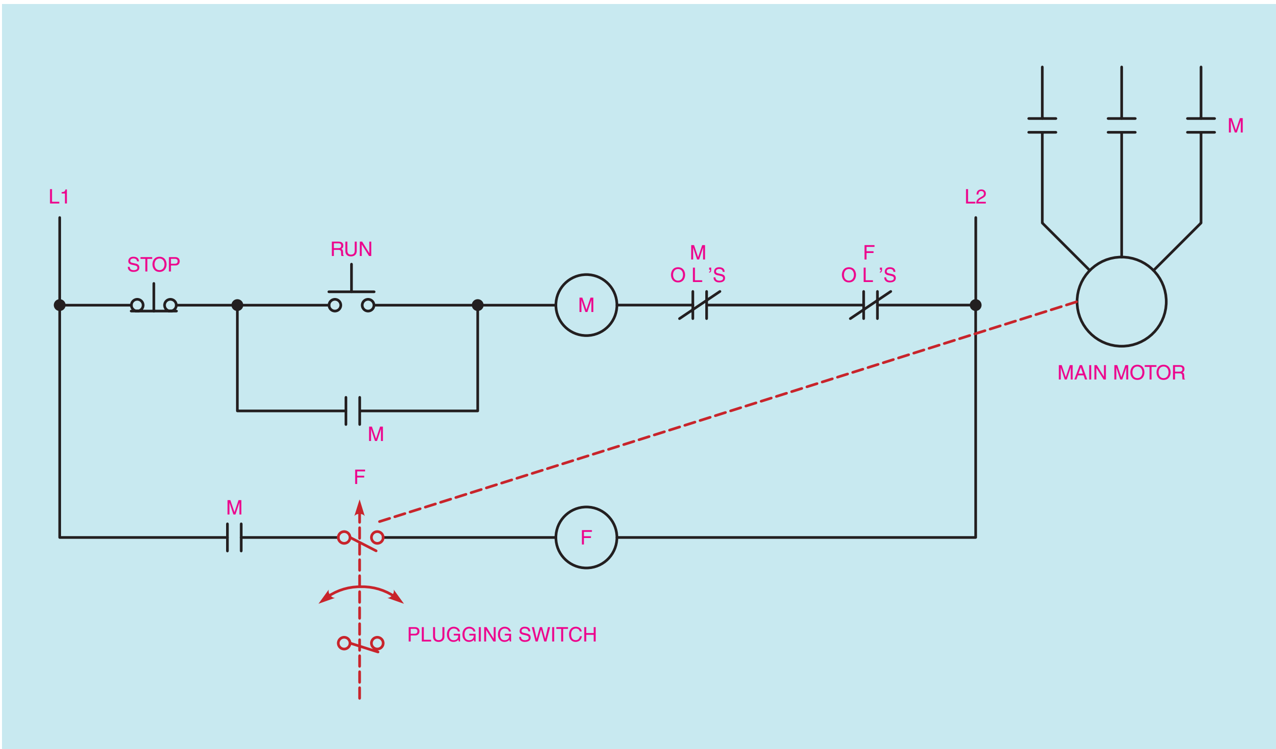


Figure 43–9 Using plugging switch as speed interlock.

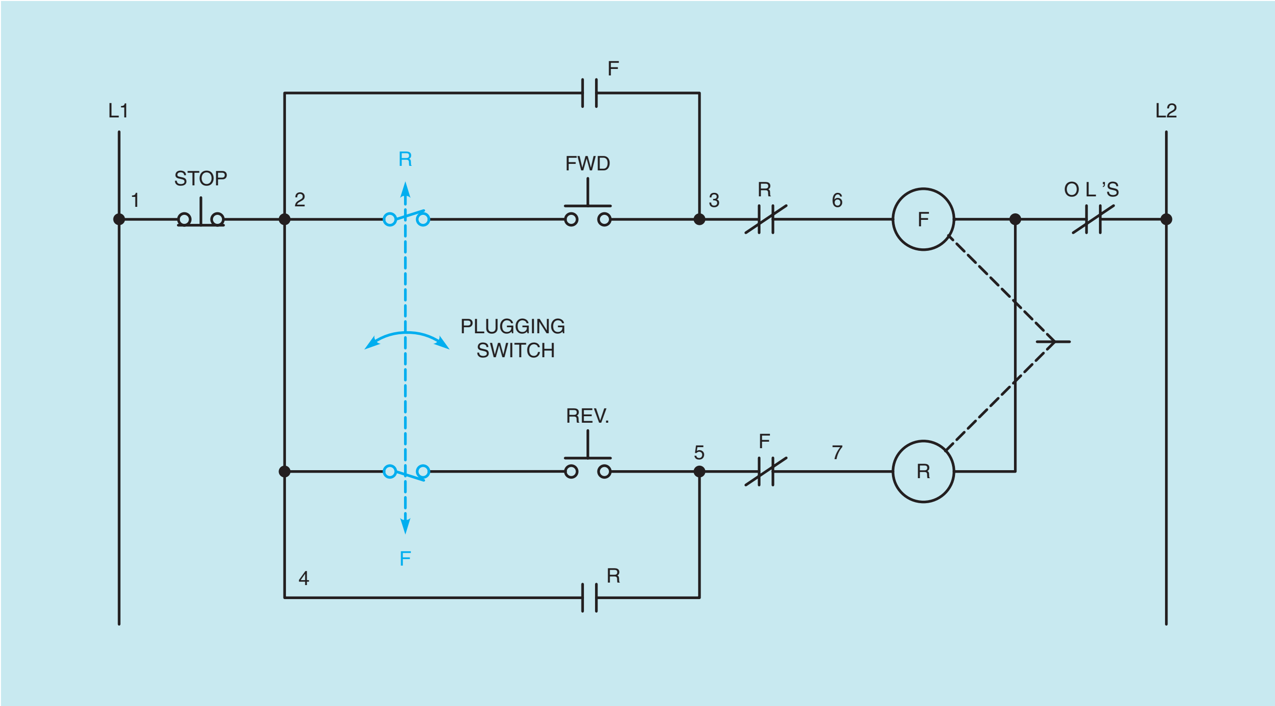


Figure 43–10 Antiplugging protection; the motor is to be reversed but not plugged.

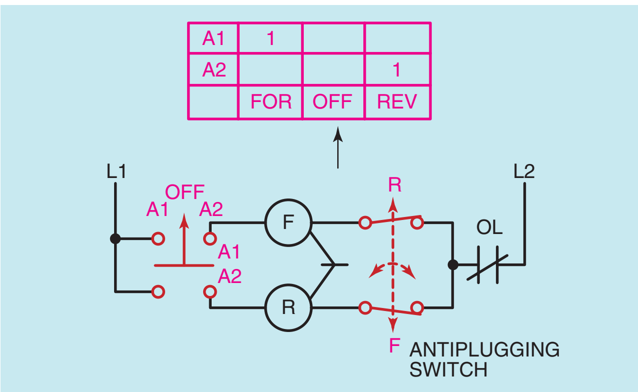


Figure 43–11 Antiplugging with rotation direction selector switch.

Alternate Antiplugging Circuits

The direction of rotation of the motor is controlled by the motor starter selector switch (Figure 43–11). The antiplugging switch completes the reverse circuit only when the motor slows to a safe, preset speed. Undervoltage protection is not available.

In Figure 43–12, the direction of rotation of the motor is selected by using the maintained contact, two-position selector switch. The motor is started with the push button. The direction of rotation cannot be reversed until the motor slows to a safe, preset speed. Low-voltage protection is provided by a three-wire, start-stop, push-button station.

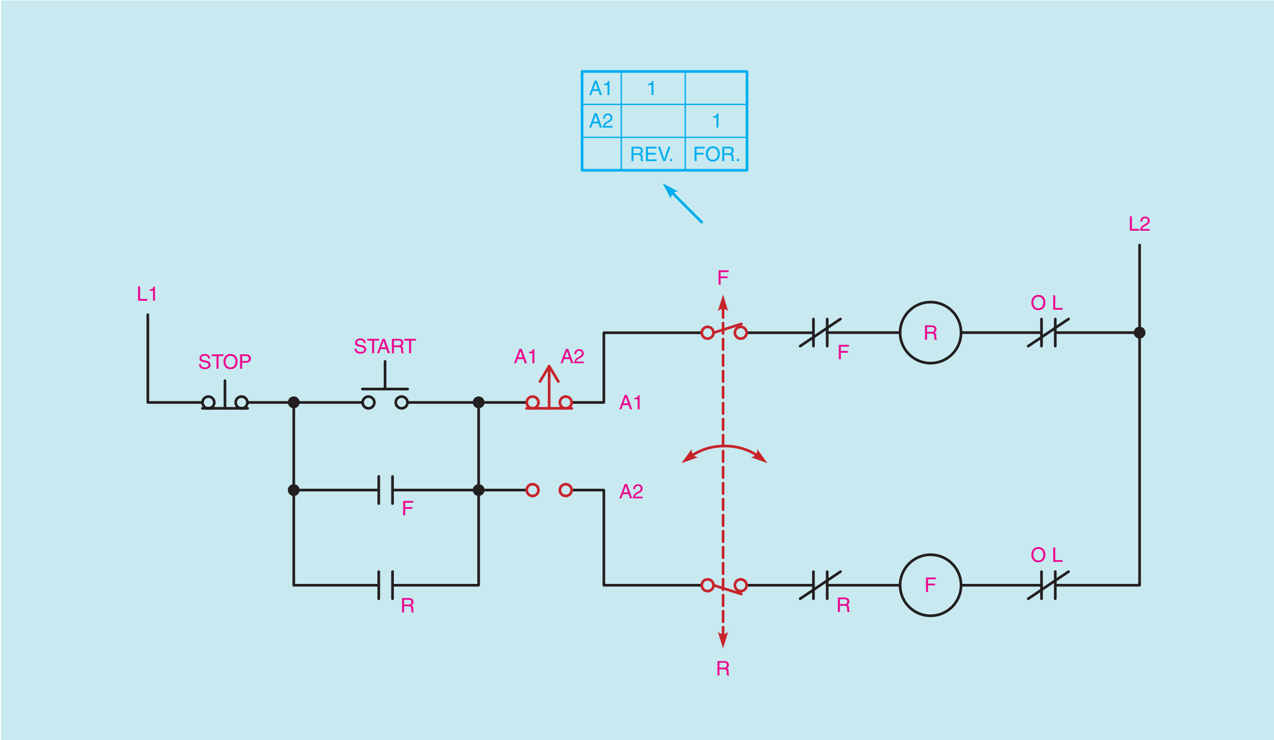


Figure 43–12 Antiplugging circuit using a selector switch and providing low-voltage protection.

Review Questions

1. In Figure 43–2, what is the purpose of normally closed contact (F)?
2. Can a time-delay relay be used satisfactorily in a plugging circuit? Explain.
3. In what position must a plugging switch be mounted? Explain.
4. What is the preferred method of connecting the plugging switch to the motor or the driven machine?
5. What happens if the zero-speed switch contacts are adjusted to open too late?
6. What is the purpose of the lockout relay or safety latch relay?
7. What happens if the REVERSE push button is closed when the motor is running in the forward direction, as in Figure 43–5?
8. What alternate methods of stopping are provided by the circuit described in Figure 43–4?
9. If the motor described in Figure 43–6 is plugging to a stop and the operator suddenly wants it to inch ahead or run, what action must be taken?
10. In Figure 43–7, is it necessary to push the STOP button when changing the direction of rotation? Explain your answer.
11. In Figure 43–8, what happens to the motor running in the forward direction if the power supply is lost for 10 minutes?
12. In Figure 43–9, how is the feeder motor protected from an overload?
13. What is antiplugging protection?
14. During normal operation, when do the antiplugging switch contacts close?
15. If the supply lines are in the proper phase sequence (L1, L2, and L3) and are connected to their proper terminals on the motor (T1, T2, and T3), will all the motors rotate in the same direction? Why?

Section 5

DC MOTOR CONTROLS

UNIT 44
DC MOTORS

OBJECTIVES

After studying this unit, the student will be able to:

- List applications of dc motors.
- Describe the electrical characteristics of dc motors.
- Describe the field structure of a dc motor.
- Change the direction of rotation of a dc motor.
- Identify the series and shunt fields and the armature winding with an ohmmeter.
- Connect motor leads to form a series, shunt, or compound motor.
- Describe the difference between a differential and cumulative compound motor.

Application

Dc motors are used in applications where variable speed and strong torque are required. They are used for cranes and hoists when loads must be started slowly and accelerated quickly. Dc motors are also used in printing presses, steel mills, pipe forming mills, and many other industrial applications where speed control is important.

Speed Control

The speed of a dc motor can be controlled by applying variable voltage to the armature or field. When full voltage is applied to both the armature and the field, the motor operates at its base or normal speed. When full voltage is applied to the field and reduced voltage is applied to the armature, the motor operates below normal speed. When full voltage is applied to the armature and

reduced voltage is applied to the field, the motor operates above normal speed.

Motor Construction

The essential parts of a dc motor are the armature, field windings, brushes, and frame (Figure 44–1).

The Armature

The armature is the rotating part of the motor. It is constructed from an iron cylinder that has slots cut into it. Wire is wound through the slots to form the windings. The ends of the windings are connected to the commutator which consists of insulated copper bars and is mounted on the same shaft as the windings. The windings and commutator together form the armature.

Carbon brushes, which press against the commutator segment, supply power to the armature from the dc power line. The commutator is a mechanical switch which forces current to flow through the armature windings in the same direction. This enables the polarity of the magnetic field produced in the armature to remain constant as it turns.

Armature resistance is kept low, generally less than 1 ohm. This is because the speed regulation of the motor is proportional to the armature resistance. The lower the armature resistance, the better the speed regulation will be. Where the brush leads extend out of the motor at the terminal box, they are labeled A1 and A2.

Field Windings

There are two types of field windings used in dc motors: series and shunt. The series field is made with a

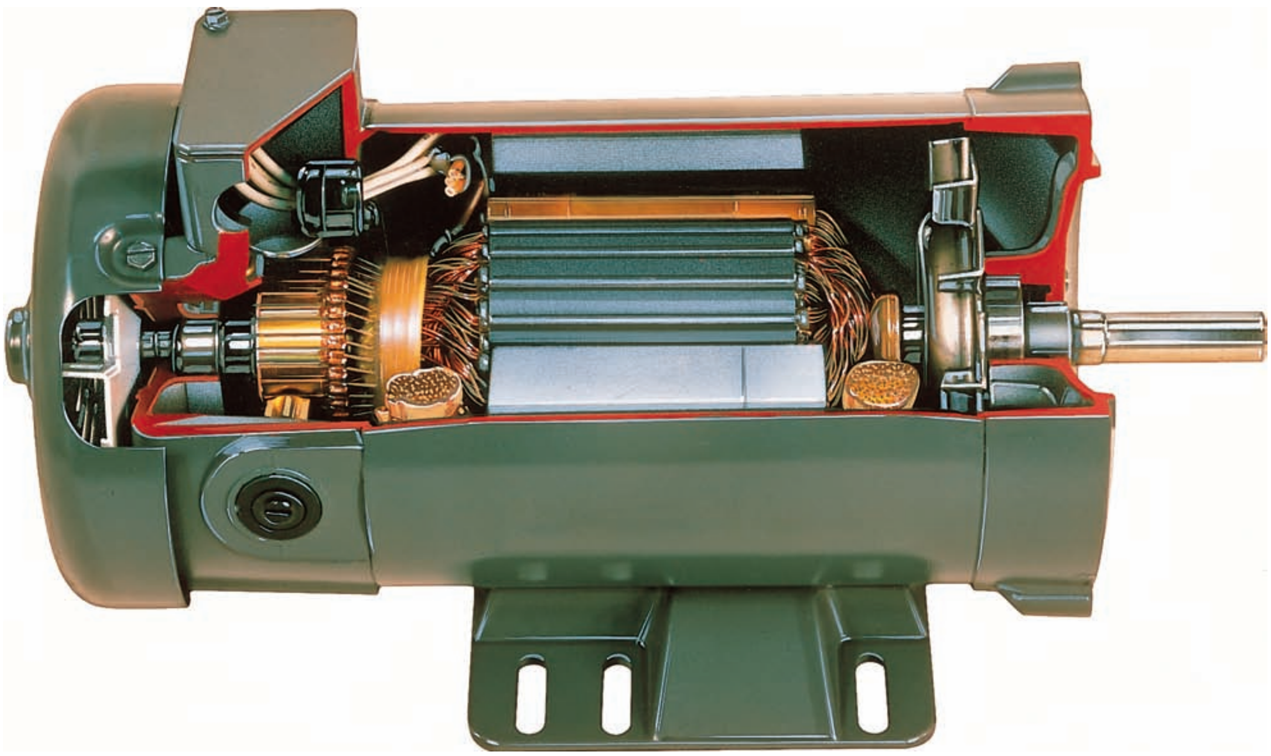


Figure 44–1 DC motor, field structure, and armature assembly. (Courtesy Reliance Electric Co.)

few turns of large wire. It has a low resistance and is designed to be connected in series with the armature. The terminal markings, S1 and S2, identify the series field windings.

The shunt field winding is made with many turns of small wire. It has a high resistance and is designed to be connected in parallel with the armature. Since the shunt field is connected in parallel with the armature, line voltage is connected across it. The current through the shunt field is, therefore, limited by its resistance. The terminal markings for the shunt field are F1 and F2.

Identifying Windings

The windings of a dc motor can be identified with an ohmmeter. The shunt field winding can be identified by the fact that it has a high resistance as compared to the other two windings. The series field and armature windings have a very low resistance. They can be identified, however, by turning the motor shaft. When the ohmmeter is connected to the series field and the motor shaft is turned, the ohmmeter reading will not be affected. When the ohmmeter is connected to the armature winding and the motor shaft is turned, the reading will become erratic as the brushes make and break contact with different commutator segments.

Types of DC Motors

There are three basic types of dc motors: the series, the shunt, and the compound. The type of motor used is determined by the requirements of the load. The series motor, for example, can produce very high starting torque, but its speed regulation is poor. The only thing that limits the speed of a series motor is the amount of load connected to it. A very common application of a series motor is the started motor used on automobiles. Shunt and compound motors are used in applications where speed control is essential.

Figure 44–2 shows the basic connections for series, shunt, and compound motors. Notice that the series motor contains only the series field connected in series with the armature. The shunt motor contains only the shunt field connected parallel to the armature. A rheostat is shown connected in series with the shunt field to provide above normal speed control.

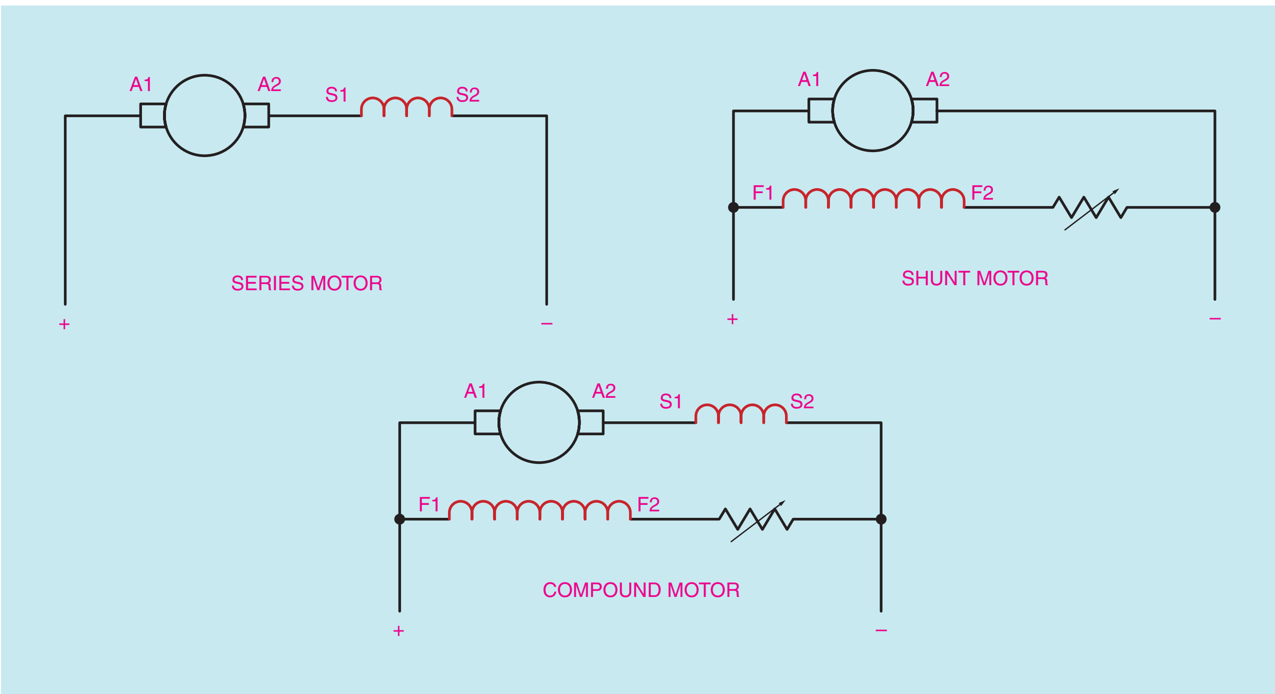


Figure 44–2 DC motor connections.

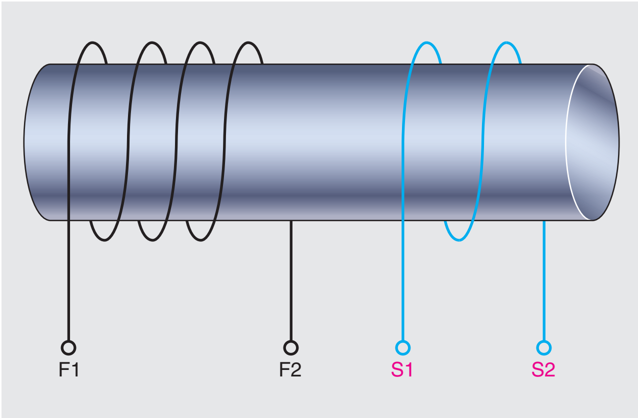


Figure 44–3 Series and shunt field windings are wound.

The compound motor has both series and shunt field windings. Each pole piece in the motor will have both windings wound on it (Figure 44–3). There are different ways of connecting compound motors. For instance, a motor can be connected as a long shunt compound or as a short shunt compound (Figure 44–4). When a long shunt connection is made, the shunt field is connected parallel to both the armature and the series field. When a short shunt connection is made, the shunt field is connected parallel to the armature, but in series with the series field.

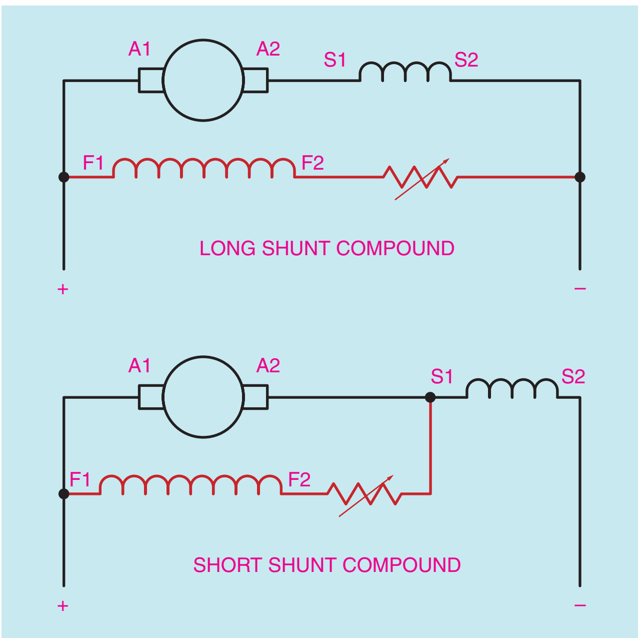


Figure 44–4 Compound motor connections.

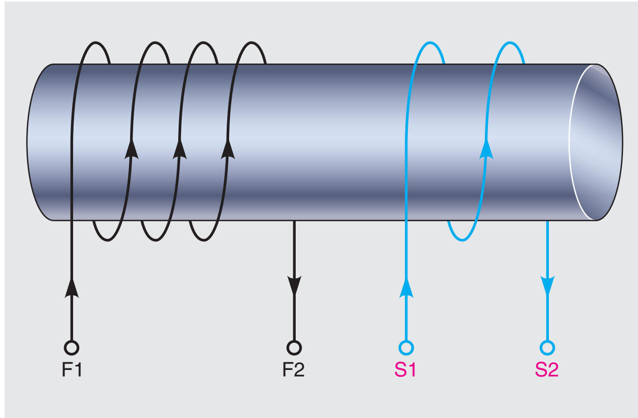


Figure 44–5 Cumulative compound connection.

Compound motors can also be connected as cumulative or differential. When a motor is connected as a cumulative compound, the shunt and series fields are connected in such a manner that as current flows through the windings they aid each other in the production of magnetism (Figure 44–5). When the motor is connected as a differential compound, the shunt and series field windings are connected in such a manner that as current flows through them they oppose each other in the production of magnetism (Figure 44–6).

Direction of Rotation

The direction of rotation of the armature is determined by the relationship of the polarity of the magnetic field

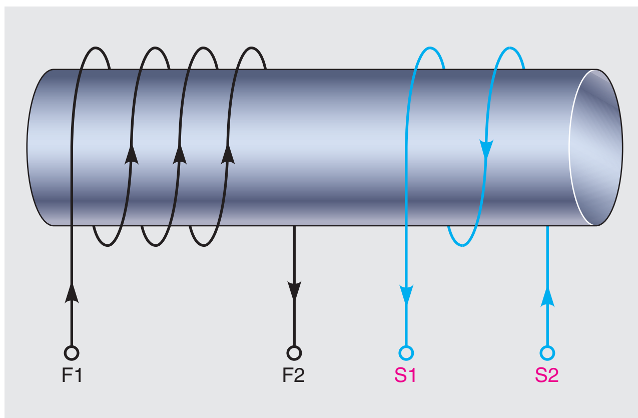


Figure 44–6 Differential compound connection.

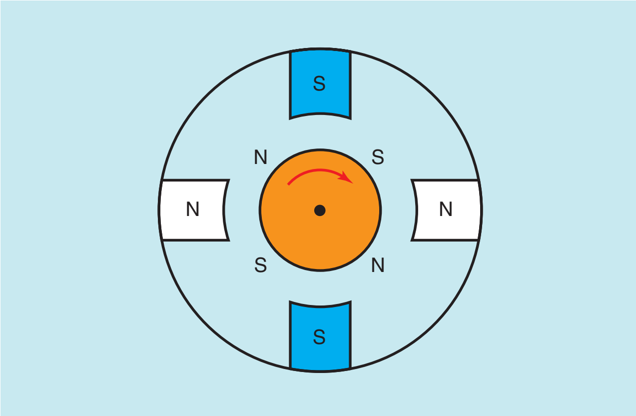


Figure 44–7 Armature rotates in a clockwise direction.

of the armature to the polarity of the magnetic field of the pole pieces. Figure 44–7 shows a motor connected in such a manner that the armature will rotate in a clockwise direction due to the attraction and repulsion of magnetic fields. If the input lines to the motor are reversed, the magnetic polarity of both the pole pieces and the armature will be reversed and the motor will continue to operate in the same direction (Figure 44–8).

To reverse the direction of rotation of the armature, the magnetic polarity of the armature and the field must be changed in relation to each other. In Figure 44–9, the armature leads have been changed, but the field leads have not. Notice that the attraction and repulsion of the magnetic fields now cause the armature to turn in a counterclockwise direction.

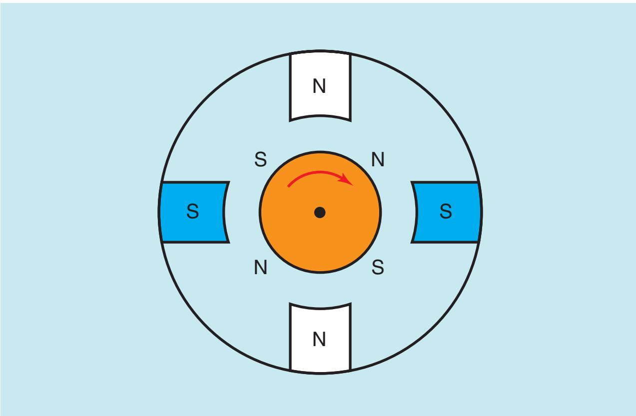


Figure 44–8 Changing input lines will not reverse the direction of rotation.

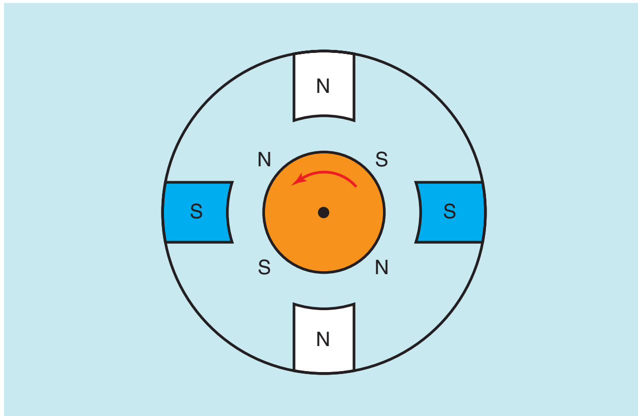


Figure 44–9 When the armature leads are reversed, only the direction of rotation is changed.

When the direction of rotation of a series or shunt motor is to be changed, either the field or the armature leads can be reversed. Many small dc shunt motors are reversed by reversing the connection of the shunt field leads. This is done because the current flow through the shunt field is much lower than the current flow through the armature. This permits a small switch, instead of a large solenoid switch, to be used as a reversing switch. Figure 44–10 shows a double-pole, double-throw (DPDT) switch used as a reversing switch. Power is connected to the common terminals of the switch and the stationary terminals are cross connected.

When a compound motor is to be reversed, only the armature leads are changed. If the motor is reversed by changing the shunt field leads, the motor will be changed from a cumulative compound motor to a differential compound motor. If this happens, the motor speed will drop sharply when load is added to the motor. Figure 44–11 shows a reversing circuit using magnetic contactors to change the direction of current flow through the armature. Notice that the direction of current flow through the series and shunt fields remains the same whether the F contacts or the R contacts are closed.

Standard Connections

When dc motors are wound, the terminal leads are marked in a standard manner. This permits the direction of rotation to be determined when the motor windings

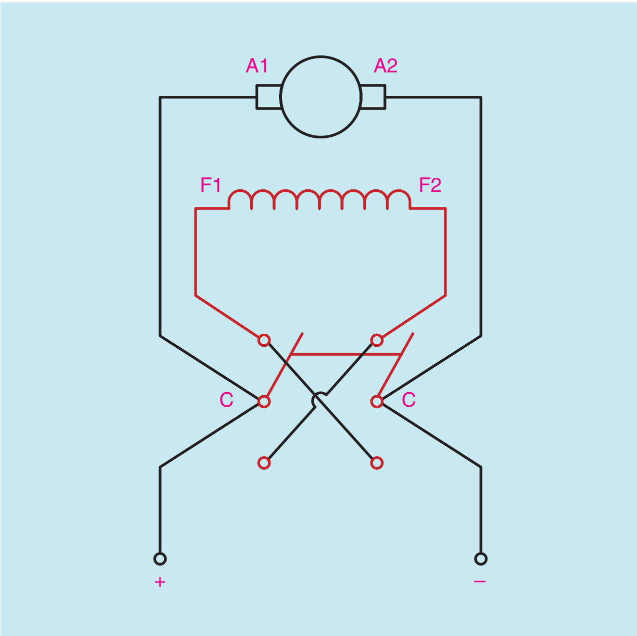


Figure 44–10 Double-pole, double-throw switch used to reverse the direction of rotation of a shunt motor.

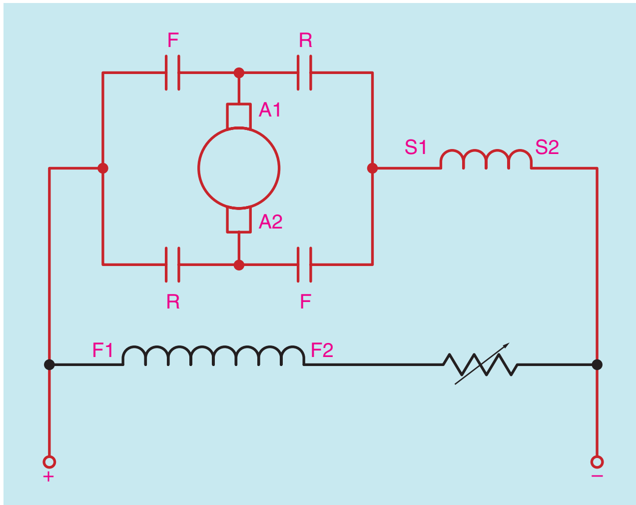


Figure 44–11 Contactors reverse the direction of current flow through the armature.

are connected. The direction of rotation is determined by facing the commutator end of the motor, which is generally located on the rear of the motor, but not always. Figure 44–12 shows the standard connections for a series motor, Figure 44–13 shows the standard connections for a shunt motor, and Figure 44–14 shows the standard connections for a cumulative compound motor.

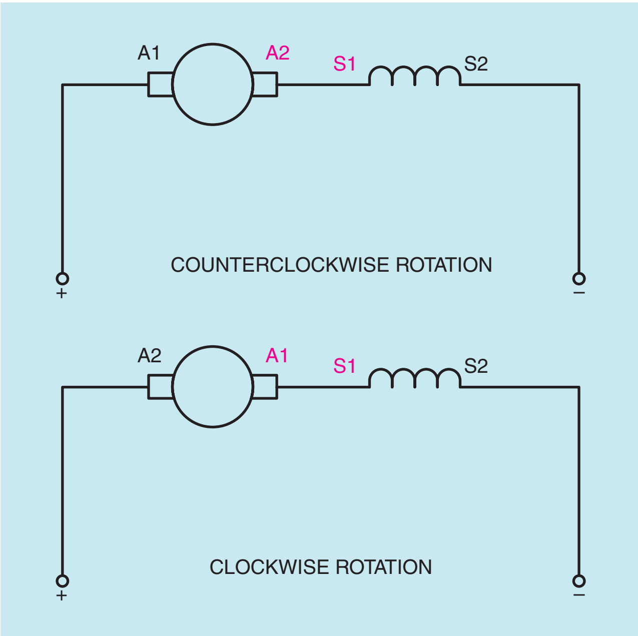


Figure 44–12 Standard connections for series motors.

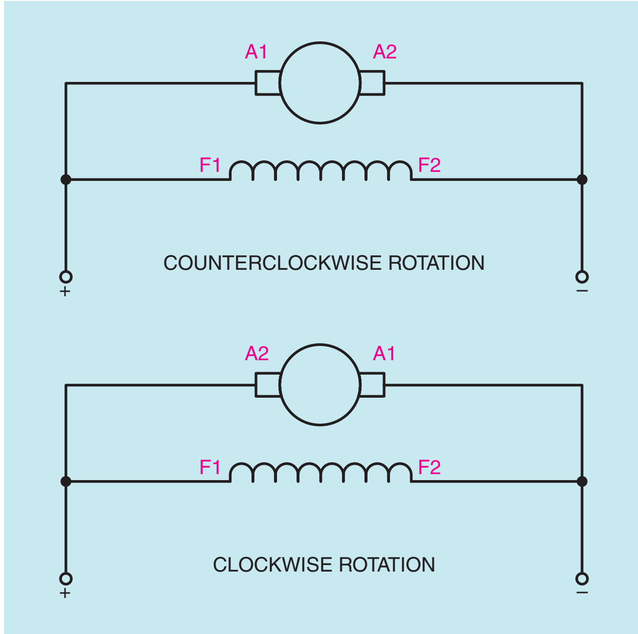


Figure 44–13 Standard connections for shunt motors.

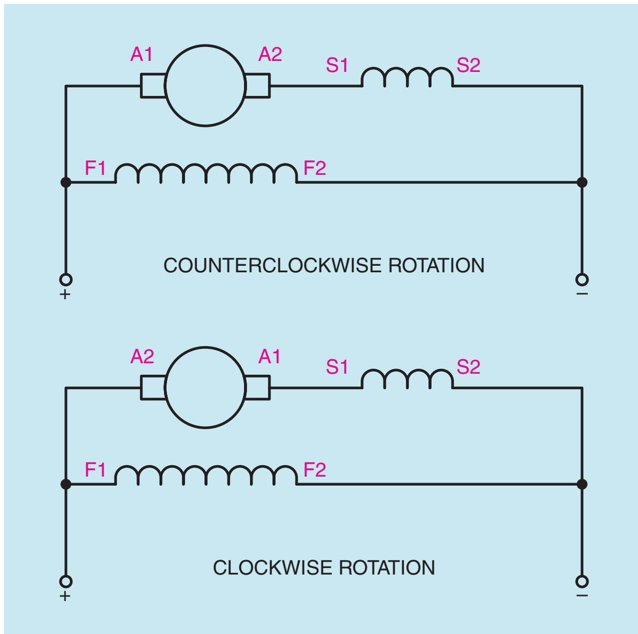


Figure 44–14 Standard connections for compound motors.

Review Questions

1. How can a dc motor be made to operate below its normal speed?
2. Name the three basic types of dc motors.
3. Explain the physical difference between series field windings and shunt field windings.
4. The speed regulation of a dc motor is proportional to what?
5. What connection is made to form a long shunt compound motor?
6. Explain the difference between the connection of a cumulative compound and a differential compound motor.
7. How is the direction of rotation of a dc motor changed?
8. Why is it important to reverse only the armature leads when changing the rotation of a compound motor?

UNIT 45
ACROSS-THE-LINE STARTING

OBJECTIVES

After studying this unit, the student will be able to:

- Describe across-the-line starting for small dc motors.
- State why a current-limiting resistor may be used in the starting circuit for a dc motor.
- Connect across-the-line starters used with small dc motors.
- Recommend troubleshooting solutions for across-the-line starters.
- Draw diagrams for three motor starter control circuits.

Small dc motors can be connected directly across the line for starting because a small amount of friction and inertia is overcome quickly in gaining full speed and developing a counter emf. Fractional horsepower manual starters (discussed in unit 12) or magnetic contactors and starters (unit 13) are used for across-the-line starting of small dc motors (Figure 45–1).

Magnetic across-the-line control of small dc motors is similar to ac control or to two- or three-wire control. Some dc across-the-line starter coils have dual windings because of the added load of multiple break contacts and the fact that the dc circuit lacks the inductive reactance which is present with ac electromagnets. Both windings are used to lift and close the contacts, but only one winding remains in the holding position. The starting (or lifting) winding of the coil is designed for momentary duty only. In Figure 45–2, assume that coil M is energized momentarily by the start button. When the starter is closed, it maintains itself through the normally open maintaining contact (M) and the upper winding of the coil since the normally closed contact (M) is now open. Power contacts M close, and the motor starts across the full line voltage. The double-break power contacts are designed to minimize the effects of arcing. (Dc arcs are greater than those due to alternating current.)

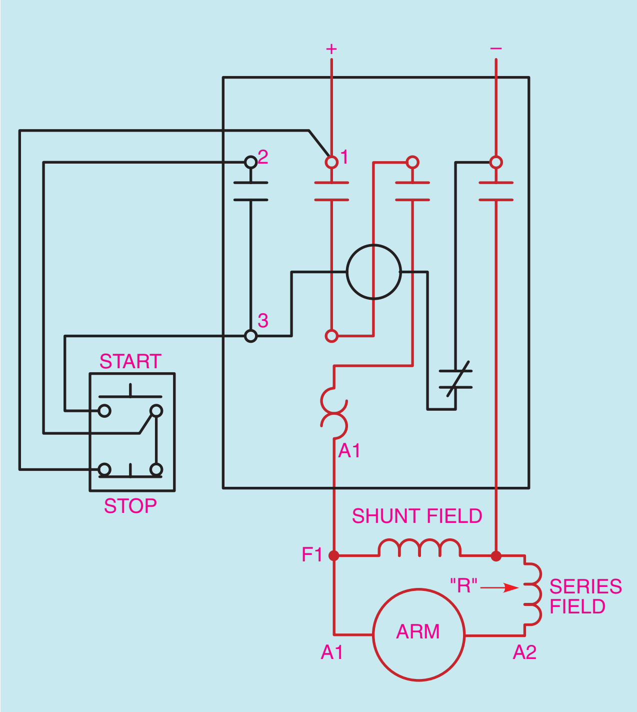


Figure 45–1 DC full voltage starter wiring diagram. Connection ("R") is removed with use of series field.

Figure 45–3 shows another control method used to start a dc motor. In this method, a current-limiting resistor is provided to prevent coil burnout. It is used to limit a continuous duty current flow to some coils or when the coils are overheating.

The coil first receives the maximum current required to close the starter. It then receives the minimum current necessary to hold in the contacts and for continuous duty through the current-limiting resistor.

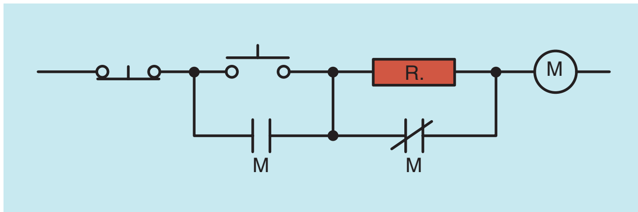


Figure 45–3 DC starting circuit using current limiting resistor.

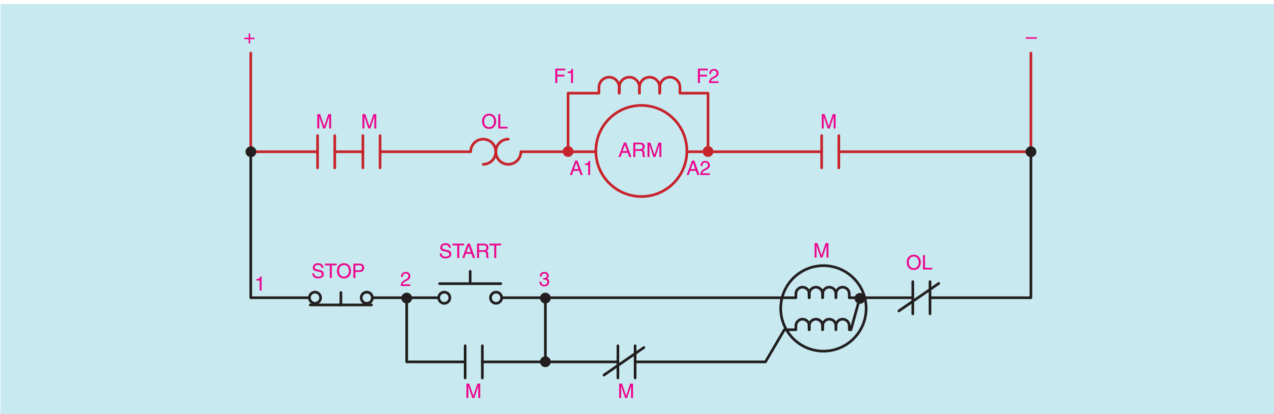


Figure 45–2 Line diagram of dc motor starter with dual winding coil.

Review Questions

1. Why may small dc motors be started directly across the line?
2. When using a coil that is not designed for continuous duty, what may happen if a resistor is not added to the circuit?
3. What is the purpose of a double-break power contact?

UNIT 46

DEFINITE TIME STARTING CONTROL

OBJECTIVES

After studying this unit, the student will be able to:

- Describe field current protection for a dc motor.
- Describe the use of series resistance for limiting the armature current when starting a dc motor.
- Connect a timed starting control for a dc motor.

When large dc motors are to be started, current inrush to the armature must be limited. One method of limiting this current is to connect resistors in series with the armature. When the armature begins to turn, counter-emf is developed in the armature. As counter-emf increases, resistance can be shunted out of the armature circuit, permitting the armature to turn at a higher speed. When armature speed increases, counter-emf also increases. Resistance can be shunted out of the circuit in steps until the armature is connected directly to the power line.

Limiting the starting current of the armature is not the only factor that should be considered in a dc control circuit. Most dc motor control circuits use a *field current relay (FCR)* connected in series with the shunt field of the motor. The field current relay insures that current is flowing through the shunt field before voltage can be connected to the armature.

If the motor is running and the shunt field opens, the motor will become a series motor and begin to increase rapidly in speed. If this happens, both the motor and the equipment it is operating can be destroyed. For this reason, the shunt field relay must disconnect the armature from the line if shunt field current stops flowing.

The circuit shown in Figure 46–1 is a dc motor control with two steps of resistance connected in series with the armature. When the motor is started, both resistors limit current flow to the armature. Time-delay relays are used to shunt the starting resistors out of the circuit in time intervals of five seconds each until the armature is connected directly to the line.

The circuit operates as follows: When the start button is pushed, current is supplied to relay coil F and all F contacts change position. One F contact is connected parallel to the start button and acts as a holding contact. Another F contact connects the field current relay and the shunt field to the line.

When shunt field current begins to flow, contact FCR closes. When contact FCR closes, a circuit is completed to motor starter coil M and coil TR1. When starter

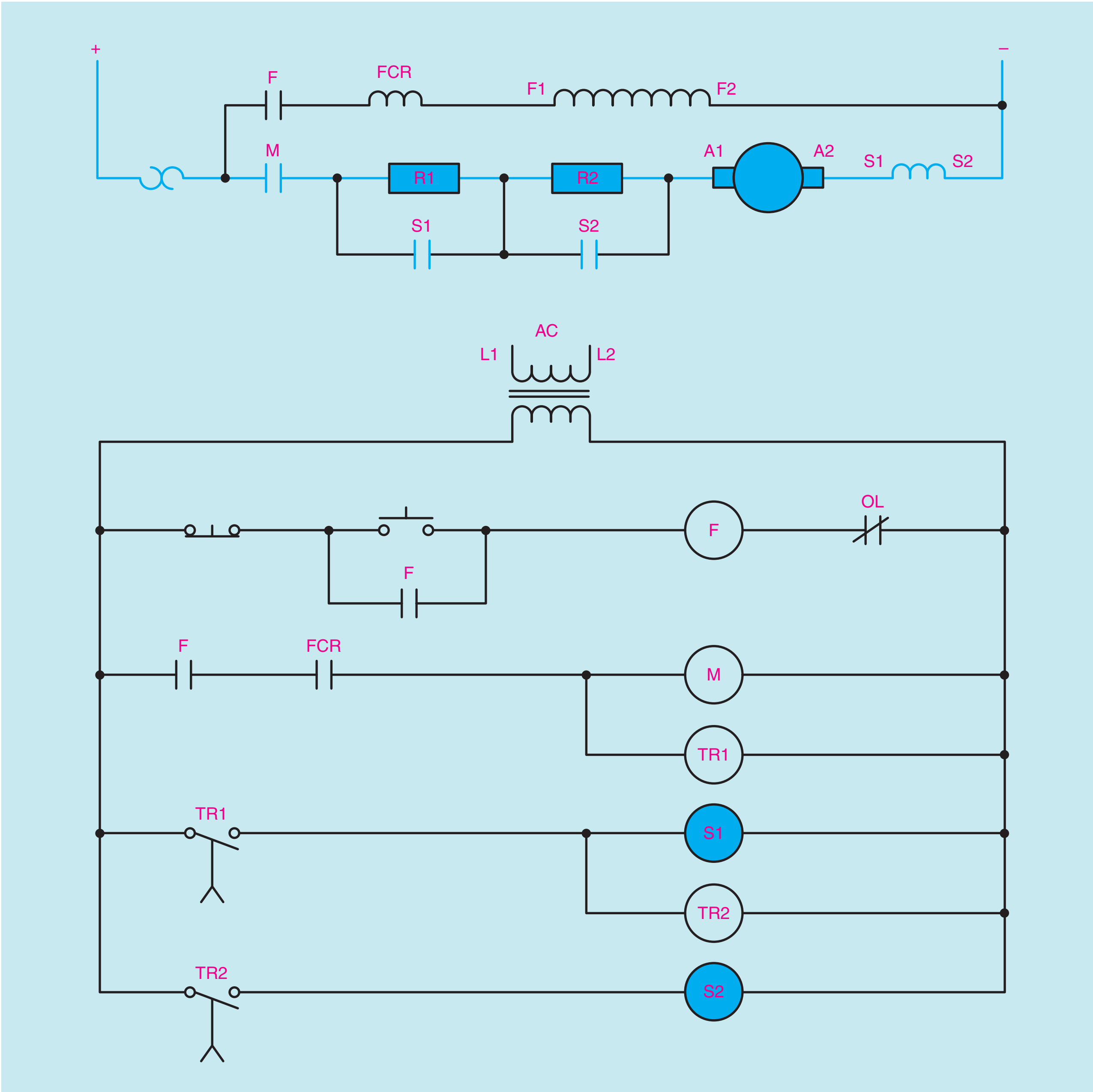


Figure 46–1 Time-delay starter for a dc motor.

M energizes, contact M closes and connects the armature circuit to the dc line. Five seconds after coil TR1 energizes, contact TR1 closes. This permits current to flow to relay coils S1 and TR2. When contact S1 closes, resistor R1 is shunted out of the circuit. Five seconds after relay coil TR2 energizes, contact TR2 closes. When contact TR2 closes, current can flow to coil S2. When contact S2 closes, resistor R2 is shunted out of the circuit and the armature is connected directly to the dc power line.

When the STOP button is pushed, relay F de-energizes and opens all F contacts. This breaks the circuit to starter coil M which causes contact M to open and disconnect the armature from the line. When coil TR1 de-energizes, contact TR1 opens immediately and de-energizes coils S1 and TR2. When coil TR2 de-energizes, contact TR2 opens immediately and de-energizes coil S2. All contacts in the circuit are back in their original positions, and the circuit is ready to be started again.

Review Questions

1. Why is resistance sometimes connected in series with large dc motors?
2. Is the field current relay a current relay or a voltage relay?
3. What happens if the motor is operating and the shunt field current stops flowing?
4. Describe the action of this circuit if TR1 and TR2 are replaced with off-delay relays.

UNIT 47
SOLID-STATE DC MOTOR CONTROLS

OBJECTIVES

After studying this unit, the student will be able to:

- Describe armature control.
- Discuss dc voltage control with a three-phase bridge rectifier.
- Describe methods of current limit control.
- Discuss feedback for constant speed control.

Direct current motors are used throughout much of industry because of their ability to produce high torque at low speed, and because of their variable speed characteristics. Dc motors are generally operated at or below *normal speed.* Normal speed for a dc motor is obtained by operating the motor with full rated voltage applied to the field and armature. The motor can be operated at below normal speed by applying rated voltage to the field and reduced voltage to the armature.

In unit 46, resistance was connected in series with the armature to limit current and, therefore, speed. Although this method does work and was used in industry for many years, it is seldom used today. When resistance is used for speed control, much of the power applied to the circuit is wasted in heating the resistors, and the speed control of the motor is not smooth because resistance is taken out of the circuit in steps.

Speed control of a dc motor is much smoother if two separate *power supplies,* which convert the ac voltage to dc voltage, are used to control the motor instead of resistors connected in series with the armature (Figure 47–1). Notice that one power supply is used to supply a constant voltage to the shunt field of the motor, and the other power supply is variable and supplies voltage to the armature only.

The Shunt Field Power Supply

Most solid-state dc motor controllers provide a separate dc power supply which is used to furnish excitation current to the shunt field. The shunt field of most industrial motors requires a current of only a few amps to excite the field magnets; therefore, a small power supply can be

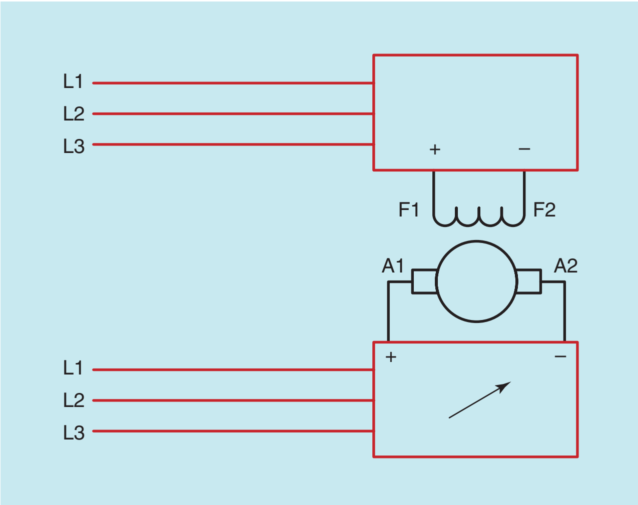


Figure 47–1 Separate power supplies used to control armature and field.

used to fulfill this need. The shunt field power supply is generally designed to remain turned on even when the main (armature) power supply is turned off. If power is connected to the shunt field even when the motor is not operating, the shunt field will act as a small resistance heater for the motor. This heat helps prevent moisture from forming in the motor due to condensation.

The Armature Power Supply

The armature power supply is used to provide variable dc voltage to the armature of the motor. This power supply is the heart of the solid-state motor controller. Depending on the size and power rating of the controller, armature power supplies can be designed to produce from a few amps to hundreds of amps. Most of the solid-state motor controllers intended to provide the dc power needed to operate large dc motors convert three-phase ac voltage directly into dc voltage with a three-phase bridge rectifier. (See Figure 3–6.)

The diodes of the rectifier, however, are replaced with SCRs to provide control of the output voltage (Figure 47–2). Figure 47–3 shows SCRs used for this type of dc motor controller. A large diode is often connected across the output of the bridge. This diode is known as a *freewheeling* or *kickback* diode and is used to kill inductive spike voltages produced in the armature. If armature power is suddenly interrupted, the collapsing magnetic field induces a high voltage into the armature windings. The diode is reverse biased when the power supply is operating under normal conditions, but an induced voltage is opposite in polarity to the applied voltage. This means the kickback diode will

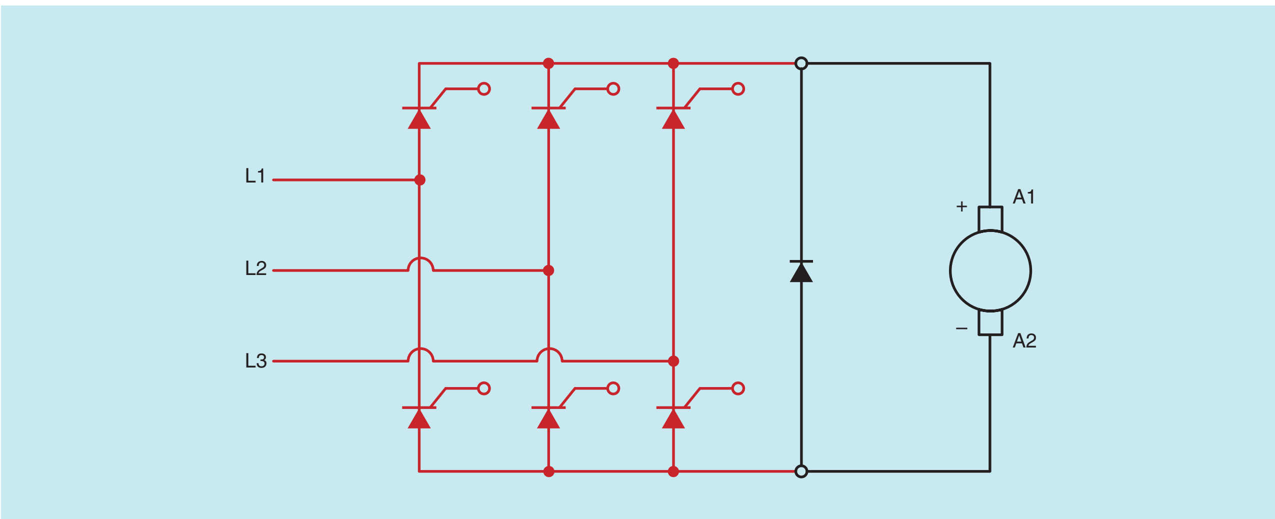


Figure 47–2 Three-phase bridge rectifier.

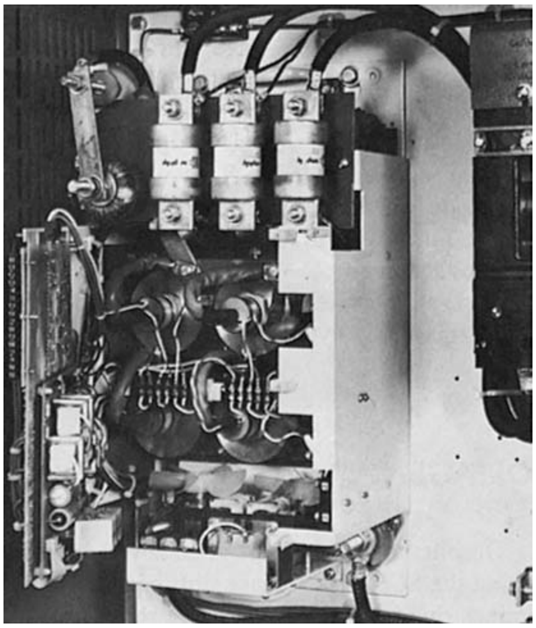


Figure 47–3 SCR controller for providing power to large DC motors. (Courtesy Eaton Corp., Cutler-Hammer Products.)

be forward biased to any voltage induced into the armature. Since a silicon diode has a voltage drop of .6 to .7 volts in the forward direction, a high voltage spike cannot be produced in the armature.

Voltage Control

Output voltage control is achieved by phase shifting the SCRs. The phase shift control unit determines the output voltage of the rectifier (Figure 47–4). Since the phase shift unit is the real controller of the circuit, other sections of the circuit provide information to the phase shift control unit. Figure 47–5 shows a typical phase shift control unit.

Field Failure Control

As stated previously, if current flow through the shunt field is interrupted, a compound wound, dc motor will become a series motor and race to high speeds. Some

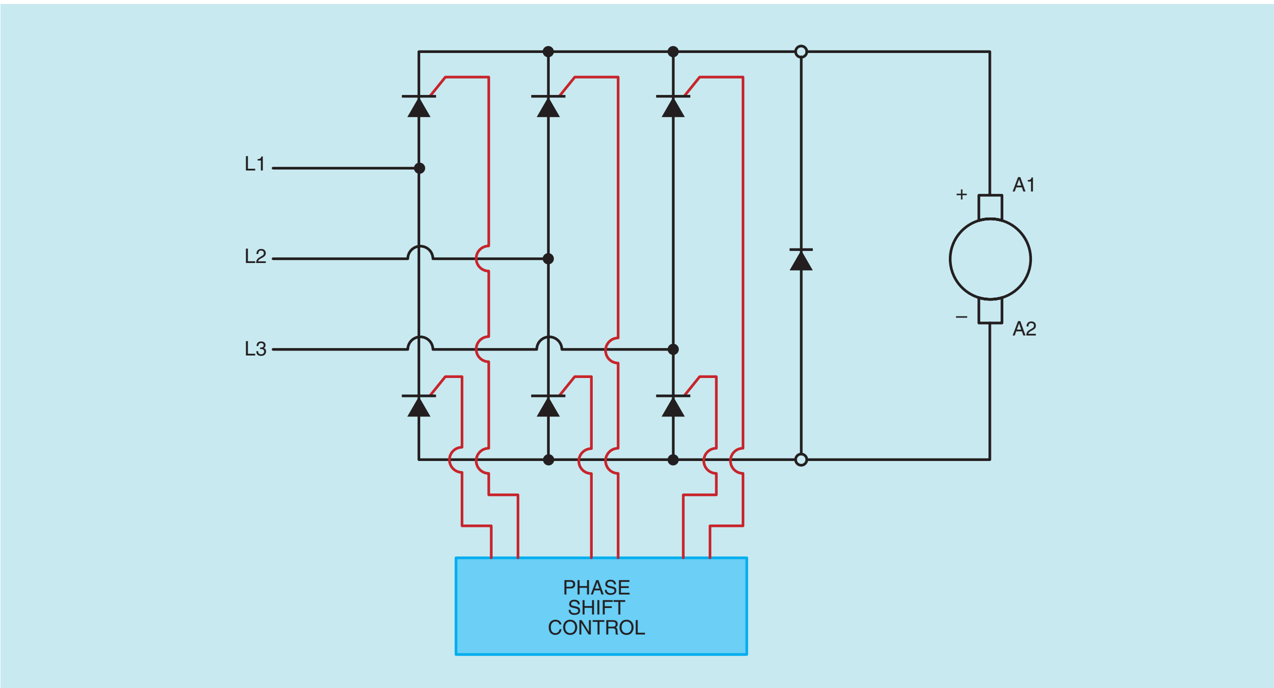


Figure 47–4 Phase shift controls output voltage.

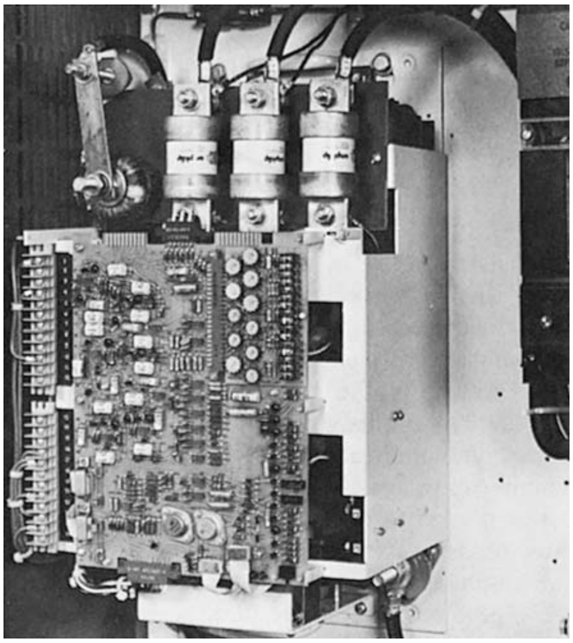


Figure 47–5 Phase shift control board for controlling SCRs. (Courtesy Eaton Corp., Cutler-Hammer Products.)

method must be provided to disconnect the armature from the circuit in case current flow through the shunt field stops. Several methods can be used to sense current flow through the shunt field. In unit 46, a current relay was connected in series with the shunt field. A contact of the current relay was connected in series with the coil of a motor starter used to connect the armature to the power line. If current flow were stopped, the contact of the current relay would open causing the circuit of the motor starter coil to open.

Another method used to sense current flow is to connect a low value of resistance in series with the shunt field (Figure 47–6). The voltage drop across the sense resistor is proportional to the current flowing through the resistor ($E = I \times R$). Since the sense resistor is connected in series with the shunt field, the current flow through the sense resistor must be the same as the current flow through the shunt field. A circuit can be designed to measure the voltage drop across the sense resistor. If this voltage falls below a certain level, a signal is sent to the phase shift control unit and the SCRs are turned off (Figure 47–7).

Current Limit Control

The armature of a large dc motor has a very low resistance, typically less than 1 ohm. If the controller is turned on with full voltage applied to the armature, or if the motor stalls while full voltage is applied to the armature, a very large current will flow. This current can damage the armature of the motor or the electronic components of the controller. For this reason, most solid-state, dc motor controls use some method to limit the current to a safe value.

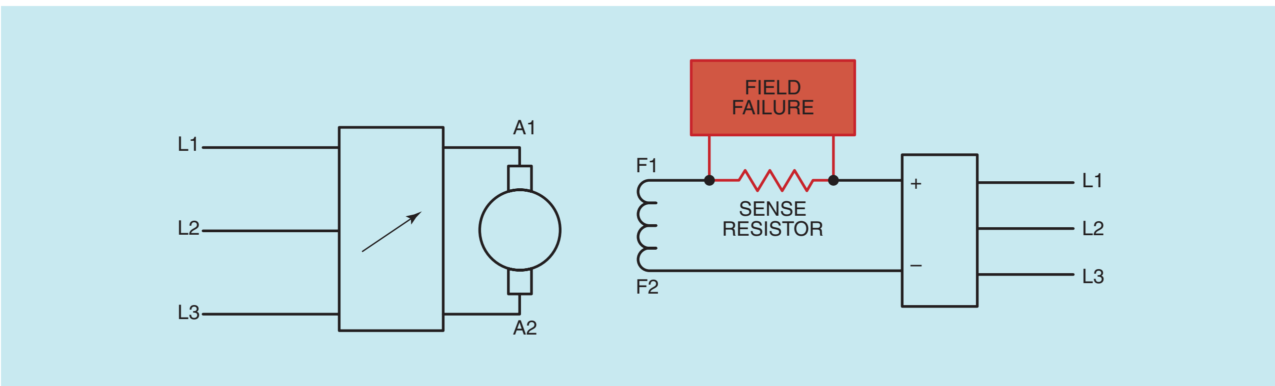


Figure 47–6 Resistor used to sense current flow through field.

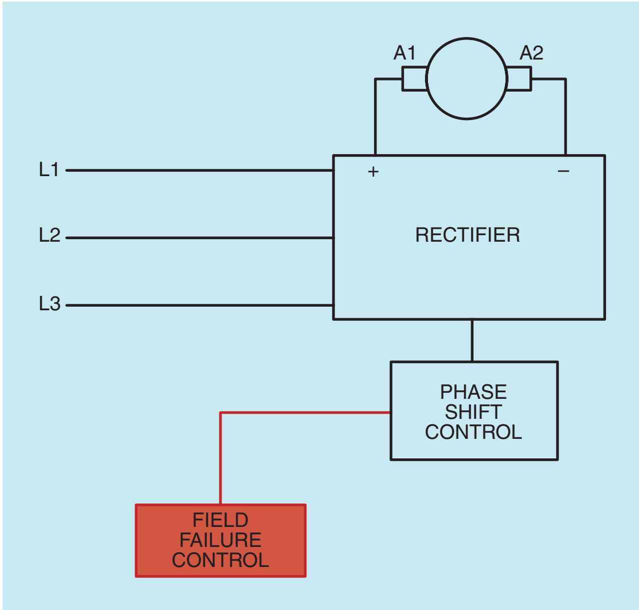


Figure 47–7 Field failure control signals the phase shift control.

One method of sensing the current is to insert a low value of resistance in series with the armature circuit. The amount of voltage dropped across the sense resistor in proportional to the current flow through the resistor. When the voltage drop reaches a certain level, a signal is sent to the phase shift control telling it not to permit any more voltage to be applied to the armature.

When dc motors of about 25 hp or larger are to be controlled, resistance connected in series with the armature can cause problems. Therefore, another method of sensing armature current can be used (Figure 47–8). In this circuit, current transformers are connected to the ac input lines. The current supplied to the rectifier will be proportional to the current supplied to the armature. When a predetermined amount of current is detected by the current transformers, a signal is sent to the phase shift control telling it not to permit the voltage applied to the armature to increase (Figure 47–9). This method of sensing the armature current has the advantage of not adding resistance to the armature circuit. Regardless of the method used, the current limit control signals the phase shift control, and the phase shift control limits the voltage applied to the armature.

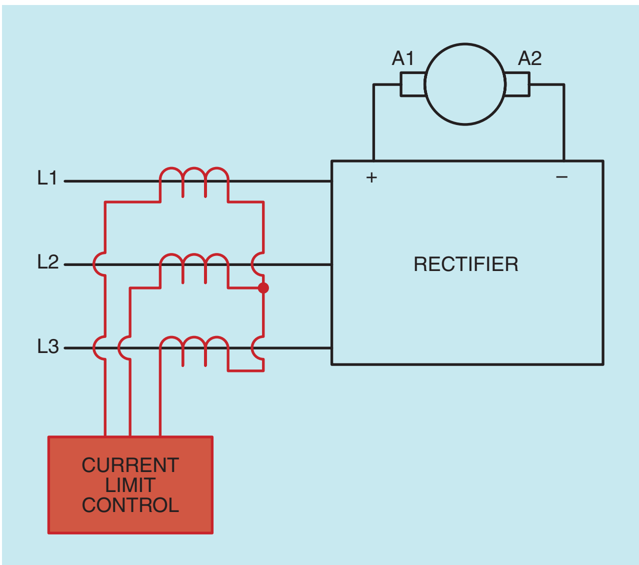


Figure 47–8 Current transformers measure ac line current.

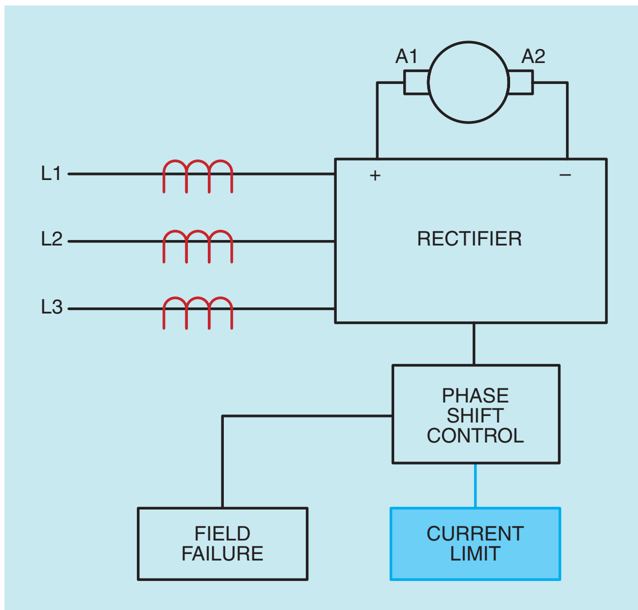


Figure 47–9 Current flow to armature is limited.

Speed Control

The greatest advantage of using direct current motors is their variable speed characteristic. Although the ability to change motor speed is often desirable, it is generally necessary that the motor maintain a constant speed once it has been set. For example, assume that a dc motor can be adjusted to operate at any speed from 0 to 1800 rpm. Now assume that the operator has adjusted the motor to operate at 1200 rpm. The operator controls are connected to the phase shift control unit (Figure 47–10). If the operator desires to change speed, a signal is sent to the phase shift control unit and the phase shift control permits the voltage applied to the armature to increase or decrease.

Dc motors, like many other motors, will change speed if the load is changed. If the voltage connected to the armature remains constant, an increase in load will cause the motor speed to decrease, or a decrease in load will cause the motor speed to increase. Since the phase shift unit controls the voltage applied to the armature, it can be used to control motor speed. If the motor speed is to be held constant, some means must be used to detect the speed of the motor. A very common method of detecting motor speed is with the use of an *electrotachometer* (Figure 47–11). An electrotachometer is a small, permanent, magnet generator connected to the motor shaft. The output voltage of the generator is proportional to its speed. The output voltage of the generator is connected to the phase shift control unit (Figure 47–12). If load is added to the motor, the motor speed will decrease. When the motor speed decreases, the output voltage of the electrotachometer drops. The phase shift unit detects the voltage drop of the tachometer and increases the armature voltage until the tachometer voltage returns to the proper value.

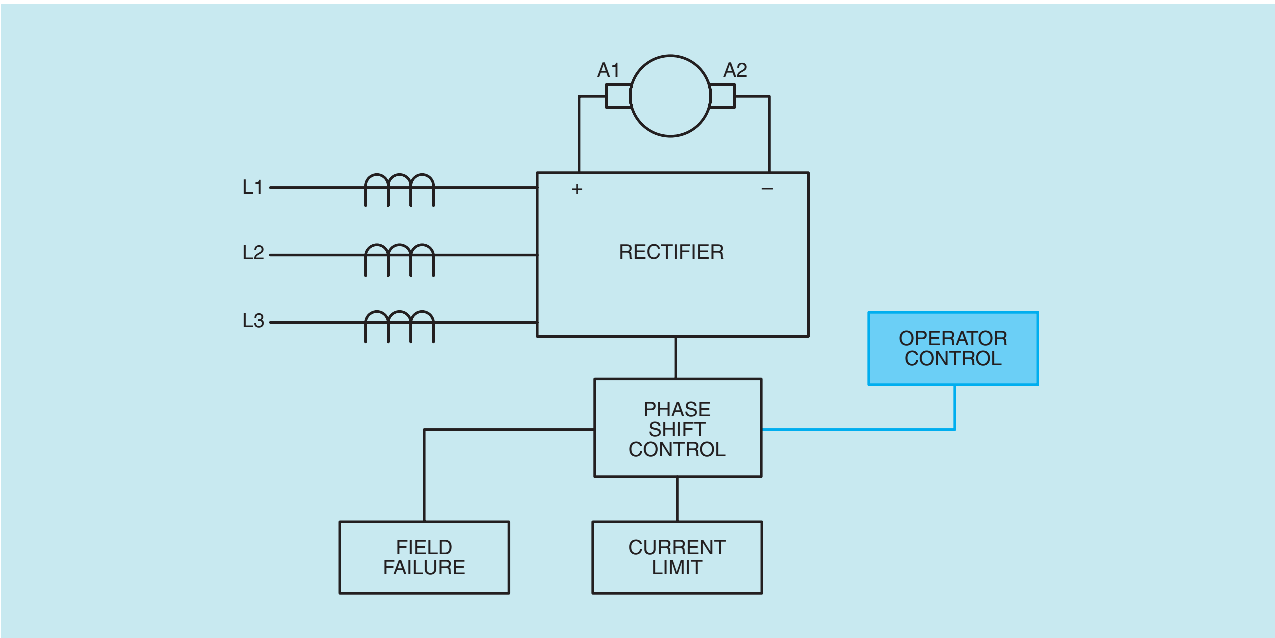


Figure 47–10 Operator control is connected to the phase shift control unit.

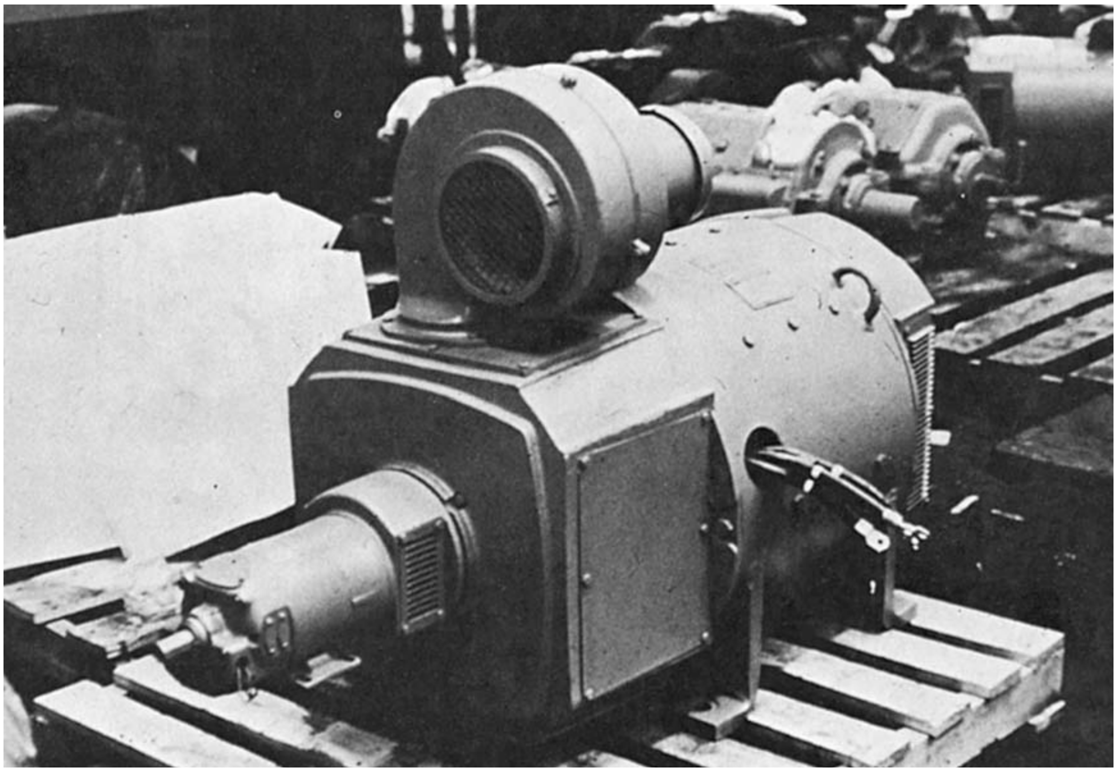


Figure 47–11 Direct current motor with tachometer attached for measuring motor speed. (Courtesy Allen-Bradley Co., Drives Division.)

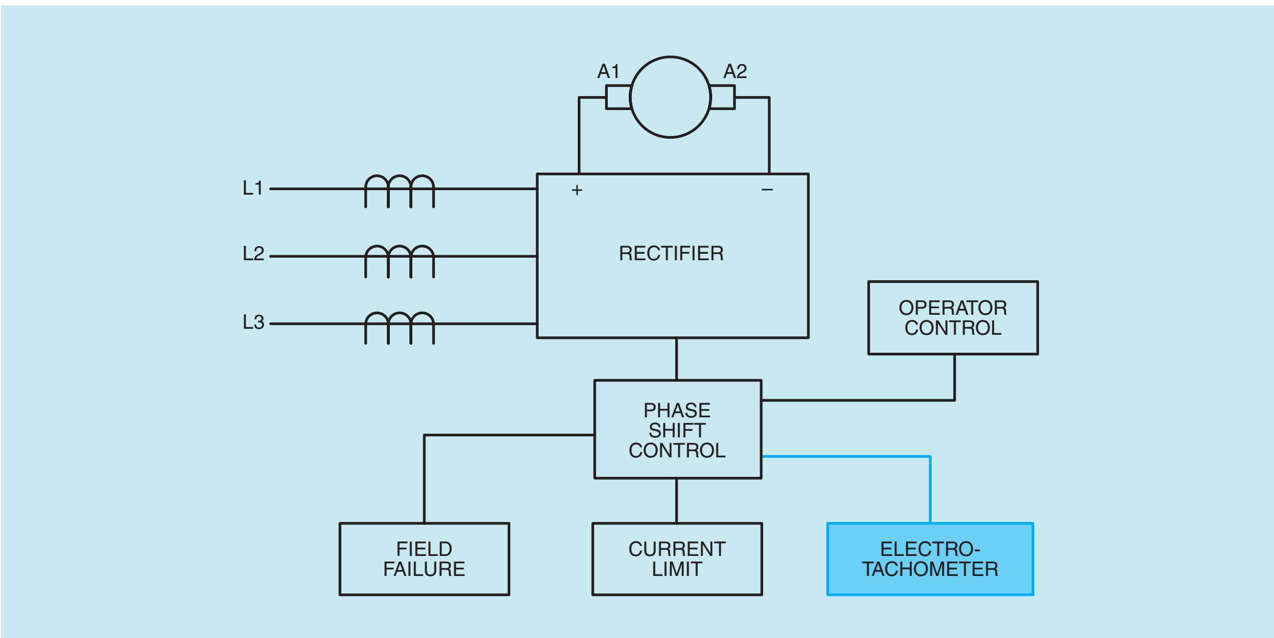


Figure 47–12 Electrotachometer measures motor speed.

If the load is removed, the motor speed will increase. An increase in motor speed causes an increase in the output voltage of the tachometer. The phase shift unit detects the increase of tachometer voltage and causes a decrease in the voltage applied to the armature. Electronic components respond so fast that there is almost no noticeable change in motor speed when load is added or removed. An SCR motor control unit is shown in Figure 47–13.

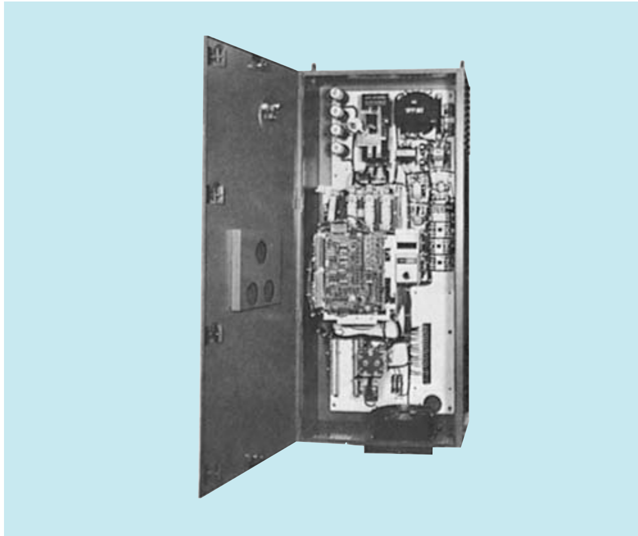


Figure 47–13 SCR motor control unit mounted in a cabinet. (Courtesy Eaton Corp., Cutler-Hammer Products.)

Review Questions

1. What electronic component is generally used to change the ac voltage into dc voltage in large dc motor controllers?
2. Why is this component used instead of a diode?
3. What is a "freewheeling" or "kickback" diode?
4. Name two methods of sensing the current flow through the shunt field.
5. Name two methods of sensing armature current.
6. What unit controls the voltage applied to the armature?
7. What device is often used to sense motor speed?
8. If the motor speed decreases, does the output voltage of the electrotachometer increase or decrease?

Section 6

AC MOTOR CONTROL

UNIT 48
STEPPING MOTORS

OBJECTIVES

After studying this unit, the student will be able to:

- Describe the operation of a dc stepping motor.
- Describe the operation of a stepping motor when connected to ac power.
- Discuss the differences between stepping motors and other types of motors.
- Discuss the differences between four-step and eight-step switching.

Stepping motors are devices that convert electrical impulses into mechanical movement. Stepping motors differ from other types of dc or ac motors in that their output shaft moves through a specific angular rotation each time the motor receives a pulse. Each time a pulse is received, the motor shaft moves a precise amount. The stepping motor allows a load to be controlled with regard to speed, distance, or position. These motors are very accurate in their control performance. Generally, less than 5% error per angle of rotation exists, and this error is not cumulative regardless of the number of rotations. Stepping motors are operated on dc power, but can be used as a two-phase synchronous motor when connected to ac power.

Theory of Operation

Stepping motors operate on the theory that like magnetic poles repel and unlike magnetic poles attract. Consider the circuit shown in Figure 48–1. In this illustration, the rotor is a permanent magnet and the stator winding consists of two electromagnetics. If current flows through the winding of stator pole A in such a direction that it creates a north magnetic pole, and through B in such a direction that it creates a south magnetic pole, it would be impossible to determine the direction of rotation. In this condition, the rotor could turn in either direction.

Now consider the circuit shown in Figure 48–2. In this circuit, the motor contains four stator poles instead

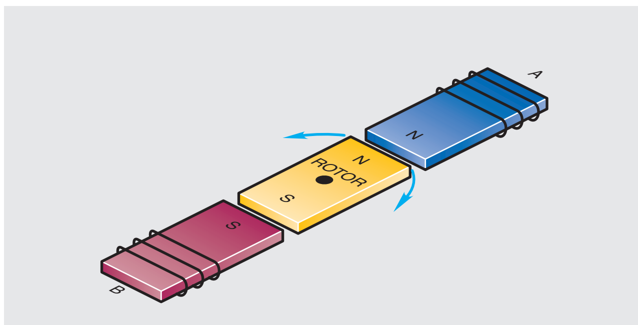


Figure 48–1 The rotor could turn in either direction.

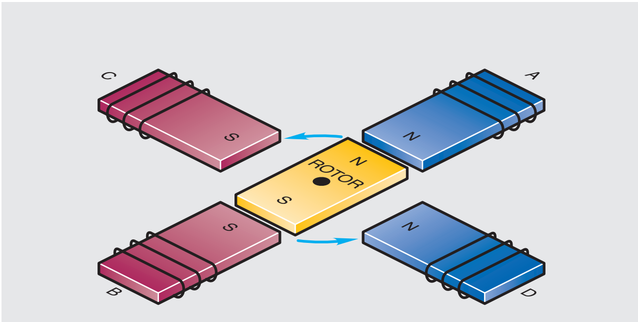


Figure 48–2 Direction of rotation is known.

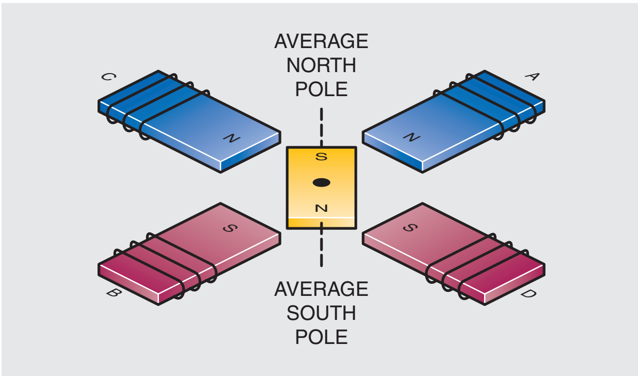


Figure 48–3 Rotor is positioned between the pole pieces.

of two. The direction of current flow through stator pole A is still in such a direction as to produce a north magnetic field; the current flow through pole B produces a south magnetic field. The current flow through stator pole C, however, produces a south magnetic field, and the current flow through pole D produces a north magnetic field. As illustrated, there is no doubt regarding the direction or angle of rotation. In this example, the rotor shaft will turn 90° in a counter-clockwise direction.

Figure 48–3 shows yet another condition. In this example, the current flow through poles A and C is in such a direction as to form a north magnetic pole, and the direction of current flow through poles B and D forms south magnetic poles. In this illustration, the permanent magnetic rotor has rotated to a position between the actual pole pieces.

To allow for better stepping resolution, most stepping motors have eight stator poles, and the pole pieces and rotor have teeth machined into them as shown in Figure 48–4. In practice, the number of teeth machined in the stator and rotor determines the angular rotation achieved each time the motor is stepped. The stator-rotor tooth configuration shown in Figure 48–4 produces an angular rotation of 1.8° per step.

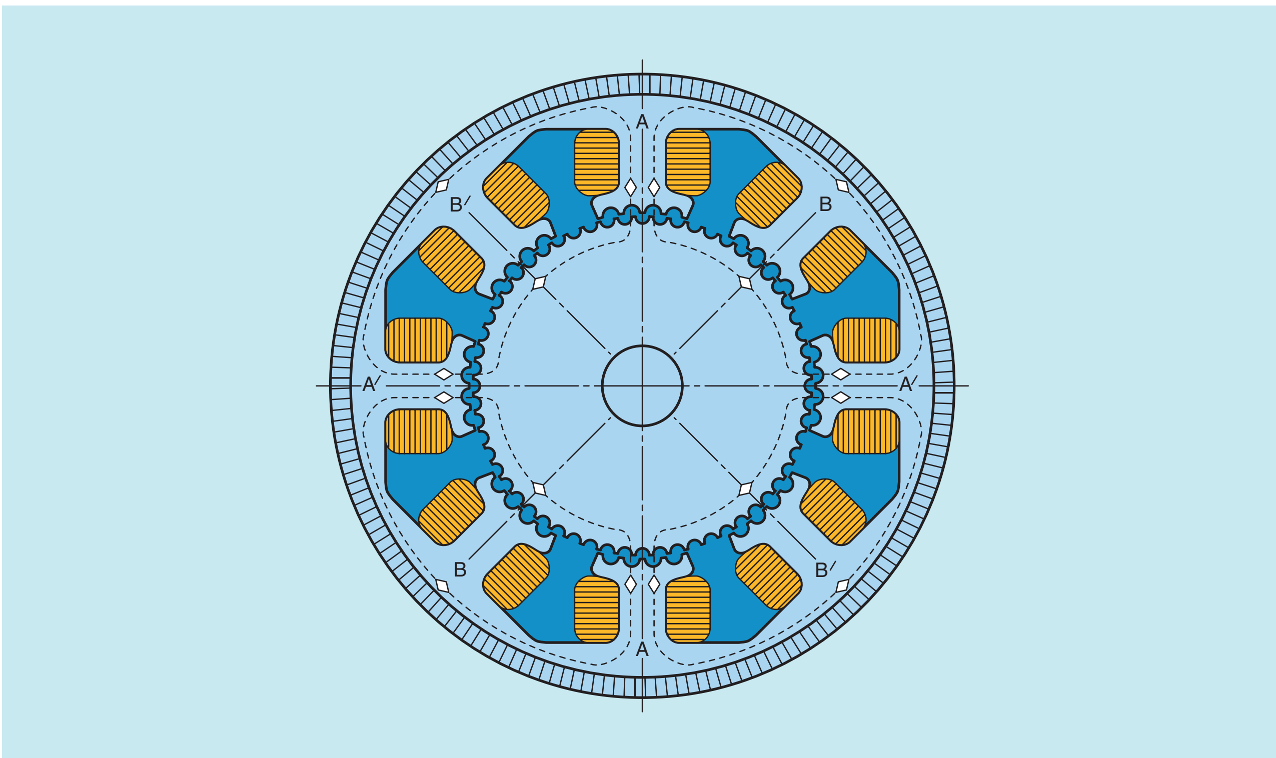


Figure 48–4 Construction of a dc stepping motor. (Courtesy The Superior Electric Company.)

Windings

There are different methods for winding stepper motors. A standard three-lead motor is shown in Figure 48–5. The common terminal of the two windings is connected to ground of an above- and below-ground power supply. Terminal 1 is connected to the common of a single-pole double-throw switch (switch #1) and terminal 3 is connected to the common of another single-pole double-throw switch (switch #2). One of the stationary contacts of each switch is connected to the positive or above-ground voltage, and the other stationary contact is connected to the negative or below-ground voltage. The polarity of each winding is determined by the position setting of its control switch.

Stepping motors can also be wound *bifilar* as shown in Figure 48–6. The term *bifilar* means that there are two windings wound together. This is similar to a transformer winding with a center tap lead. Bifilar stepping motors have twice as many windings as the three-lead type, which makes it necessary to use smaller wire in the windings. This results in higher wire resistance in the winding, producing a better inductive-resistive (L/R) time constant for the bifilar wound motor. The increased L/R time constant results in better motor performance. The use of a bifilar stepper motor also simplifies the drive circuitry requirements. Notice that the bifilar motor does not require an above- and below-ground power supply. As a general rule, the power supply voltage should be about five times greater than the motor voltage. A current-limiting resistance is used in the common lead of the motor. This current-limiting resistor also helps to improve the L/R time constant.

Four-Step Switching (Full Stepping)

The switching arrangement shown in Figure 48–6 can be used for a four-step sequence. Each time one of the switches changes position, the rotor will advance one-fourth of a tooth. After four steps, the rotor has turned the angular rotation of one "full" tooth. If the rotor and stator have fifty teeth, it will require 200 steps for the motor to rotate one full revolution. This corresponds to an angular rotation of 1.8° per step. (360°/200 steps = 1.8° per step.) Figure 48–7 illustrates the switch positions for each step.

Eight-Step Switching (Half Stepping)

Figure 48–8 illustrates the connections for an eight-stepping sequence. In this arrangement, the center tap leads for phases A and B are connected through their

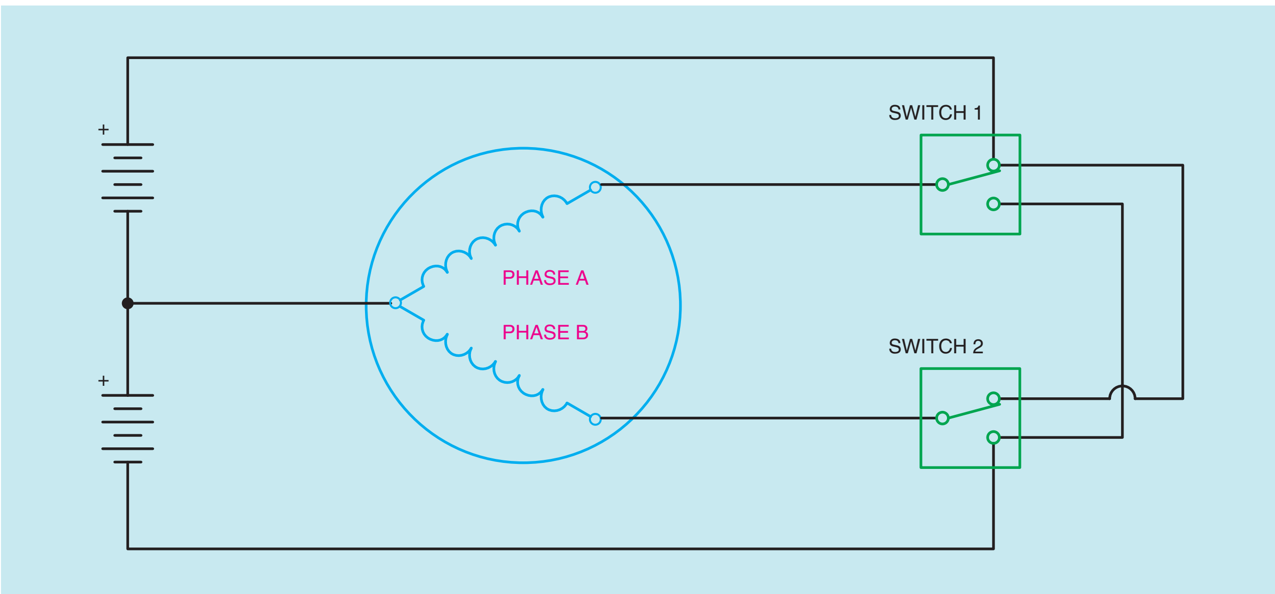


Figure 48–5 Standard three-lead motor.

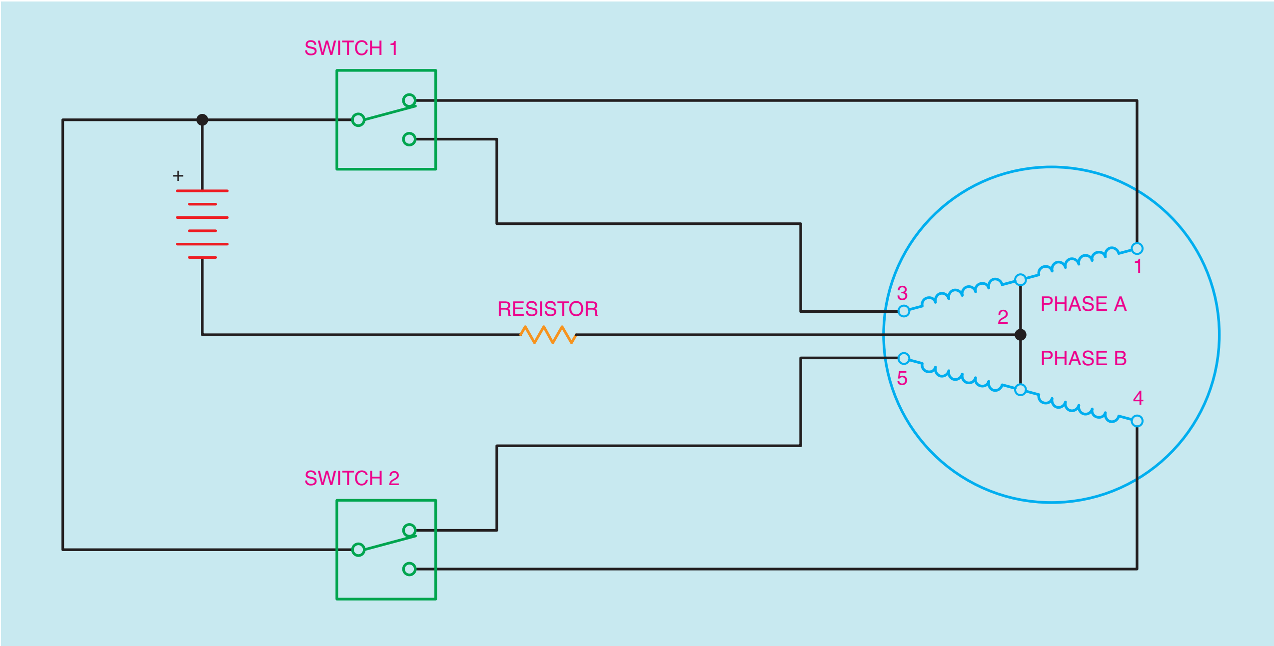


Figure 48–6 Bifilar wound stepping motor.

own separate current limiting resistors back to the negative of the power supply. This circuit contains four separate single pole switches instead of two switches. The advantage of this arrangement is that each step causes the motor to rotate one-eighth of a tooth instead of one-fourth of a tooth. The motor now requires 400 steps to produce one revolution which produces an angular rotation of 0.9° per step. This results in better stepping resolution and greater speed capability. The chart in Figure 48–9 illustrates the switch position for each step. Figure 48–10 depicts a solid-state switching circuit for an eight-step switching arrangement. A stepping motor is shown in Figure 48–11.

STEP	SWITCH #1	SWITCH #2
1	1	5
2	1	4
3	3	4
4	3	5
1	1	5

Figure 48–7 Four-step switching sequence.

AC Operation

Stepping motors can be operated on ac voltage. In this mode of operation, they become two-phase ac synchronous constant speed motors and are classified as a *permanent magnet induction motor.* Refer to the exploded diagram of a stepping motor in Figure 48–12. Notice that this motor has no brushes, slip rings, commutator, gears, or belts. Bearings maintain a constant air gap between the permanent magnet rotor and the stator windings. A typical eight-stator pole stepping motor will have a synchronous speed of 72 rpm when connected to a 60-hertz two-phase ac power line.

A resistive-capacitive network can be used to provide the 90° phase shift needed to change single-phase ac into two-phase ac. A simple forward-off-reverse switch can be added to provide directional control. A sample circuit of this type is shown in Figure 48–13. The correct values of resistance and capacitance are necessary for proper operation. Incorrect values can result in random direction of rotation when the motor is started, change of direction when the load is varied,

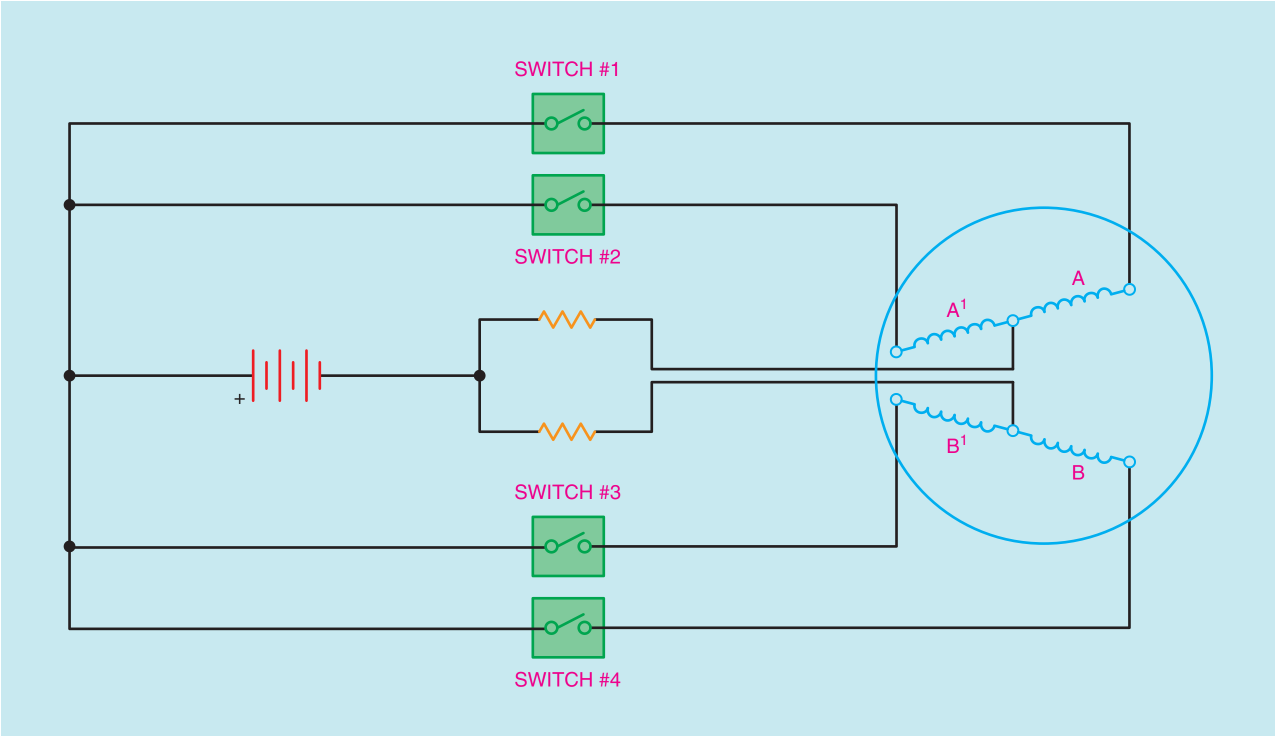


Figure 48–8 Eight-step switching.

STEP	SW #1	SW #2	SW #3	SW #4
1	ON	OFF	ON	OFF
2	ON	OFF	OFF	OFF
3	ON	OFF	OFF	ON
4	OFF	OFF	OFF	ON
5	OFF	ON	OFF	ON
6	OFF	ON	OFF	OFF
7	OFF	ON	ON	OFF
8	OFF	OFF	ON	OFF
1	ON	OFF	ON	OFF

Figure 48–9 Eight-step switching sequence.

erratic and unstable operation, as well as failure of the motor to start. The correct values of resistance and capacitance will be different with different stepping motors. The manufacturer's recommendations should be followed for the particular type of stepping motor used.

Motor Characteristics

When stepping motors are used as two-phase synchronous motors, they have the ability to virtually start, stop, or reverse direction of rotation instantly. The motor will start within about 1½ cycles of the applied voltage and stop within 5 to 25 milliseconds.

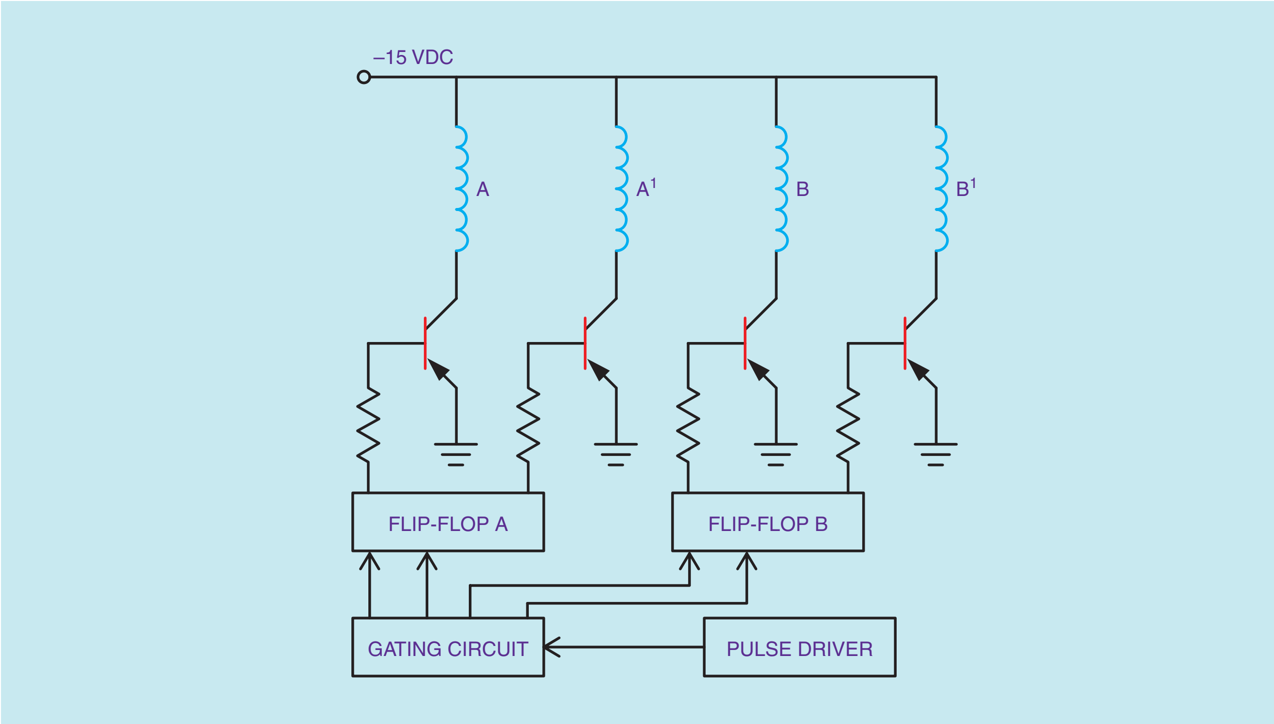


Figure 48–10 Solid state drive for eight-step switching circuit.

The motor can maintain a stalled condition without harm to it. Because the rotor is a permanent magnet, no induced current is in the rotor, and no high inrush of current occurs when the motor is started. The starting and running currents are the same. This simplifies the power requirements of the circuit used to supply the motor. Due to the permanent magnetic structure of the rotor, the motor does provide holding torque when turned off. If more holding torque is needed, dc voltage can be applied to one or both windings when the motor is turned off. An example circuit of this type is shown in Figure 48–14. If dc voltage is applied to one winding, the holding torque will be approximately 20% greater than the *rated* torque of the motor. If dc voltage is applied to both windings, the holding torque will be about 1½ times greater than the rated torque.

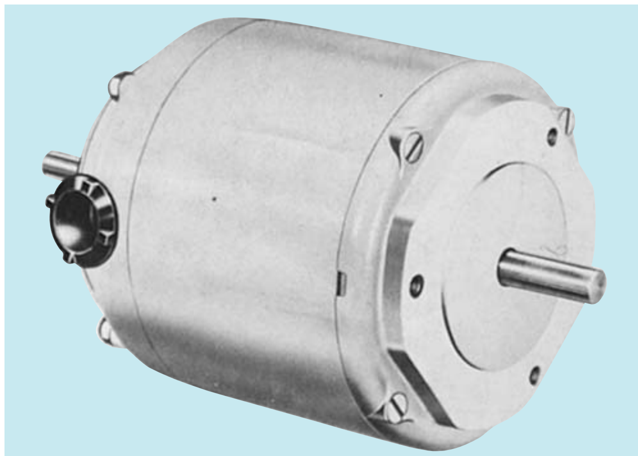


Figure 48–11 DC stepping motor. (Courtesy The Superior Electric Company.)

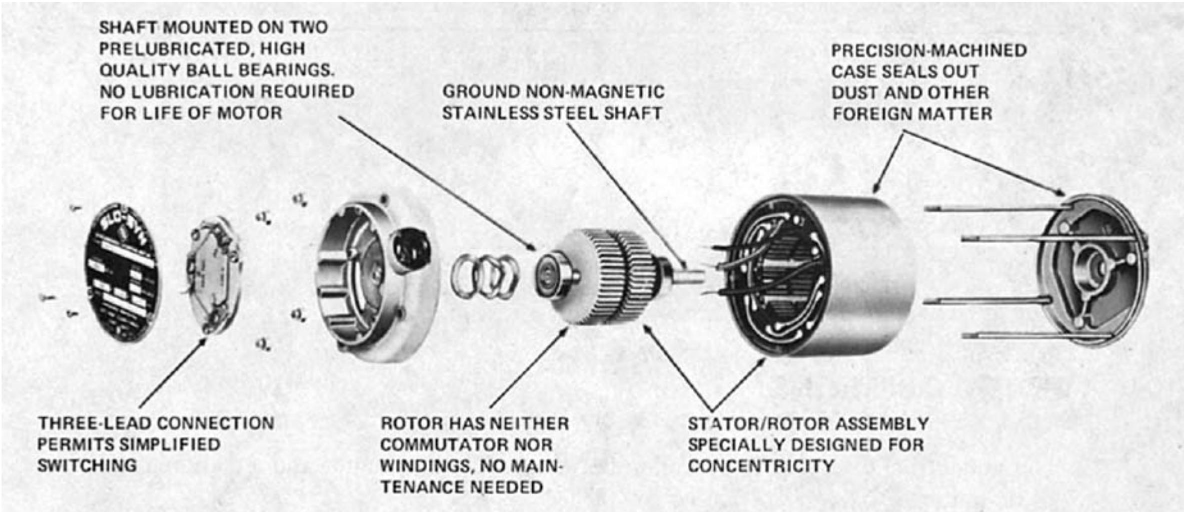


Figure 48–12 Exploded diagram of a stepping motor. (Courtesy The Superior Electric Company.)

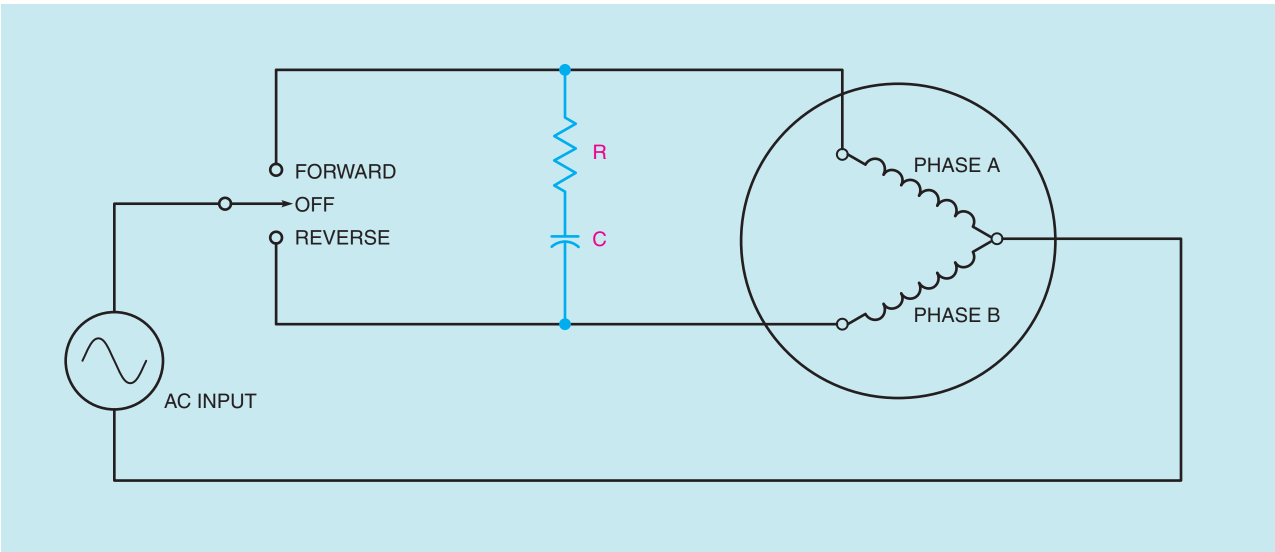


Figure 48–13 Phase shift circuit converts single-phase into two-phase.

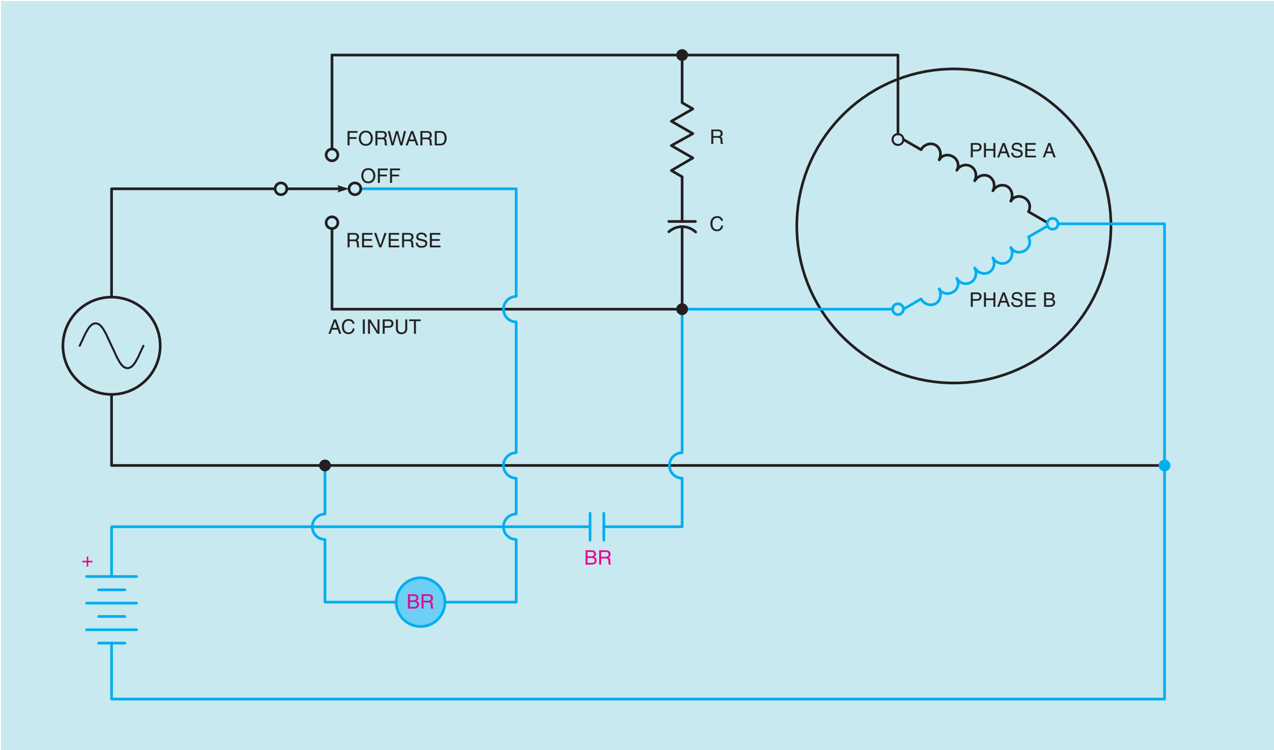


Figure 48–14 Applying dc voltage to increase holding torque.

Review Questions

1. Explain the difference in operation between a stepping motor and a common dc motor.
2. What is the principle of operation of a stepping motor?
3. What does the term bifilar mean?
4. Why do stepping motors have teeth machined in the stator poles and rotor?
5. When a stepping motor is connected to ac power, how many phases must be applied to the motor?
6. How many degrees out of phase are the voltages of a two-phase system?
7. What is the synchronous speed of an eight-pole stepping motor when connected to a two-phase 60-hertz ac line?
8. How can the holding torque of a stepping motor be increased?

UNIT 49

THE MOTOR AND STARTING METHODS

OBJECTIVES

After studying this unit, the student will be able to:

- Describe the most important factors to consider when selecting motor starting equipment.
- State why reduced current starting is important.
- Describe typical starting methods.
- Identify squirrel cage induction motors.
- Describe how a squirrel cage motor functions.

There are two reasons for the use of reduced voltage starting:

1. To reduce the high starting current drawn by the motor.
2. To reduce the starting torque provided by the motor.

The simplicity, ruggedness, and reliability of squirrel cage induction motors have made them the standard choice for alternating-current, all-purpose, constant speed motor applications. Several types of motors are available; therefore, various kinds of starting methods and control equipment are also obtainable.

The Motor

The Revolving Field

The squirrel cage motor consists of a frame, a stator, and a rotor. The *stator,* or stationary portion carries the stator windings (Figure 49–1, center). The *rotor* is a rotating member (Figure 49–1, bottom) which is constructed of steel laminations mounted rigidly on the motor shaft. The rotor winding consists of many copper, or aluminum, bars fitted into slots in the rotor. The bars are connected at each end by a closed continuous

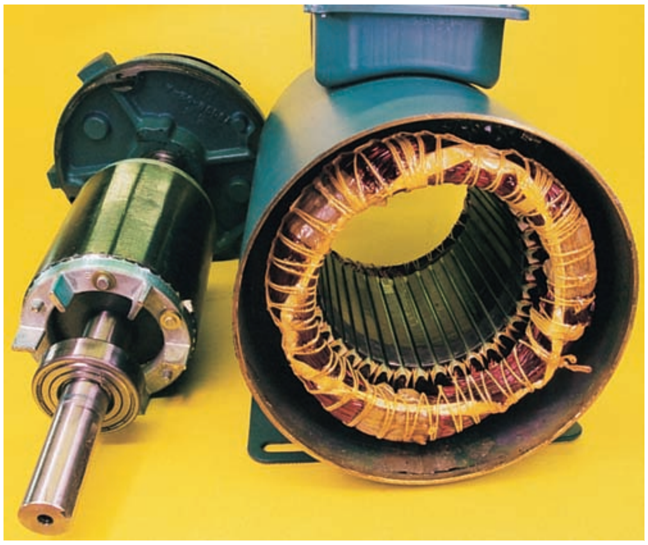


Figure 49–1 Squirrel cage induction motor frame, stator, and rotor.

ring. The assembly of the rotor bars and end rings resembles a squirrel cage. This similarity gives the motor its name, *squirrel cage motor.*

For a three-phase motor, the stator frame has three windings. The stator for a squirrel cage motor never has fewer than two poles. The stator windings are connected to the power source. When a 60-hertz current flows in the stator winding, a magnetic field is produced. Because of the three-phase alternating current and the displacement of each phase winding, this field circles the rotor at a speed equal to the number of revolutions per minute (r/min or rpm) divided by the number of pairs of stator poles. Therefore, on 60 hertz, a motor having one pair of two poles will run at 3600 r/min; a four-pole motor (two pairs of two poles each) will run at 1800 r/min (3600/2). The revolving stator magnetic field induces current in the short-circuited rotor bars. The induced current in the squirrel cage then has a magnetic field of its own. The two fields interact, with the rotor field following the stator rotating field, thereby establishing a torque on the motor shaft. The current induced has its largest value when the rotor is at a standstill. The current then decreases as the motor comes up to speed. In designing motors for specific applications, changing the resistance and reactance of the rotor will alter the characteristics of the motor. For any one rotor design, however, the characteristics are fixed. There are no external connections to the rotor. A cutaway view of an assembled squirrel cage motor is shown in Figure 49–2.

Locked Rotor Currents

The locked rotor current and the resulting torque are factors which determine if the motor can be connected across the line or if the current must be reduced to obtain the required performance. Locked rotor currents for different motor types vary from 2½ to 10 times the full-load current of the motor. Some motors, however, have even higher inrush currents.

The Induction Motor At Start

Figure 49–3 illustrates the behavior of the current taken by an induction motor at various speeds. First, note that the starting current is high compared to the running current. In addition, the starting current remains fairly constant at this high value as the motor speed increases. The current then drops sharply as the motor approaches its full rated speed. Since the motor heating rate is a function of 1^2R (copper loss), this rate is high during acceleration. For most of the acceleration

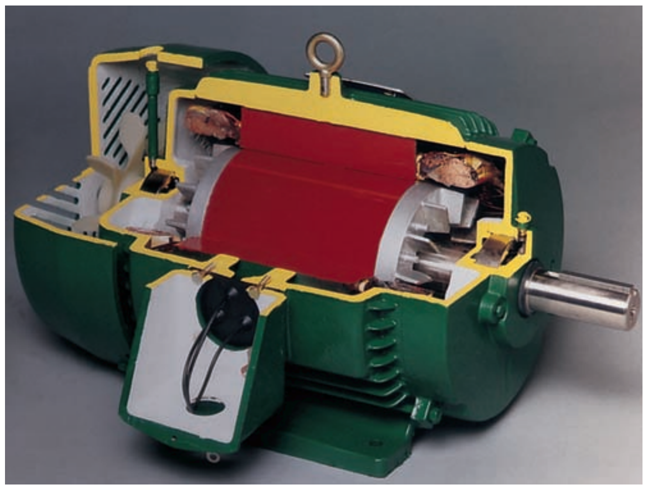


Figure 49–2 Cutaway view of a squirrel cage motor. (Courtesy Reliance Electric.)

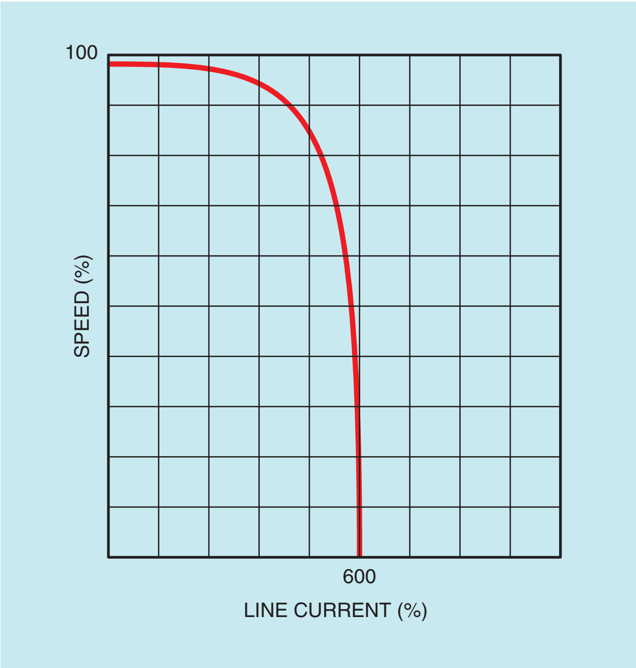


Figure 49–3 Induction motor current at various speeds.

period, the motor can be considered to be in the locked condition.

No-Load Rotor Speed

The induced current in the rotor gives rise to magnetic forces which cause the rotor to turn in the direction of rotation of the stator field. The motor accelerates until the necessary speed is reached to overcome windage and friction losses. This speed is referred to as the *no-load speed.* The motor never reaches synchronous speed since a current will not be induced in the rotor under these conditions and thus the motor will not produce a torque. *Torque* refers to the twisting or turning of the motor shaft. (The rotor bars of the squirrel cage must be cut by the rotating magnetic ac field to produce a torque.)

Speed Under Load

As the rotor slows down under load, the speed adjusts itself to the point where the forces exerted by the magnetic field on the rotor are sufficient to overcome the torque required by the load. *Slip* is the term given to the difference between the speed of the magnetic field and the speed of the rotor.

The slip necessary to carry the full load depends on the characteristics of the motor. In general, the following situations are true:

1. The higher the inrush current, the lower the slip at which the motor can carry full load, and the higher the efficiency.
2. The lower the value of inrush current, the higher the slip at which the motocan carry full load, and the lower the efficiency.

An increase in line voltage causes a decrease in the slip, and a decrease in line voltage causes an increase in the slip. In either case, sufficient current is induced in the rotor to carry the load. A decrease in the line voltage causes an increase in the heating of the motor. An increase in the line voltage decreases the heating. In other words, the motor can carry a larger load. The slip at rated load may vary from 3 percent to 20 percent for different types of motors.

Variation of Torque Requirements

Different loads have different torque requirements. This must be kept in mind when considering the starting torque required and the rate of acceleration most desirable for the load. In general, a number of motors will satisfy the load requirements of an installation under normal running conditions. However, it may be more difficult to use a motor that will perform satisfactorily during both starting and running. Often, it is necessary to decide which is the more important factor to consider for a particular application. For example, a motor may be selected to give the best starting performance, but there may be a sacrifice in the running efficiency. In another case, to obtain a high running efficiency, it may be necessary to use a motor with a high current inrush. For these and other examples, the selection of the proper starter to overcome the objectionable features is an important consideration in view of the high cost of energy today.

The machine to which the motor is connected may be started at no load, normal load, or overload conditions. Many industrial applications require that the machine be started when it is not loaded. Thus, the only torque required is that necessary to overcome the inertia of the machine. Other applications may require that the motor be started while the machine it is driving is subjected to the same load it handles during normal running. In this instance, the starting requirements

include the ability to overcome both the normal load and the starting inertia.

Important factors in providing the proper starting equipment include using a starter that satisfies the horsepower rating of the motor, and connecting the motor directly across the line. Another factor is that the motor itself must meet the torque requirements of the industrial application. Actually, the starting equipment may be selected to provide adequate control of the torque after the motor is selected.

Controlling Torque

The most common method of starting a polyphase, squirrel cage induction motor is to connect the motor directly to the plant distribution system at full voltage. In this case a manual or a magnetic starter is used. From the standpoint of the motor itself, this is a perfectly acceptable practice. As a matter of fact, it is probably the most desirable method of starting this type of motor.

Overload protective devices have reached such a degree of reliability that the motor is given every opportunity to make a safe start. The application of a reduced voltage to a motor in an attempt to prevent overheating during acceleration is generally wasted effort. The accelerating time will increase and correctly sized overload elements may still trip.

Reduced voltage starting minimizes the shock on the driven machine by reducing the starting torque of the motor. A high torque, applied suddenly, with full voltage starting, may cause belts to slip and wear or may damage gears, chains, or couplings. The material being processed, or conveyed, may be damaged by the suddenly applied jerk of high torque. By reducing the starting voltage, or current, at the motor terminals, the starting torque is decreased.

Reduced Voltage, Reduced Current, Reduced Torque

The category of reduced voltage methods generally includes all starting methods which deviate from standard, line voltage starting. Not all of these starting schemes reduce the voltage at the motor terminals. Even reduced voltage starters reduce the voltage only to achieve either the reduction of line current or the reduction of starting torque. The reduction of line current is the most commonly desired result.

You should note one important point: *When the voltage is reduced to start a motor, the current is also reduced, and so is the torque that the machine can deliver.* Regardless of the desired result (either reduced current or reduced torque), remember that the other will always follow.

If this fact is kept in mind, it is apparent that a motor which will not start a load on full voltage cannot start that same load at reduced voltage or reduced current conditions. Any attempt to use a reduced voltage or current scheme will not be successful in accelerating troublesome loads. The very process of reducing the voltage and current will further reduce the available starting torque.

Need for Reduced Current Starting

The most common function of reduced voltage starting devices is to reduce, or in some way modify, the starting current of an induction motor. In other words, the rate of change of the starting current is confined to prescribed limits, or there is a predetermined current-time picture that the motor presents to the supply wiring network.

A current-time picture for an entire area is maintained and regulated by the public power utility serving the area. The power company attempts to maintain a reasonably constant voltage at the points of supply so that lamp flicker will not be noticeable. The success of the power company in this attempt depends on the generating capacity to the area; transformer and line loading conditions and adequacies; and the automatic voltage regulating equipment in use. Voltage regulation also depends on the sudden demands imposed on the supply facilities by residential, commercial, and industrial customers. Transient overloading of the power supply may be caused by: (1) sudden high surges of reactive current from large motors on starting, (2) pulsations in current taken by electrical machinery driving reciprocating compressors and similar machinery, (3) the impulse demands of industrial x-ray equipment, and (4) the variable power factor of electric furnaces. All of these demands are capable of producing voltage fluctuations.

Therefore, each of these particularly difficult loads is regulated in some way by the power utility. The utility requires the use of some form of reduced voltage, reduced current method and helps its customers determine the best method.

Power company rules and regulations vary between individual companies and the areas served. The following list gives some commonly applied regulations. (All of the possible restricions on energy usage are not given.) An installation may be governed by just one of

these restrictions, or two or more rules may be combined. Regulations include:

1. A maximum number of starting amperes, either per horsepower or per motor.
2. A maximum horsepower for line starting. A limit in percent of full load current is set for anything above this value.
3. A maximum current in amperes for a particular feeder size. It is up to the user to determine if the motor will conform to the power company requirements.
4. A maximum rate of change of line current taken by the motor; for example, 200 amperes per half-second.

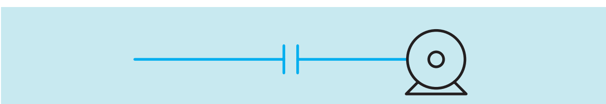
It should be apparent that it is very important for the electrician to understand the behavior of an induction motor during the startup and acceleration periods. Such an understanding enables you to select the proper starting method to conform to local power company regulations. Although several starting methods may appear to be appropriate, a careful examination of the specific application will usually indicate the one best method for motor starting.

Typical Starting Methods

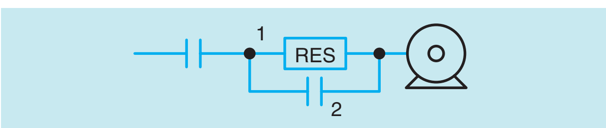
Starting Methods for Polyphase Motors

The most common methods of starting polyphase squirrel cage motors include:

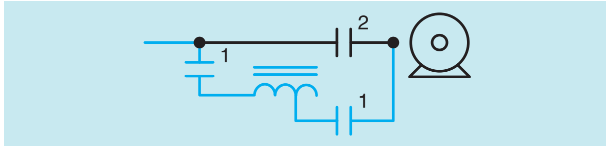
- *Full voltage starting:* a hand-operated or automatic starting switch throws the motor directly across the line.



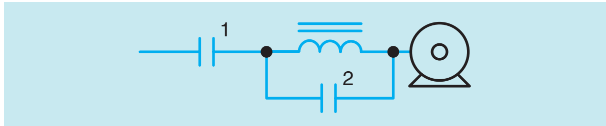
- *Primary resistance starting:* a resistance unit connected in series with the stator reduces the starting current.



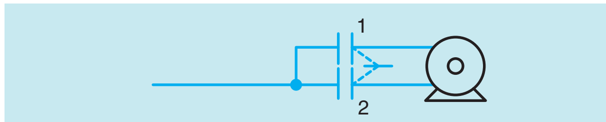
- *Auto transformer or compensator starting:* manual or automatic switching between the taps of the autotransformer gives reduced voltage starting.



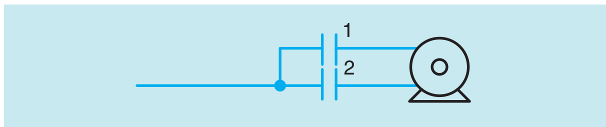
- *Impedance starting:* reactors are used in series with the motor.



- *Star-delta starting:* The stator of the motor is star connected for starting and delta connected for running.



- *Part winding starting:* the stator windings of the motor are made up of two or more circuits; the individual circuits are connected to the line in series for starting and in parallel for normal operation.



Of these methods, the two most fundamental ways of starting squirrel cage motors are full voltage starting and reduced voltage starting. Once again, full voltage starting can be used where the driven load can stand the shock of starting and objectionable line disturbances are not created. Reduced voltage starting may be required if the starting torque must be applied gradually or if the starting current produces objectionable line disturbances.

Starting Methods for Single-Phase Motors

Starting methods for single-phase motors involve disconnecting the start-winding of a split-phase motor when the motor reaches about 75% of its rated speed, as opposed to how the motor is connected to the power line. Single-phase motors are small horsepower and almost all are started across the line. There are several

different types of single-phase motors. The motors described in this unit are the split-phase type.

Split-phase motors derive their name from the manner in which they produce a rotating magnetic field in the stator winding. A rotating magnetic field is used to start the rotor turning and cannot be produced with a single phase. At least two phases must be present to produce a rotating field. Split-phase motors simulate the currents of a two-phase system, which are 90° out of phase with each other. This is accomplished by placing two separate windings in the core of the stator 90° apart, Figure 49–4. The run-winding is made of larger wire and is placed deeper in the slots of the core material. The start-winding is made with smaller wire and placed near the top of the slots in the core material. The run-winding, therefore, has less resistance and more inductance than the start-winding.

When the motor is started, these two windings are connected in parallel, Figure 49–5. Since the run-winding has more inductive reactance and less resistance than the start-winding, the current flow through the run-winding lags the voltage more than the current flow through the start-winding, producing an out of phase condition for these two currents. It is this out of phase condition that produces the rotating magnetic field. This type of split-phase motor is called a *resistance start* motor and produces a phase angle of about 35° to 40° between the current in the run-winding and the current in the start-winding. Although this phase angle is not 90°, it is enough to produce a rotating magnetic field to start the motor. When the rotor reaches about 75% of its rated speed, the start-winding is disconnected and the motor continues to operate with only the run-winding energized.

Although the resistance start motor will start with only a 35° to 40° phase shift between run-winding current and start-winding current, it produces a weak starting torque. Maximum starting torque is obtained when the run-winding and start-winding currents are 90° out of phase with each other. Some motors accomplish this by inserting an ac electrolytic capacitor in series with the start-winding (Figure 49–6). The capacitive reactance of

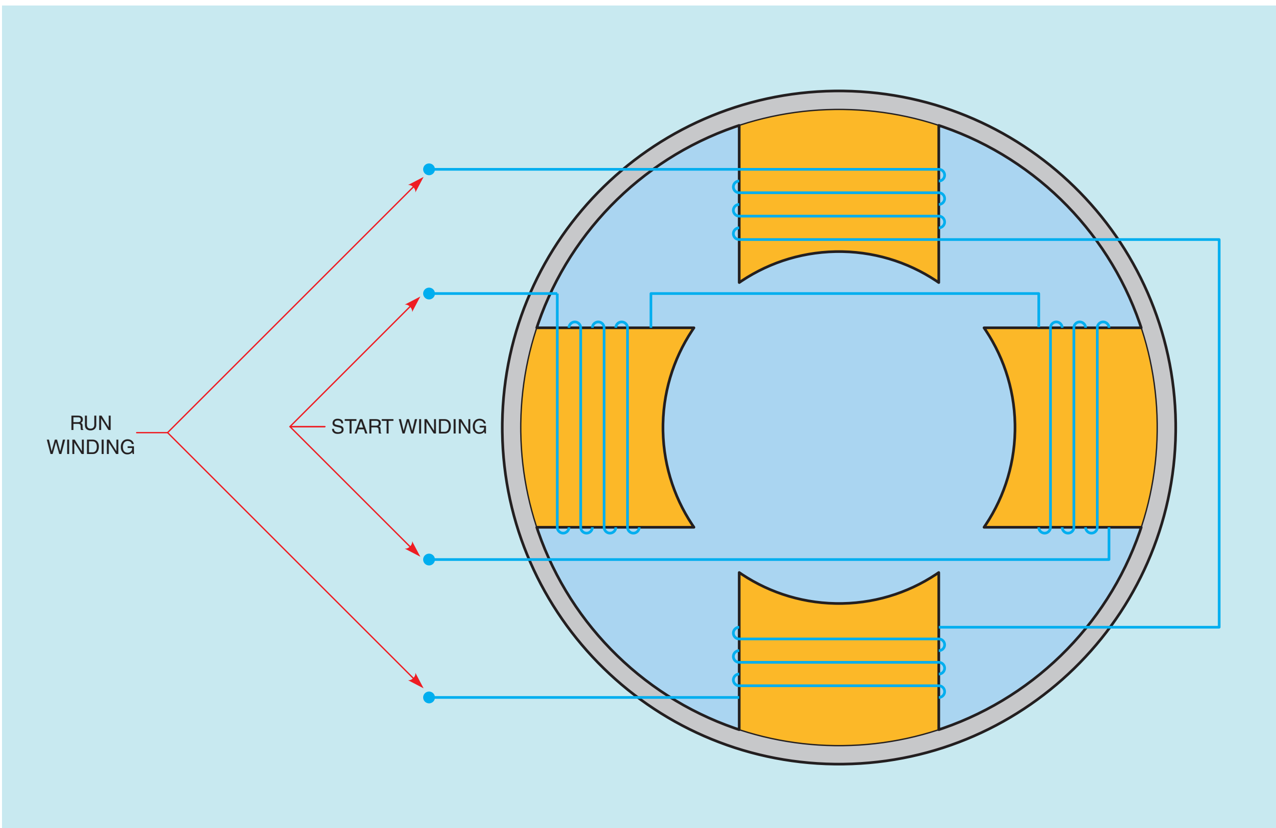


Figure 49–4 The run winding and start winding are connected in parallel with each other.

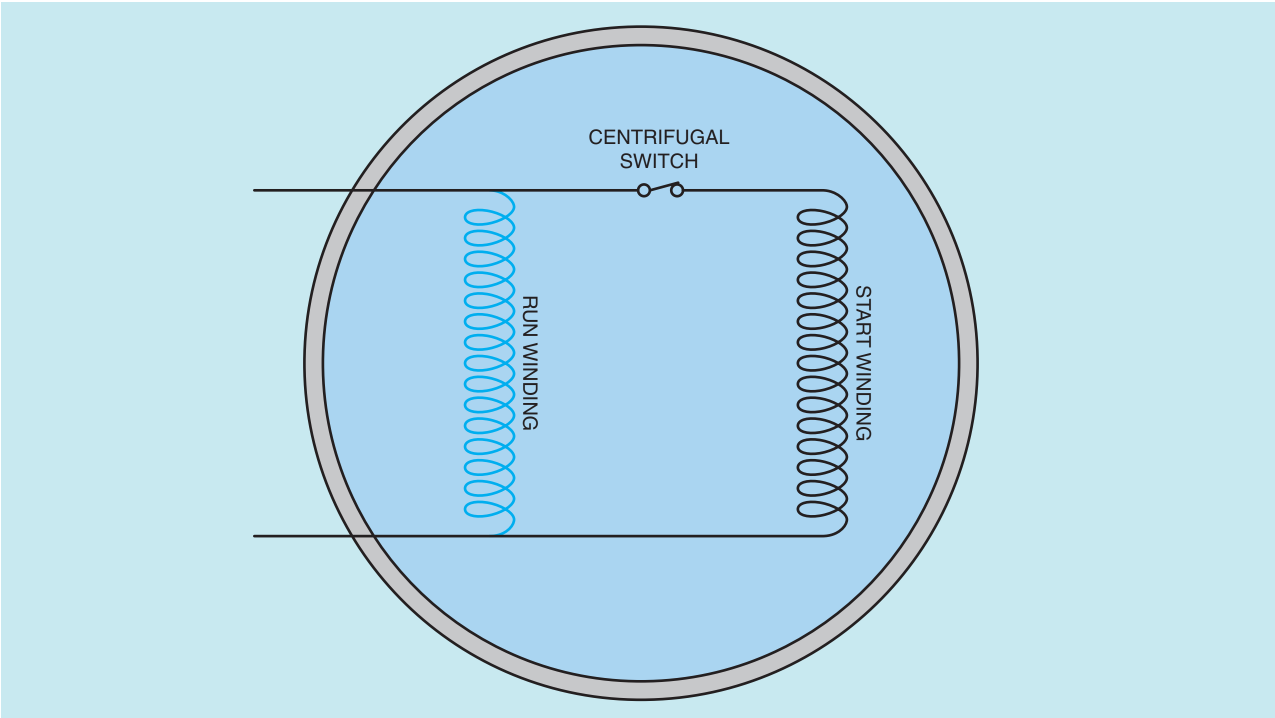


Figure 49–5 The run winding and start winding are connected in parallel with each other.

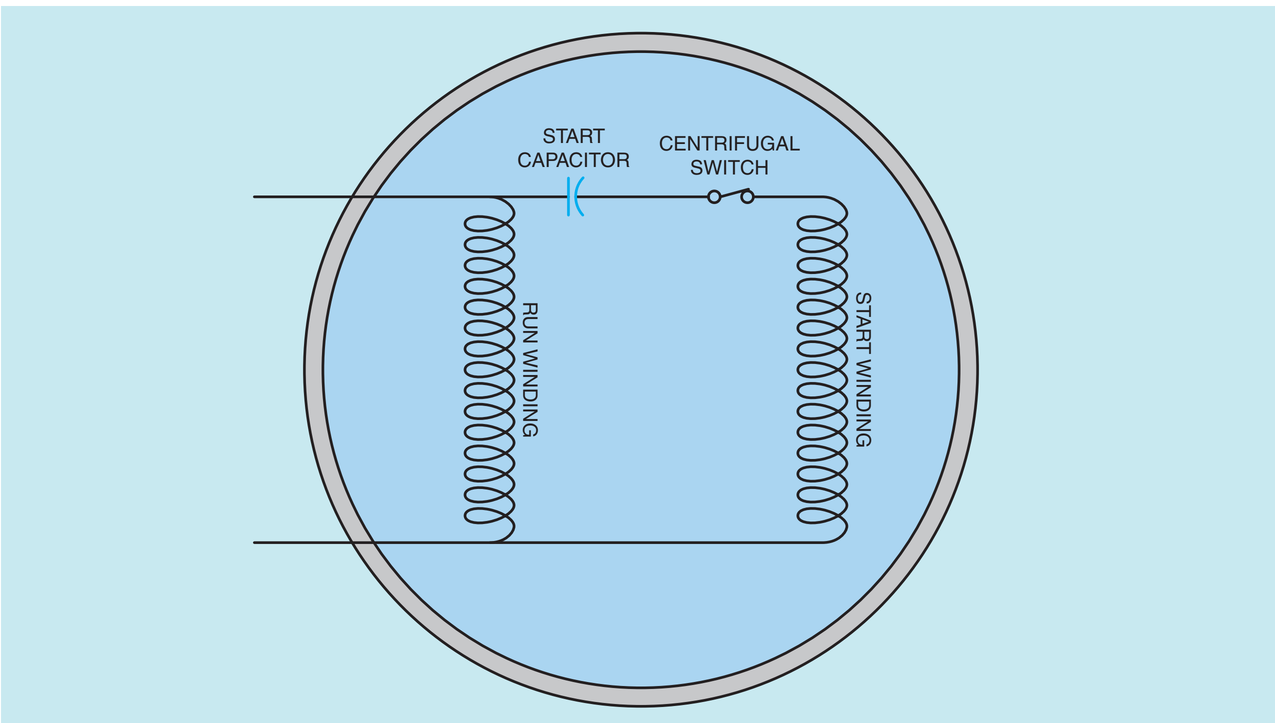


Figure 49–6 The starting capacitor produces a 90° phase shift between run winding current and start winding current.

the capacitor causes the start-winding current to lead the voltage and produce a 90° phase shift between the run-winding current and start-winding current.

Regardless of which method is used to produce the rotating magnetic field, the start-winding of either motor must be disconnected from the power line when the rotor reaches about 75% of its rated speed. Failure to do so would result in damage to the start-winding.

Centrifugal Switch

Split-phase motors intended to operate in the open accomplish this by the use of a centrifugal switch connected to the shaft of the rotor (Figure 49–7). The centrifugal switch is operated by spring loaded counter weights. When the rotor reaches a certain speed, the counter weights overcome the springs and open the switch, disconnecting the starting-winding from the power line.

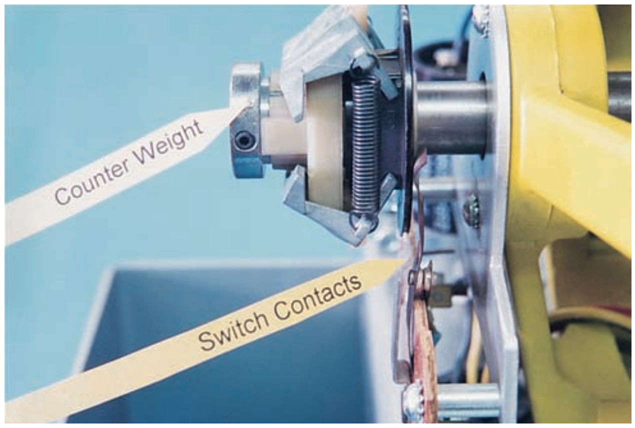


Figure 49–7 Centrifugal switch.

Hot Wire Starting Relay

Centrifugal switches cannot be used on all types of split-phase motors, however. Hermetically sealed motors used in refrigeration and air conditioning, or submerged pump motors must use some other means to disconnect the start-winding. Although the *hot wire relay* is seldom used anymore, it is found on some older units that are still in service. The hot wire relay functions as both a starting relay and an overload relay. In the circuit shown in Figure 49–8, it is assumed that

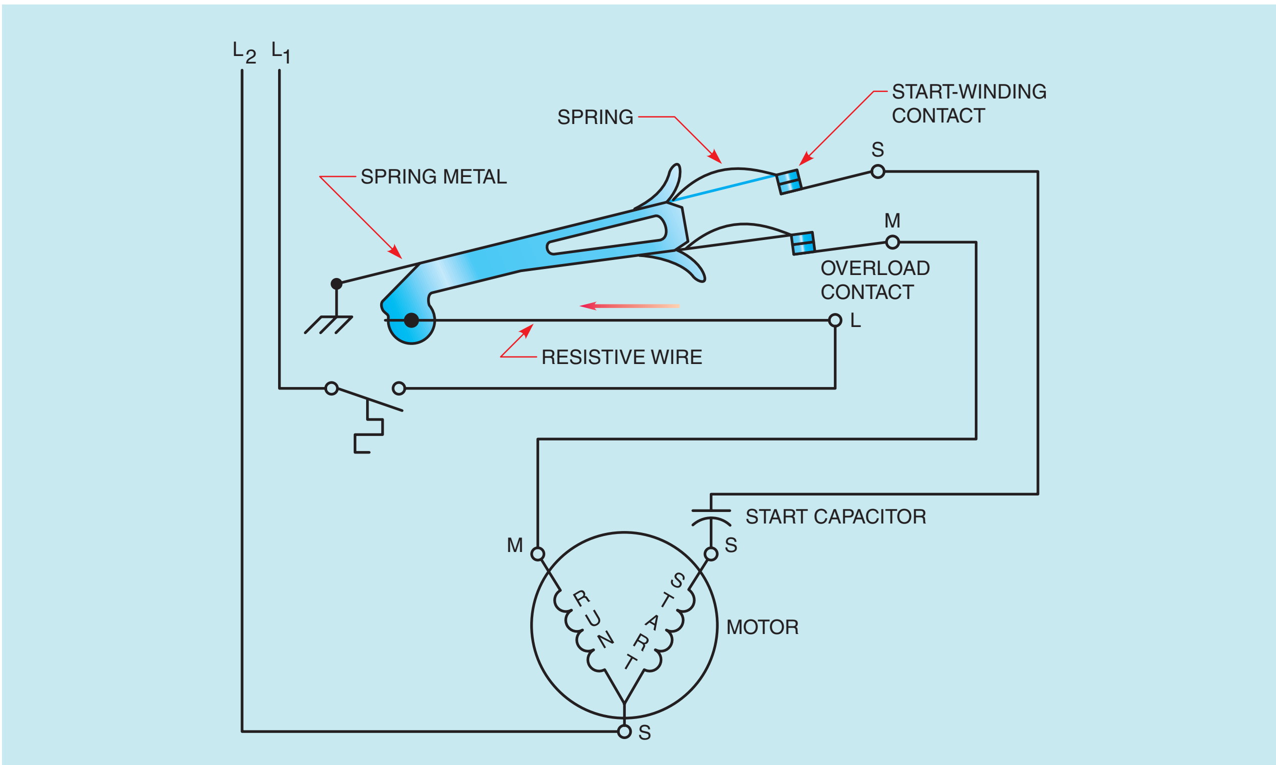


Figure 49–8 Hot-wire relay connection.

a thermostat controls the operation of the motor. When the thermostat closes, current flows through a resistive wire and two normally closed contacts connected to the start and run-windings of the motor. The starting current of the motor is high, which rapidly heats the resistive wire causing it to expand. The expansion of the wire causes the spring loaded startwinding contact to open and disconnect the start-winding from the circuit, reducing motor current. If the motor is not overloaded the resistive wire never becomes hot enough to cause the overload contact to open, and the motor continues to run. If the motor should become overloaded, however, the resistive wire will expand enough to open the overload contact and disconnect the motor from the line (Figure 49–9).

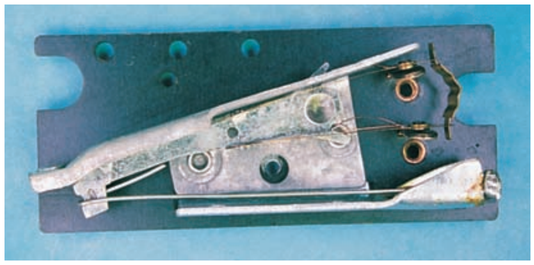


Figure 49–9 Hot-wire type of starting relay.

Current Relay

The *current relay* operates by sensing the amount of current flow in the circuit. This type of relay operates on the principle of a magnetic field instead of expanding metal. The current relay contains a coil with a few turns of large wire and a set of normally open contacts (Figure 49–10). The coil of the relay is connected in series with the run-winding of the motor, and the contacts are connected in series with the start-winding as shown in Figure 49–11. When the thermostat contact closes, power is applied to the run-winding of the motor. Since the start-winding is open, the motor

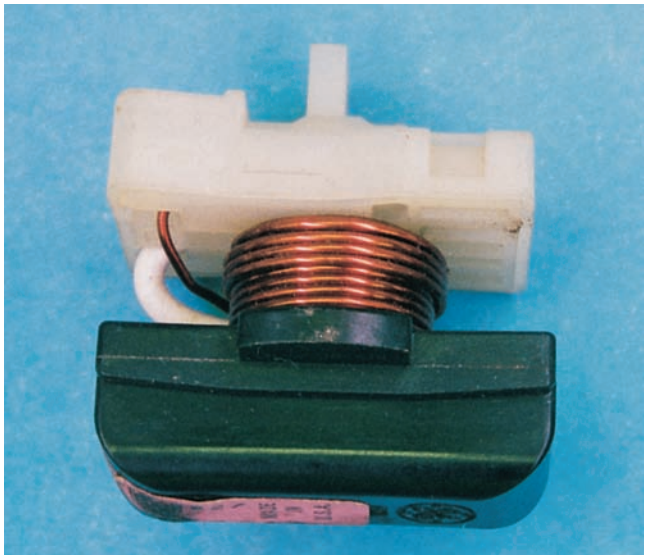


Figure 49–10 Current type of starting relay.

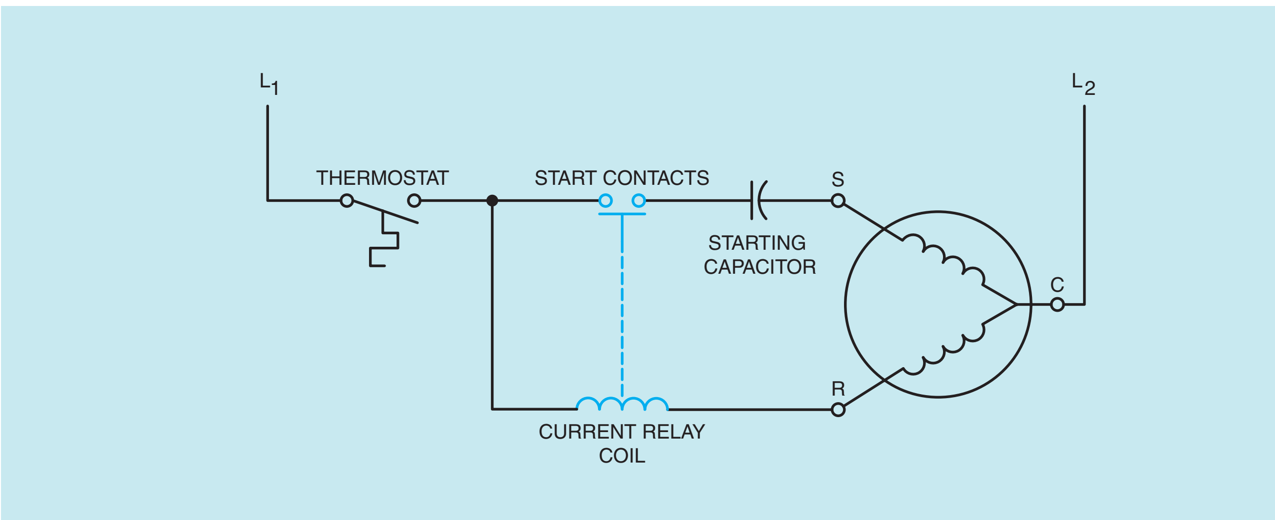


Figure 49–11 Current relay connection.

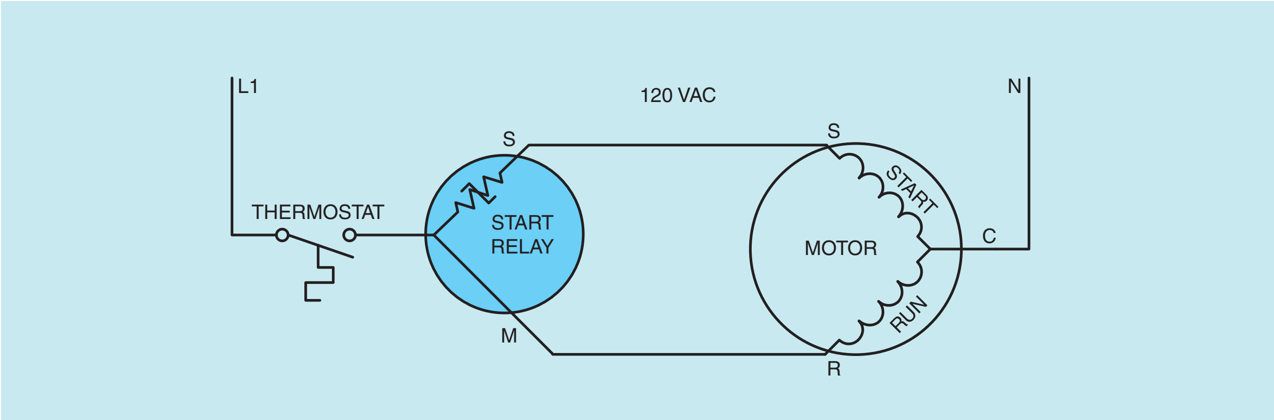


Figure 49–12 Solid state starting relay circuit.

cannot start. This causes a high current to flow in the run-winding circuit. This high current flow produces a strong magnetic field in the coil of the relay, causing the normally open contacts to close and connect the start-winding to the circuit. When the motor starts, the run-winding current is greatly reduced, permitting the start contacts to reopen and disconnect the start-winding from the circuit.

Solid State Starting Relay

The *solid state starting relay* is rapidly replacing the current starting relay. The solid state relay uses a solid state component called a *thermistor,* and therefore has no moving parts or contacts to wear or burn. A thermistor exhibits a rapid change of resistance when the temperature reaches a certain point. This particular thermistor has a positive coefficient of resistance, which means that it increases its resistance with an increase of temperature. The schematic diagram in Figure 49–12 illustrates the connection for a solid state starting relay.

When power is first applied to the circuit, the resistance of the thermistor is relatively low, 3 or 4 ohms, and current flows to both the run and start-windings. As current flows through the thermistor its temperature increases. When the temperature becomes high enough, the thermistor suddenly changes from a low resistance to a high resistance reducing the start-winding current to approximately 30 to 50 ma. This has the effect of disconnecting the start-winding from the circuit. Although a small amount of *leakage current* continues to flow, it has no effect on the operation of the motor. This leakage current maintains the temperature of the thermistor and prevents it from returning to a low resistance while the motor is in operation. When the motor is stopped, a cool-down period of 2 or 3 minutes should be allowed to permit the thermistor to return to a low resistance.

Potential Starting Relay

The *potential starting relay* is used with a different type of split-phase motor called the *capacitor start-capacitor run* or *permanent-split capacitor motor.* This type of split-phase motor does not disconnect the start-windings from the circuit. Since the start-winding remains energized, it operates very similarly to a true two-phase motor. All of these motors contain a run-capacitor that remains connected in the start-winding circuit at all times. Many of these motors contain a second capacitor that is used during the starting period only. This capacitor must be disconnected from the circuit when the motor reaches about 75% of its rated speed. Open case motors generally use a centrifugal switch to perform this function, but hermetically sealed motors generally depend on a potential starting relay (Figure 49–13). The potential relay operates by sensing the increase of voltage induced in the start-winding when the motor is in operation. The coil of the relay is connected in parallel with the start-winding of the motor. A normally closed SR contact is connected in series with the starting-capacitor. When power is connected to the motor, both the run and start-windings are energized. At this time, both the run and start-capacitors are connected in the start-winding circuit.

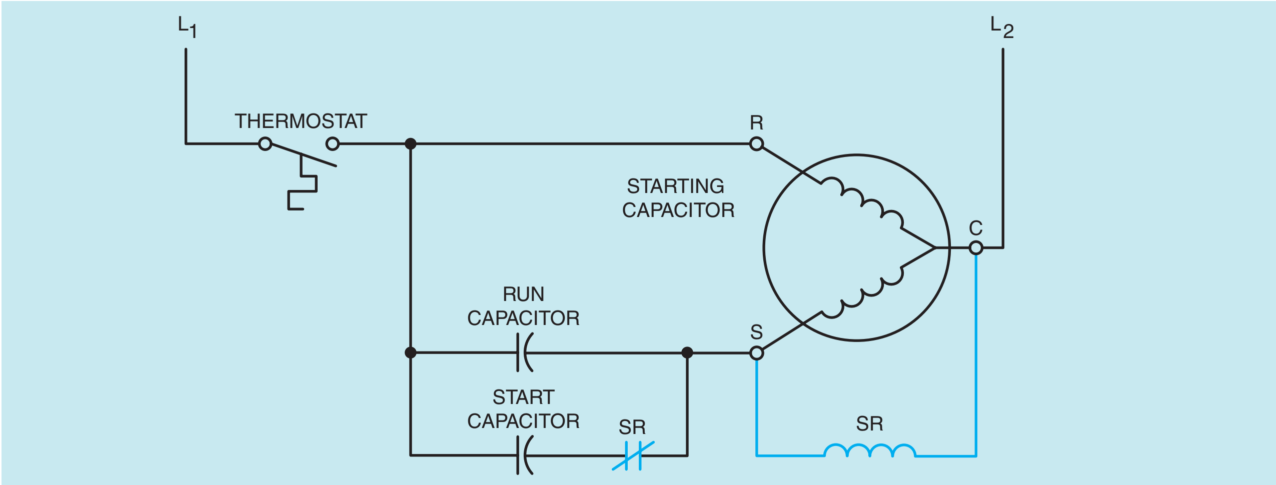


Figure 49–13 Potential relay connection.

The rotating magnetic field of the stator induces a current in the rotor of the motor. As the rotor begins to turn, its magnetic field induces a voltage into the start-winding, increasing the total voltage across the winding. Since the coil of the potential relay is connected in parallel with the start-winding, this voltage increase is applied to it also, causing the normally closed contact connected in series with the starting-capacitor to open and disconnect the starting-capacitor from the circuit (Figure 49–14).

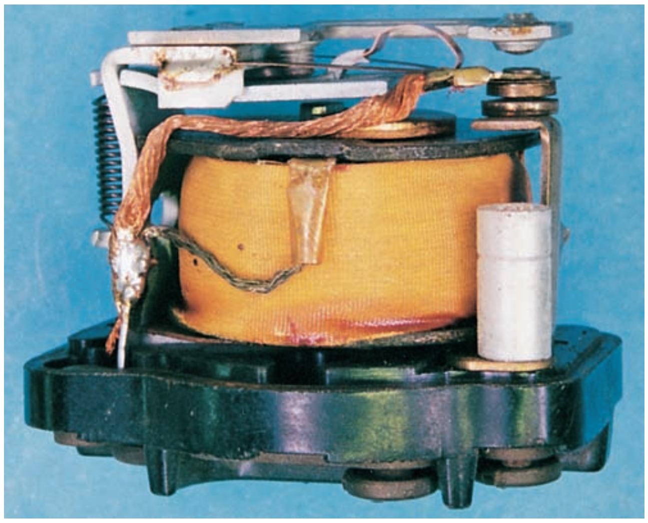


Figure 49–14 Potential starting relay.

Review Questions

1. List five commonly used starting methods.
2. When can full voltage starting be used?
3. Name the simplest, most rugged and reliable ac motor. Describe how it operates.
4. Describe the term *slip*.
5. When the voltage is reduced to start a motor, what happens to the
   a. torque?
   b. current?
6. Why is it more advisable to start some machines at reduced torque?
7. What device is generally used to disconnect the start-winding of a resistance start split-phase motor that is intended to operate in the open?
8. What electronic component is used in the construction of a solid-state starting relay?
9. When installing a current-starting relay for a single-phase motor, is the coil of the relay connected in series with the run-winding or the start-winding?
10. Which type of split-phase motor starting relay can be used to disconnect the start-winding and double as an overload protector?

UNIT 50

PRIMARY RESISTOR-TYPE STARTERS

OBJECTIVES

After studying this unit, the student will be able to:

- State why reduced current starting is important.
- Describe the construction and operation of primary resistor starters.
- Interpret and draw diagrams for primary resistor starters.
- Connect squirrel cage motors to primary resistor starters.
- Troubleshoot electrical problems on primary resistor starters.

Primary Resistor-Type Starters

A simple and common method of starting a motor at reduced voltage is used in primary resistor-type starters. In this method, a resistor is connected in series in the lines to the motor (Figure 50–1). Thus, there is a voltage drop across the resistors and the voltage is reduced at the motor terminals. Reduced motor starting speed and current are the result. As the motor accelerates, the current through the resistor decreases, reducing the voltage drop (E = IR) and increasing the voltage across the motor terminals. A smooth acceleration is obtained with gradually increasing torque and voltage.

The resistance is disconnected when the motor reaches a certain speed. The motor is then connected to run on full line voltage (Figure 50–2). The introduction

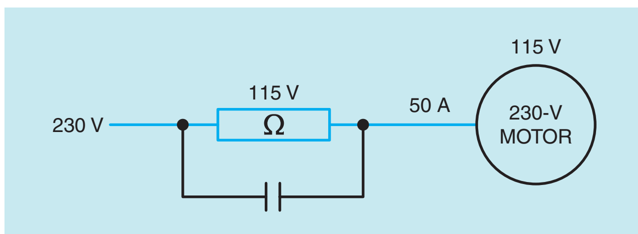


Figure 50–1 Reduced voltage starting.

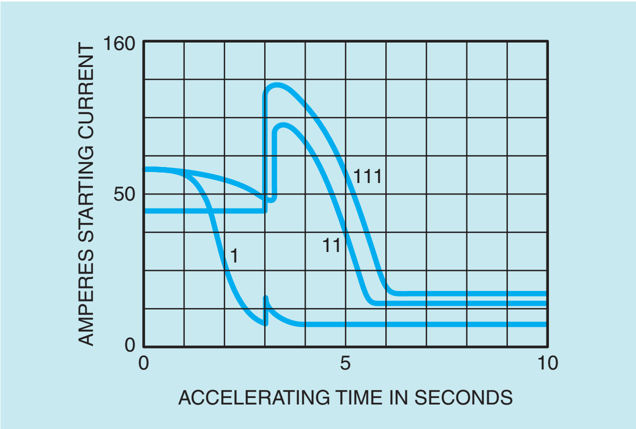


Figure 50–2 The curves illustrate how a primary resistance starter reduces the starting current of a 10-hp, 230-volt motor under three different load conditions. Curve 1 is at a light load and Curve 11 is at a heavy load. In either case, the running switch closes after three seconds. With a heavy load, an increase in the starting time reduces the second current inrush; the motor will reach a higher speed before it is connected to full line voltage. In Curve 111 the motor cannot start on the current allowed through the resistance; it comes up to speed only after connection to full line voltage.

and removal of resistance in the motor starting circuit may be accomplished manually or automatically.

Primary resistor starters are used to start squirrel cage motors in situations where limited torque is required to prevent damage to driven machinery. These starters are also used with limited current inrush to prevent excessive power line disturbances.

It is desirable to limit the starting current in the following cases:

1. When the power system does not have the capacity for full voltage starting.
2. When full voltage starting may cause serious line disturbances, such as in lighting circuits, electronic circuits, the simultaneous starting of many motors, or the motor is distant from the incoming power supply.

In these situations, reduced voltage starters may be recommended for motors with ratings as small as five horsepower.

Reduced voltage starting must be used for driving machinery that must not be subjected to a sudden high starting torque and the shock of sudden acceleration. Among typical applications are those where belt drives may slip or where large gears, fan blades, or couplings may be damaged by sudden starts.

Automatic primary resistor starters may use one or more than one step of acceleration, depending upon the size of the motor being controlled. These starters provide smooth acceleration without the line current surges normally experienced when switching autotransformer types of reduced voltage starters.

Primary resistor starters provide closed transition starting. This means the motor is never disconnected from the line from the moment it is first connected until the motor is operating at full line voltage. This feature may be important in wiring systems sensitive to voltage changes. Primary resistor starters do consume energy, with the energy being dissipated as heat. However, the motor starts at a much higher power factor than with other starting methods.

Special starters are required for very high inertia loads with long acceleration periods or where power companies require that current surges be limited to specific increments at stated intervals.

Primary Resistor-type Reduced Voltage Starter

Figures 50–3 and 50–4 illustrate an automatic, primary resistor-type, reduced voltage starter. Figure 50–4 shows the starter with two-point acceleration connected to a three-phase, squirrel cage induction motor.

When the START push button is pressed, motor starter coil M energizes and closes all M contacts. The

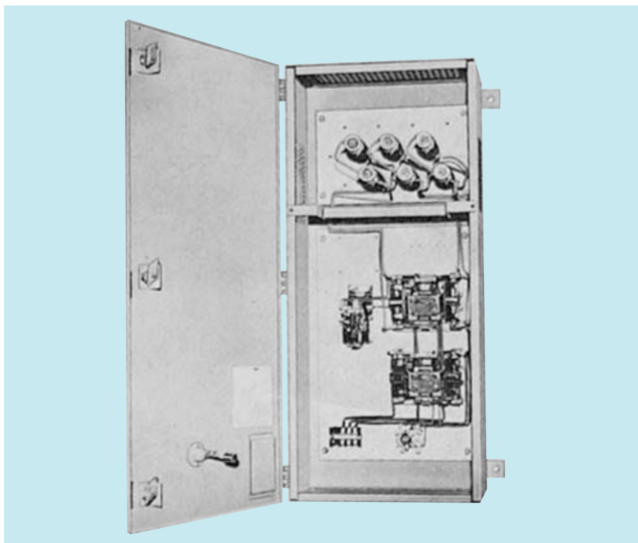


Figure 50–3 Reduced voltage, primary resistance-type starter mounted in cabinet. (Courtesy Eaton Corp., Cutler-Hammer Products.)

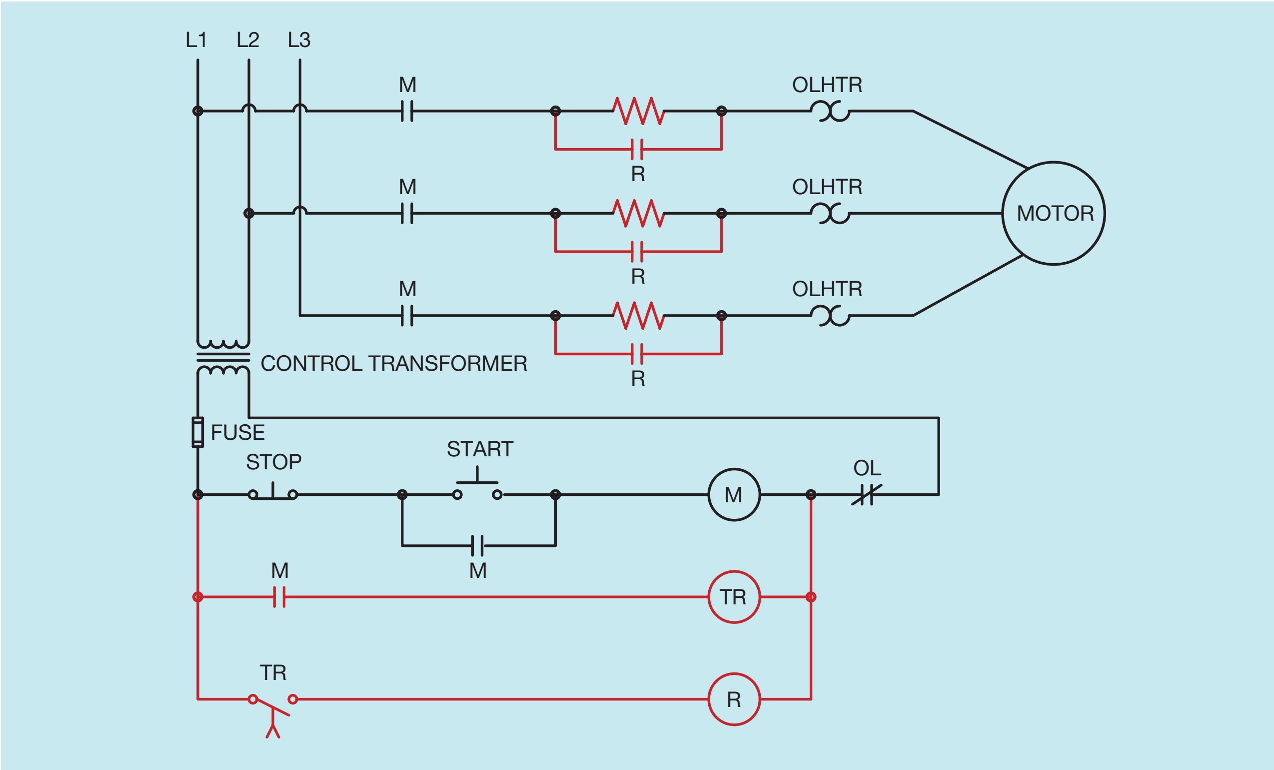


Figure 50–4 A primary resistor-type starter with two-step acceleration.

M load contacts connect the motor to the power line. Note that resistors are connected in series with the motor. The resistors limit the amount of inrush current during the starting period. The current flowing through the resistors causes a voltage drop across the resistors, and consequently a lower voltage is applied to the motor.

At the same time, the two M auxiliary contacts close. One is used to hold coil M in the circuit when the START button is released, and the other connects the coil of on-delay timer TR to the power line. When coil TR energizes, the time sequence begins. At the end of the preset time period, contact TR closes and energizes the coil of Contactor R, causing R contacts to close and shunt the resistors out of the line. The motor is now connected to full voltage.

When the STOP button is pressed, coil M de-energizes, causing all M contacts to return to their normal position. Load contacts M open and disconnect the motor from the power line. When M auxiliary contacts open, timer coil TR de-energizes, causing contact TR to open immediately and de-energize contactor coil R. When R load contacts reopen, the circuit is back to its normal de-energized state.

For maximum operating efficiency, push buttons or other pilot devices are usually mounted on the driven machinery within easy reach of the operator. The starter is located near the motor to keep the heavy power circuit wiring as short as possible. Only two or three small connecting wires are necessary between the starter and pilot device. A motor can be operated from any of several remote locations if a number of push buttons or pilot switches are used with one magnetic starter, such as on a conveyor system.

Ac primary resistor starters are available for use on single-phase and three-phase reversing operations. They are also available with multiple points of acceleration.

Four-point Resistor Starter

The elementary diagram in Figure 50–5 illustrates a four-point resistor starter. Operating the start button energizes contactor S1, connecting the motor to the line. The total resistance is in each line. The mechanically operated timer S1 closes to energize contactor S2. The closing of contacts S2 shunts out a portion of the

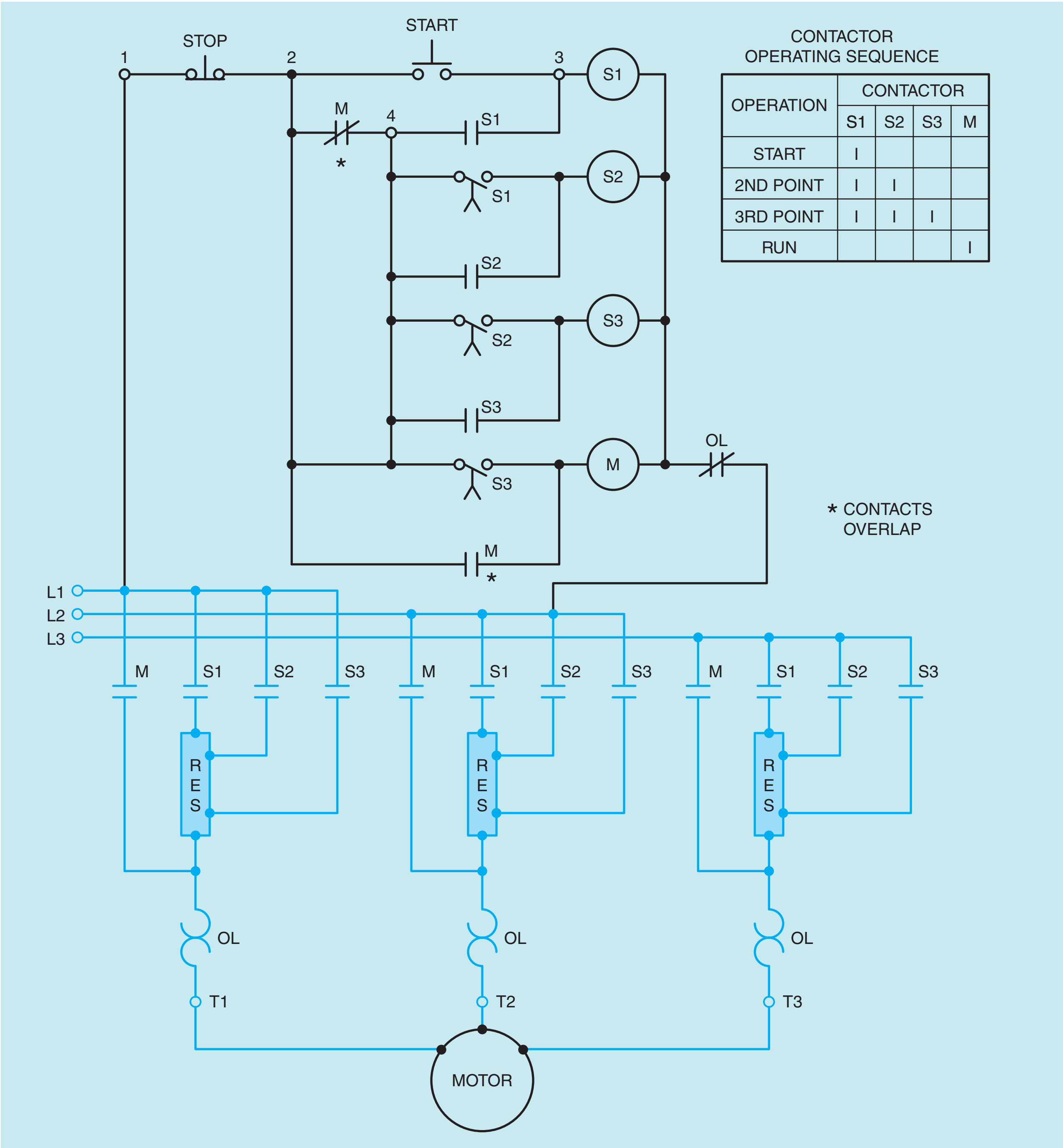


Figure 50–5 Schematic diagram of a four-point primary resistor starter.

starting resistor. The mechanically operated timer S2 closes to energize contactor S3. The closing of contacts S3 shunts out additional resistance in the resistor bank. The timer S3 closes to energize contactor M. The closing of contacts M connects the motor at full voltage. An electrical interlock on M then opens to drop out contactors S1, S2, and S3. The rotor may not start turning until the second or third point, but reduced voltage will have been accomplished.

The timers or timing relays used are of the preset time type such as pneumatic, dashpot or solid-state timers. Compensating-type current relays are also used.

Figure 50–6 shows resistors used to start small motors. The resistors (shown in Figure 50–6) consist of resistance wire wound around porcelain bases and imbedded in refractory cement.

A primary resistance-type starter has the following features:

- simple construction
- low initial cost
- low maintenance
- smooth acceleration in operation
- continuous connection of the motor to the line during the starting period
- a high power factor.

These starters should *not* be used for starting *very heavy* loads because of their low starting torque. These starters are said to have a low starting economy because the starting resistors dissipate electrical energy. Terminal connections are made at a marked terminal block.

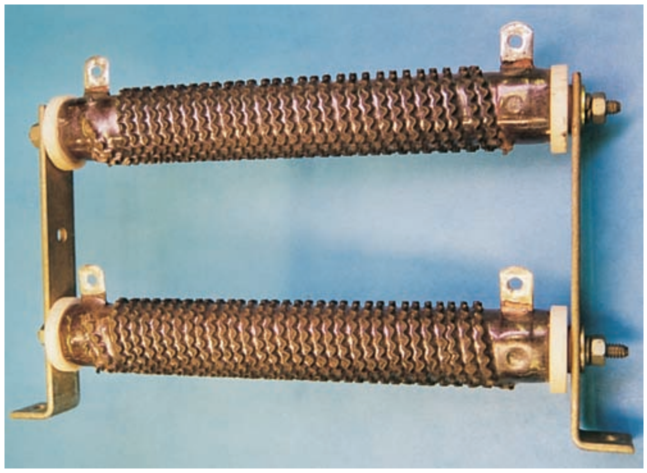


Figure 50–6 Resistors used in primary resistor-type starters.

Review Questions

1. What is the purpose of inserting resistance in the stator circuit during starting?
2. Why is the power not interrupted when the motor makes the transition from start to run?
3. What would be the action of the circuit if TR contacts are shorted closed when the START button is pressed?
4. How many additional steps of acceleration be added?
5. What is meant by the low or poor starting economy of a primary resistor starter?
6. How does this starter provide smooth acceleration and a gradual increase of torque?

UNIT 51
AUTOTRANSFORMER STARTERS

OBJECTIVES

After studying this unit, the student will be able to:

- Describe the construction and operation of autotransformer starters.
- Draw and interpret diagrams for autotransformer starters.
- Connect squirrel cage motors to autotransformer starters.
- Define what is meant by open transition and closed transition starting.
- Troubleshoot electrical problems on autotransformer starters.

Autotransformer reduced voltage starters are similar to primary resistor starters in that they are used primarily with ac squirrel cage motors to limit the inrush current or to lessen the starting strain on driven machinery (Figure 51–1.) This type of starter uses autotransformers between the motor and the supply lines to reduce the motor starting voltage. Taps are provided on the autotransformer to permit the user to start the motor at approximately 50%, 65%, or 80% of line voltage.

Most motors are successfully started at 65% of line voltage. In situations where this value of voltage does not provide sufficient starting torque, the 80% tap is available. If the 50% starting voltage creates excessive line drop to the motor, the 65% taps are available. This way of changing the starting voltage is not usually available with other types of starters. The starting transformers are inductive loads; therefore, they momentarily affect the power factor. They are suitable for long starting periods, however.

Autotransformer Starters

To reduce the voltage across the motor terminals during the accelerating period, an autotransformer-type starter generally has two autotransformers connected in open delta. During the reduced voltage starting period, the motor is connected to the taps on the autotransformer. With the lower starting voltage, the motor draws less current and develops less torque than if it were connected to the line voltage (Figure 51–2).

An adjustable time-delay relay controls the transfer from the reduced voltage condition to full voltage.

Figure 51–1 Reduced voltage autotransformer starter mounted in cabinet. (Courtesy Square D Company.)

A current-sensitive relay may be used to control the transfer to obtain current-limiting acceleration.

Figure 51–2(A) shows the power circuit for starting the motor with two autotransformers. Figure 51–2(B) shows the circuit for starting a motor with three autotransformers.

To understand the operation of the autotransformer starter more clearly, refer to the schematic diagram shown in Figure 51–3. When the START button is pressed, a circuit is completed to the coil of control relay CR, causing all CR contacts to close. One contact is employed to hold the CR coil in the circuit when the START button is released. Another completes a circuit to the coil of the TR timer, which starts the timing sequence. The CR contact connected in series with the normally closed TR contact supplies power to the coil of contactor S (start). The fourth CR contact permits power to be connected to contactor R (run) when the normally open timed TR contact closes.

When the coil of contactor S energizes, all S contacts change position. The normally closed S contact connected in series with coil R opens to prevent both S and R contactors from ever being energized at the same time. This is the same interlocking used with reversing starters. When the S load contacts close, the motor is connected to the power line through the autotransformers. The autotransformers supply 65% of the line voltage to the motor. This reduced voltage produces less inrush current during starting and also reduces the starting torque of the motor.

When the time sequence for the TR timer is completed, both TR contacts change position. The normally closed TR contact opens and disconnects contactor S from the line, causing all S contacts to return to their normal position. The normally open TR contact closes and supplies power through the now closed S

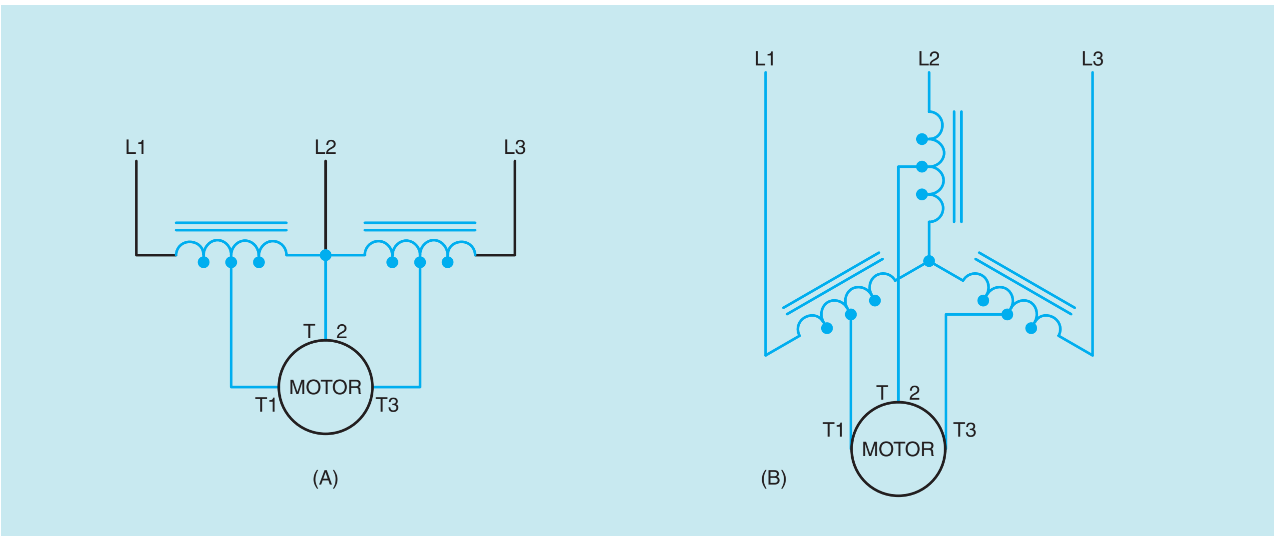


Figure 51–2 Power circuit connections showing two and three authotransformers used for reduced voltage starting.

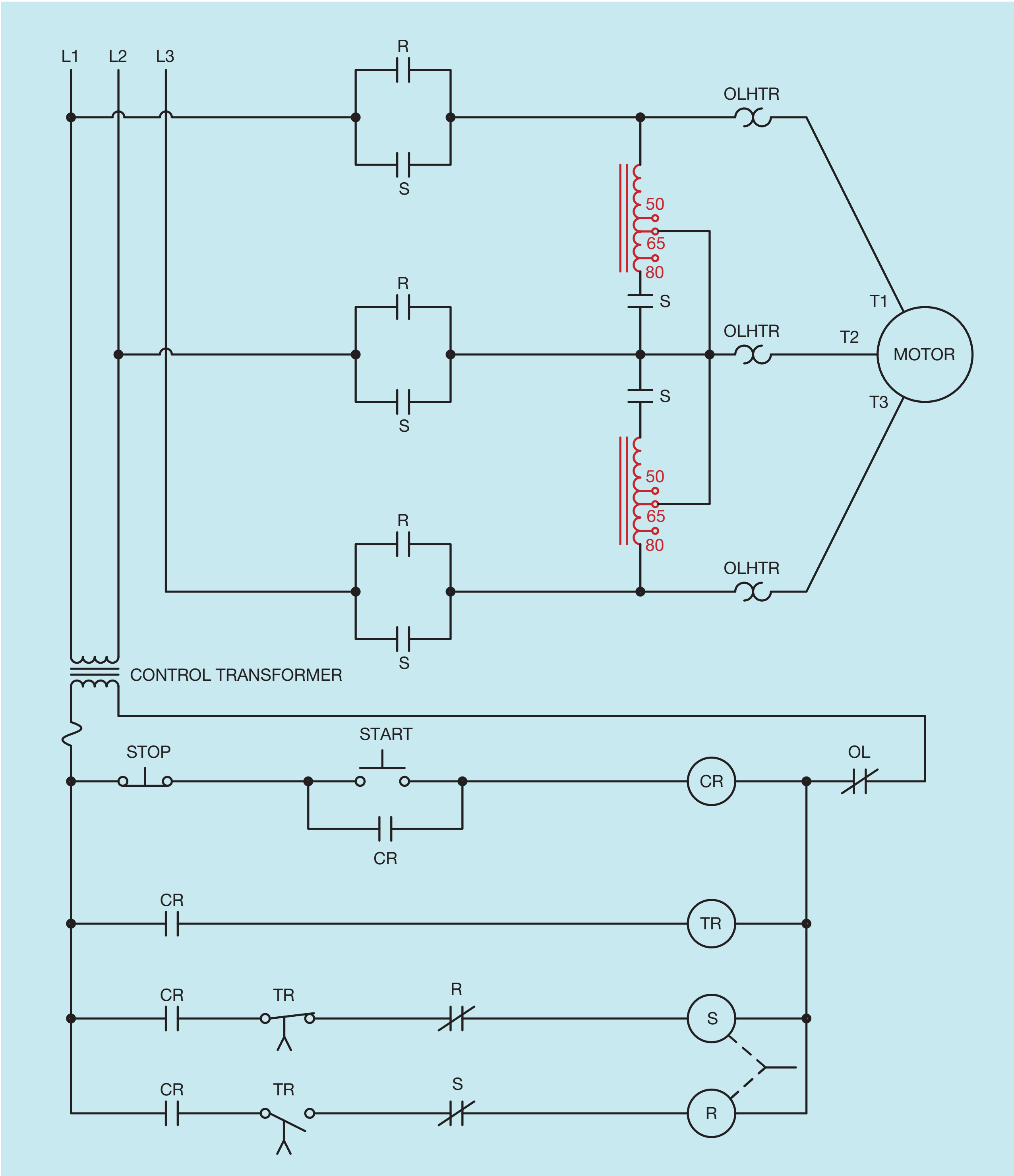


Figure 51–3 Autotransformer starters provide greater starting torque per ampere drawn from the line than any other type of reduced voltage starter. This is a typical schematic diagram for a time-controlled autotransformer starter.

contact to coil R. When contactor R energizes, all R contacts change position. The normally closed R contact connected in series with the S coil opens to provide interlocking for the circuit. The R load contacts close and connect the motor to full voltage.

When the STOP button is pressed, control relay CR de-energizes and opens all CR contacts. This disconnects all other control components from the power line, and the circuit returns to its normal position. A wiring diagram for this circuit is shown in Figure 51–4.

Full line voltage is applied to the outside terminals of the autotransformer on starting. Reduced voltage for starting the motor is obtained from the autotransformer taps. The current taken by a motor varies directly with the applied voltage.

Starting compensators (autotransformer starters) using a five-pole starting contactor are classified as open transition starters. The motor is disconnected momentarily from the line during the transfer from the start to the run conditions.

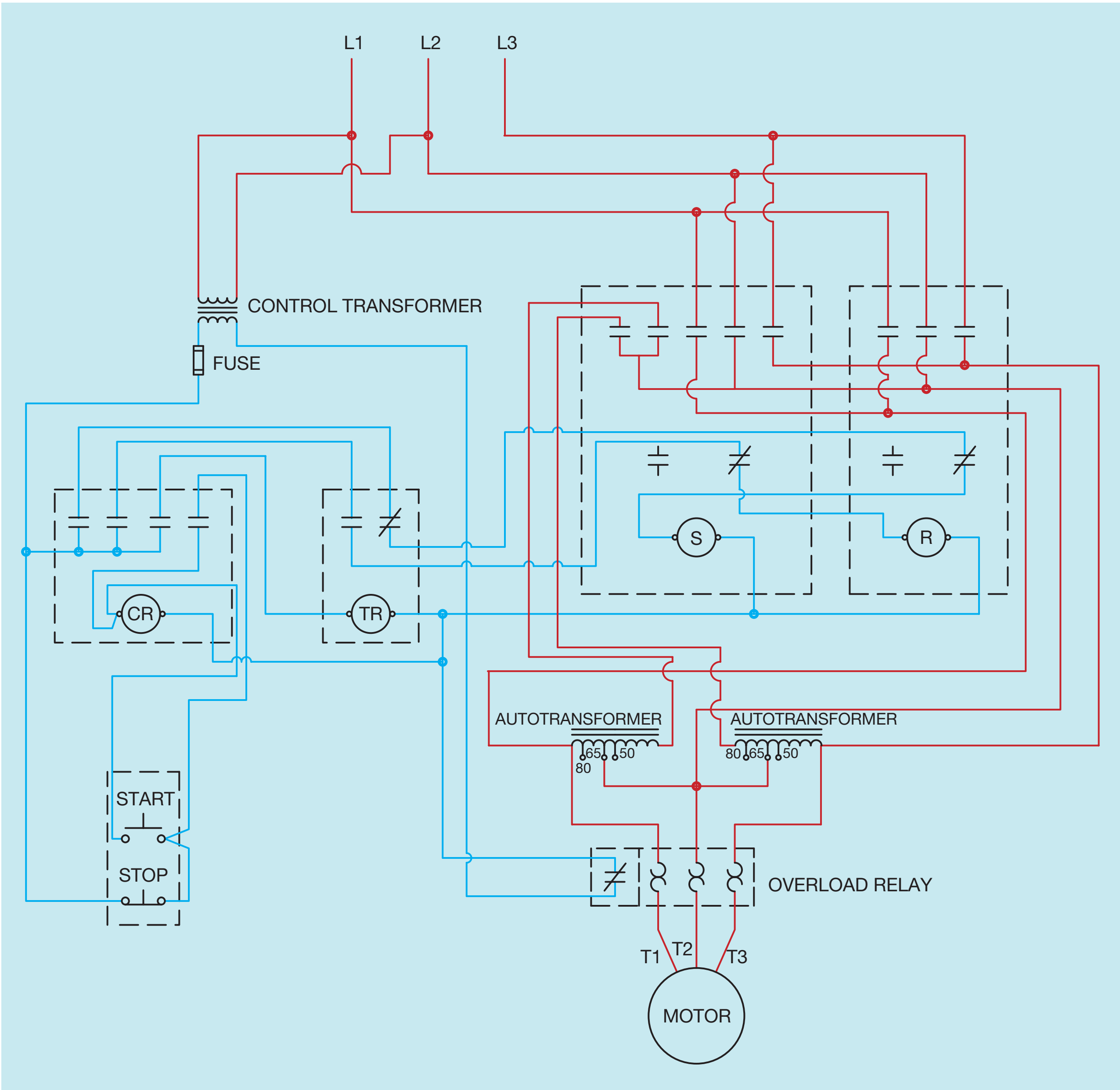


Figure 51–4 Wiring diagram for a typical autotransformer reduced voltage starter.

Closed transition connections are usually found on standard size 6 and larger starters. For the closed transition starter (Figure 51–5), the starting contactors consist of a three-pole (S2) and a two-pole (S1) contactor operating independently of each other. During the transfer from start to run, the two-pole contactor is open and the three-pole contactor remains closed. The motor continues to accelerate with the autotransformer serving as a reactor. With this type of starter, the motor is not disconnected from the line during the transfer period. Thus, there is less line disturbance and a smoother acceleration.

The transformers are de-energized while in the running position. This is done to conserve electrical energy and to extend their life.

The (CT) designations in Figure 51–5 indicate current transformers. These transformers are used on large motor starters to step down the current so that a conventional overload relay and heater size may be used. Magnetic overload relays are used on large reduced voltage starters also.

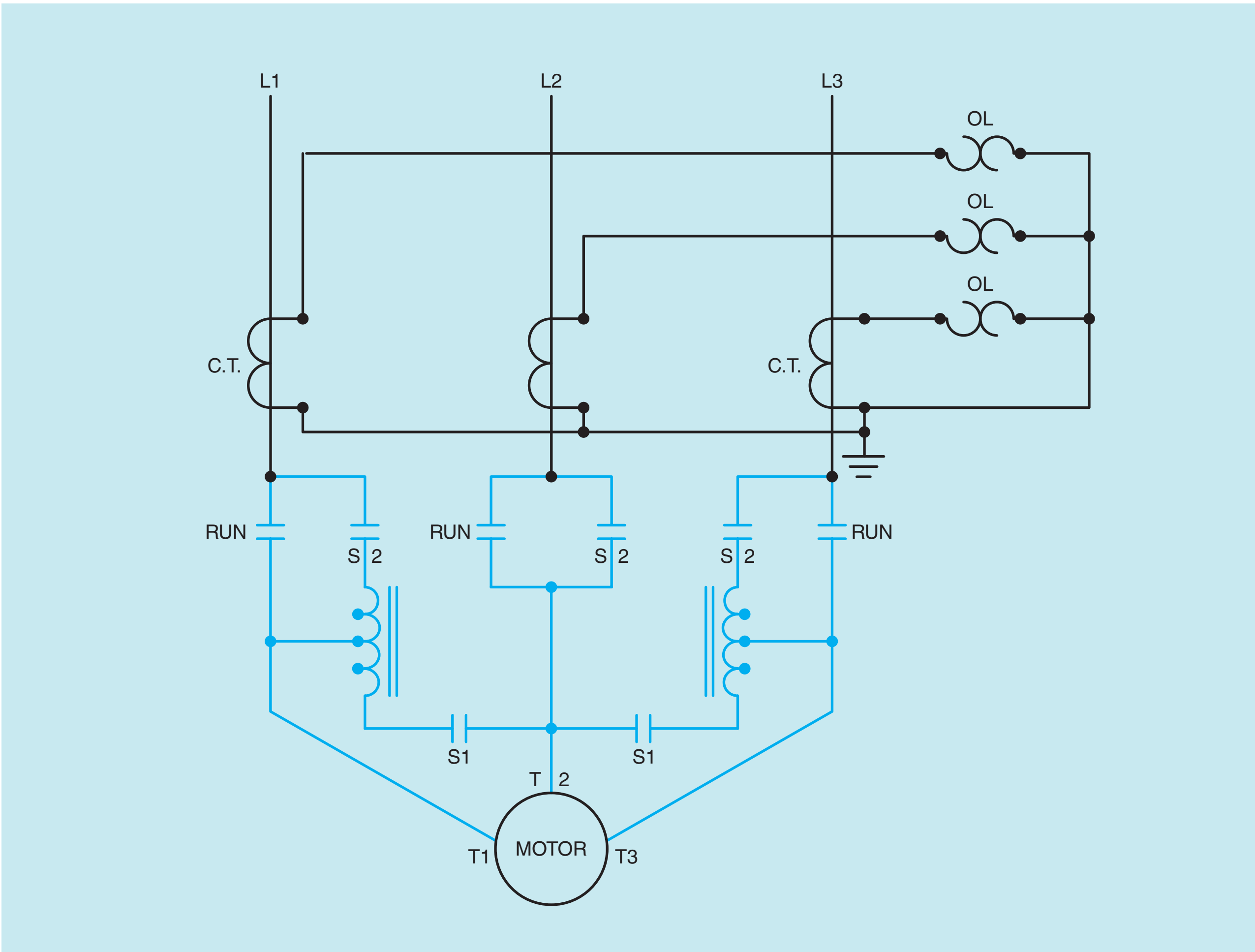


Figure 51–5 Closed transition (Korndorfer) connection.

Review Questions

1. Why is it desirable to remove the autotransformers from the line when the motor reaches its rated speed?
2. What is meant by an "open transition" from start to run? Why is this condition objectionable at times when used with large horsepower motors?
3. Which of the following applies to an autotransformer starter with a five-pole starting contactor: open transition or closed transition? Locate in Figure 51–3.
4. How are reduced voltages obtained from autotransformer starters?
5. Assume the motor is running. What happens when the stop button is pressed and then the start button is pressed immediately?
6. What is a disadvantage of starting with autotransformer coils rather than with resistors?
7. What is one advantage of using an autotransformer starter?
8. Refer to the autotransformer circuit shown in Figure 51–3. Assume that timer TR has been set for a time delay of 5 seconds. When the START button is pressed, the motor does not start. After a delay of 5 seconds, the motor starts with full line voltage applied to the motor. Which of the following could cause this condition?
   a. Control relay CR is defective.
   b. Timer coil TR is open.
   c. S contactor coil is open.
   d. S contactor coil is shorted.
9. When the START button shown in Figure 51–3 is pressed, the motor starts with reduced voltage applied to it. After 5 seconds the motor accelerates due to full voltage being applied to the motor. When the STOP button is pressed, the motor continues to run at normal speed. Which of the following could **not** cause this condition?
   a. The START button contacts are shorted.
   b. The STOP button contacts are shorted together.
   c. The contacts of control relay CR have become welded together.
   d. The load contacts of contactor R have become welded together.
10. When the START button in Figure 51–3 is pressed, the motor does not start. After a delay of 10 seconds the motor still has not started. Which of the following could **not** cause this condition?
    a. The control transformer is defective.
    b. The START button is defective and does not produce a closed circuit when pressed.
    c. The coil of timer TR is open.
    d. The overload contact is open.

UNIT 52
AUTOMATIC STARTERS FOR STAR-DELTA MOTORS

OBJECTIVES

After studying this unit, the student will be able to:

- Identify terminal markings for a star-delta motor and motor starter.
- Describe the purpose and function of star-delta starting.
- Troubleshoot star-delta motor starters.
- Connect star-delta motors and starters.

A commonly used means of reducing inrush currents without the need of external devices is star-delta motor starting (sometimes called wye-delta starting). Figure 52–1 shows a typical star-delta starter.

Star-delta motors are similar in construction to standard squirrel cage motors. However, in star-delta motors, both ends of each of the three windings are brought out to the terminals. If the starter used has the required number of properly wired contacts, the motor can be started in star and run in delta.

The motor must be wound in such a manner that it will run with its stator windings connected in delta. The leads of all of the windings must be brought out to the motor terminals for their proper connection in the field.

Applications

The primary applications of star-delta motors are for driving centrifugal chillers of large, central air conditioning units for loads such as fans, blowers, pumps, or centrifuges, and for situations where a reduced starting torque is necessary. Star-delta motors also may be used where a reduced starting current is required. Since all of the stator winding is used and there are no limiting devices such as resistors or autotransformers, star-delta motors are widely used on loads having high inertia and a long acceleration period.

The speed of a star-delta or wye-delta squirrel cage induction motor depends on the frequency of the applied

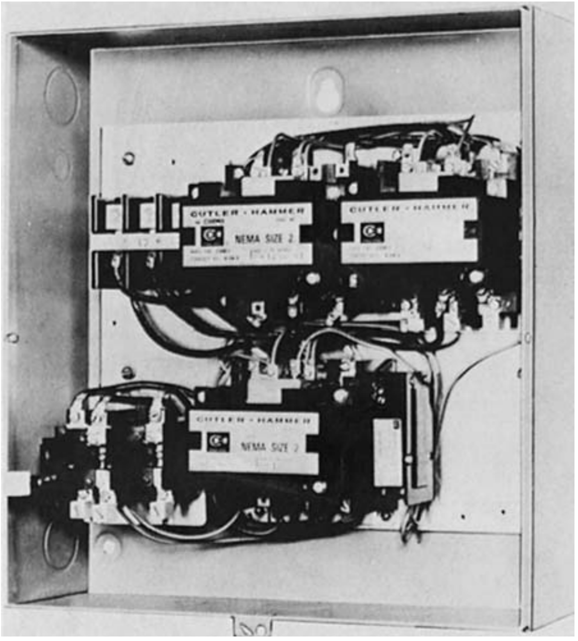


Figure 52–1 Star-delta or Wye-delta starter mounted in cabinet. (Courtesy Eaton Corp., Cutler-Hammer Products.)

voltage and the number of stator poles. Since both these values are the same for the wye or delta connection, the motor will run at approximately the same speed regardless of how the windings are connected. The inrush line current is much less when the windings are connected in wye, however. Assume that a motor is to be connected directly to a 480 volt line during the starting period. Also assume that each winding exhibits an impedance of 0.4 W during the starting period. If the windings are connected in delta when power is first applied to the motor, 480 volts will be connected directly across the phase windings (Figure 52–2). This will produce a phase current of 1200 amps.

$$I_{Phase} = \frac{E_{Phase}}{Z_{Phase}}$$

$$I_{Phase} = \frac{480}{0.4}$$

$$I_{Phase} = 1200 \text{ amps}$$

Since the line current supplying a delta connection is 1.732 times greater than the phase current, the line current will be 2078.4 amps (1200 × 1.732 = 2078.4).

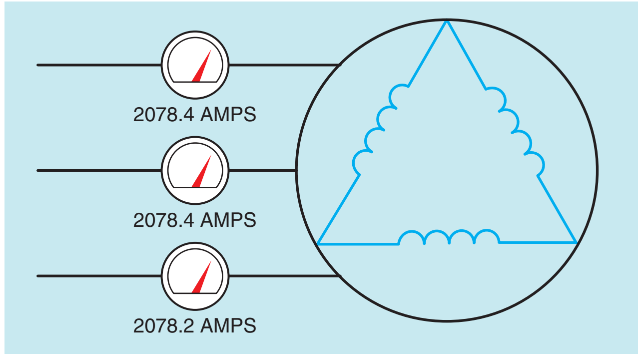


Figure 52–2 Delta inrush current is high.

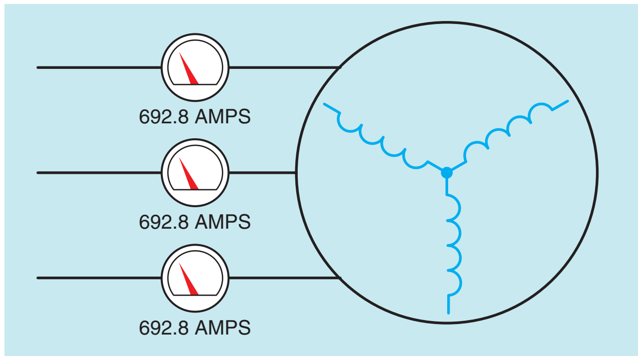


Figure 52–3 A wye-connected winding draws one third the starting current of a delta-connected winding.

If the stator windings are connected in a wye configuration during the starting period (Figure 52–3), the inrush line current will be only one third the value of the delta connection. Since the windings are now connected in a wye or star, the voltage applied across each phase winding will be less than the line voltage by a factor of 1.732 or 277 volts (480/1.732 = 277). This will produce a phase current of 692.8 amps when power is first connected to the motor.

$$I_{Phase} = \frac{E_{Phase}}{Z_{Phase}}$$

$$I_{Phase} = \frac{277}{0.4}$$

$$I_{Phase} = 692.8 \text{ amps}$$

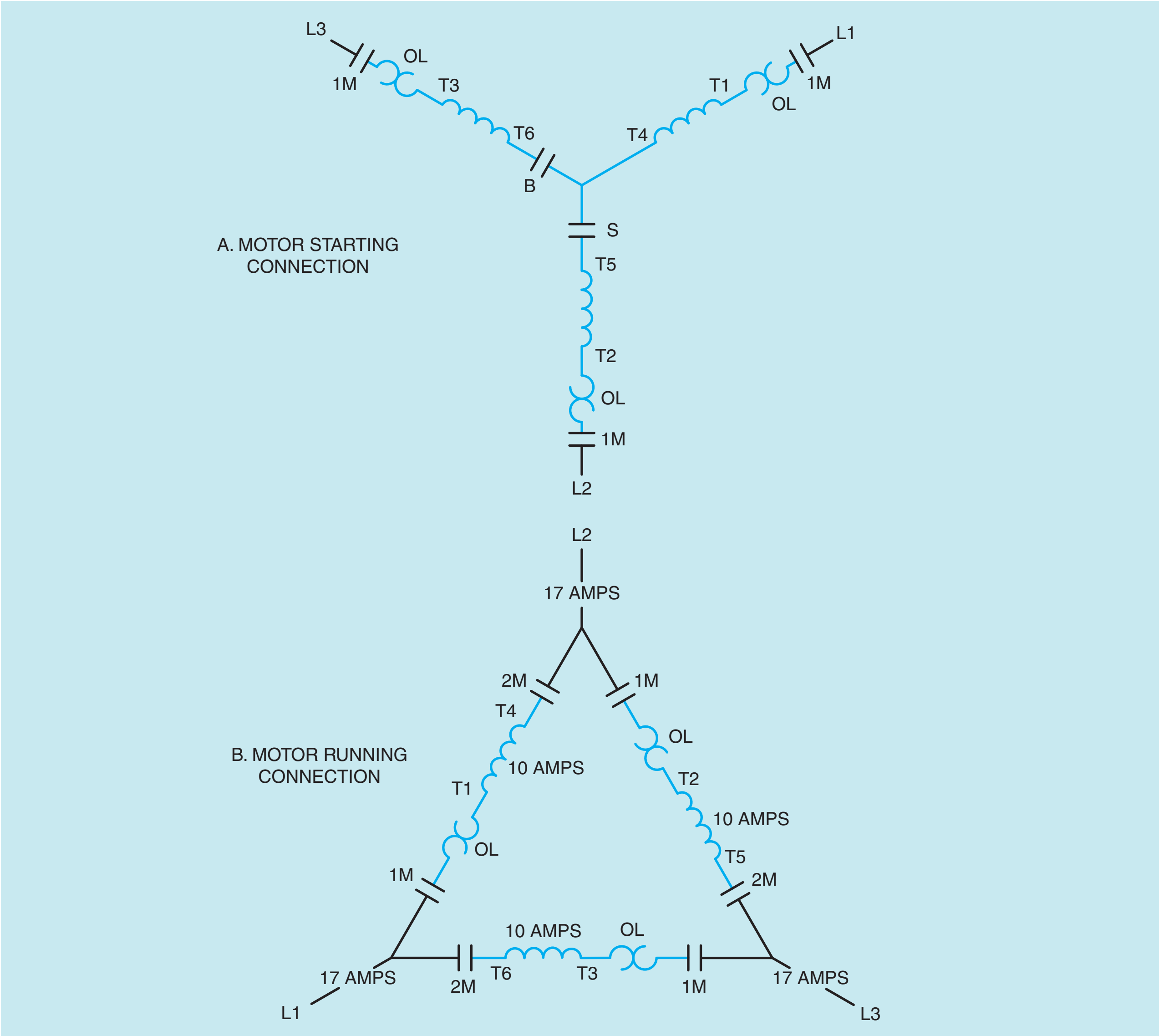


Figure 52–4 Elementary diagrams of motor power circuits of Figure 52–3. Controller connects motor in wye on start and in delta for run. Note that the overload relays are connected in the motor winding circuit, not in the line. Note also that the line current is higher that the phase winding current in the diagram for the delta connection (B). Winding current is the same as the line current in diagram A.

In a wye-connected system, the line current and phase current are the same. Therefore, the line current has been reduced from 2078.2 amps to 692.8 amps during the initial starting period.

Overload Protection

Three overload relays are connected in the phase windings during both the starting and running period (Figure 52–4). This means that the overload heaters must be selected on the basis of the winding or phase current, not on the full load line current indicated on the motor nameplate. To determine the proper current for the overload heaters, divide the line current by 1.732. A diagram of the entire connection for the motor windings, overload heaters, and load contacts is shown in Figure 52–5.

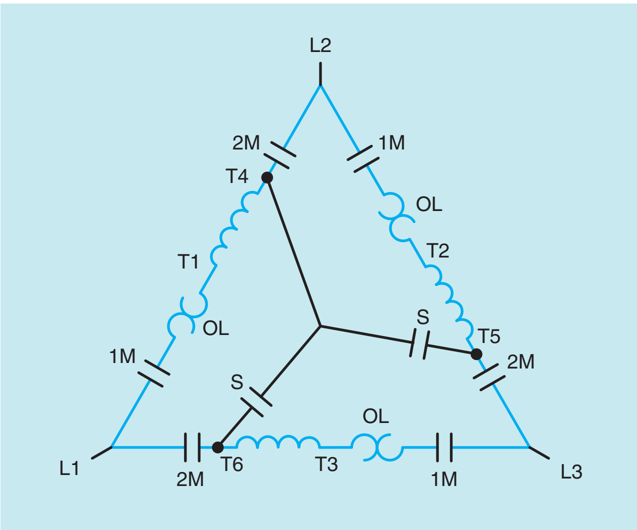


Figure 52–5 Stator connection for wye-delta starting.

Open Transition Starting

Probably the most common method for wye-delta starting is *open transition* starting. This method receives its name from the fact that the motor windings are open during the transition period of changing the windings from a wye connection to a delta connection. A control circuit for performing this transition is shown in Figure 52–6. In this circuit, an on delay timer is used to change the motor windings from a wye connection to a delta connection. When the start button is pressed, coils 1M, TR, and S energize immediately. Coil 1M closes all 1M contacts to supply power to the motor windings. Coil S closes both of the S contacts that connect the motor windings in a wye.

After some period of time, both TR contacts change position. The normally closed contact connected in a series with an S coil opens and de-energizes the S coil. The S load contacts open and disconnect the motor windings. When the normally open TR contact closes, coil 2M energizes and reconnects the motor windings in a delta configuration. It is the transition period between S contacts opening and 2M contacts closing that this starting method receives its name. The normally closed S and 2M contacts act as interlocks to prevent the possibility of coils S and 2M being energized at the same time.

Care should be exercised when connecting the stator windings to the load contacts. If the circuit is not connected properly, it will generally result in the motor reversing direction of rotation when the windings are changed from wye to delta. Figure 52–7 illustrates a schematic diagram of the stator winding connection and a wiring diagram of the motor connection to the load contacts. Notice that the wire numbers have been added to the stator schematic which corresponds to the components shown in the wiring diagram.

Closed Transition Starting

In Figure 52–8, resistors maintain continuity to the motor to avoid the difficulties associated with the open circuit form of transition between start and run.

With closed transition starting, the transfer from the star to delta connections is made without disconnecting the motor from the line. When the transfer from star to delta is made in open transition starting, the starter momentarily disconnects the motor and then reconnects it in delta. While an open transition is satisfactory in many cases, some installations may require closed transition starting to prevent power line disturbances. Closed transition starting is achieved by adding a three-pole contactor and three resistors to the starter circuit. The connections are made as shown in the closed transition schematic diagram (Figure 52–8). The contactor is energized only during the transition from star to delta. It keeps the motor connected to the power source through the resistors during the transition period (Figure 52–9). There is a reduction in the incremental current surge which results from the transition. The balance of the operating sequence of the closed transition starter is similar to that of the open transition star-delta motor starter.

A single method of reduced current starting may not achieve the desired results because the motor starting requirements are so involved, the restrictions so stringent, and the needs so conflicting. It may be necessary to use a combination starting methods before satisfactory performance is realized. For special installations, it may be necessary to design a starting system to fit the particular conditions.

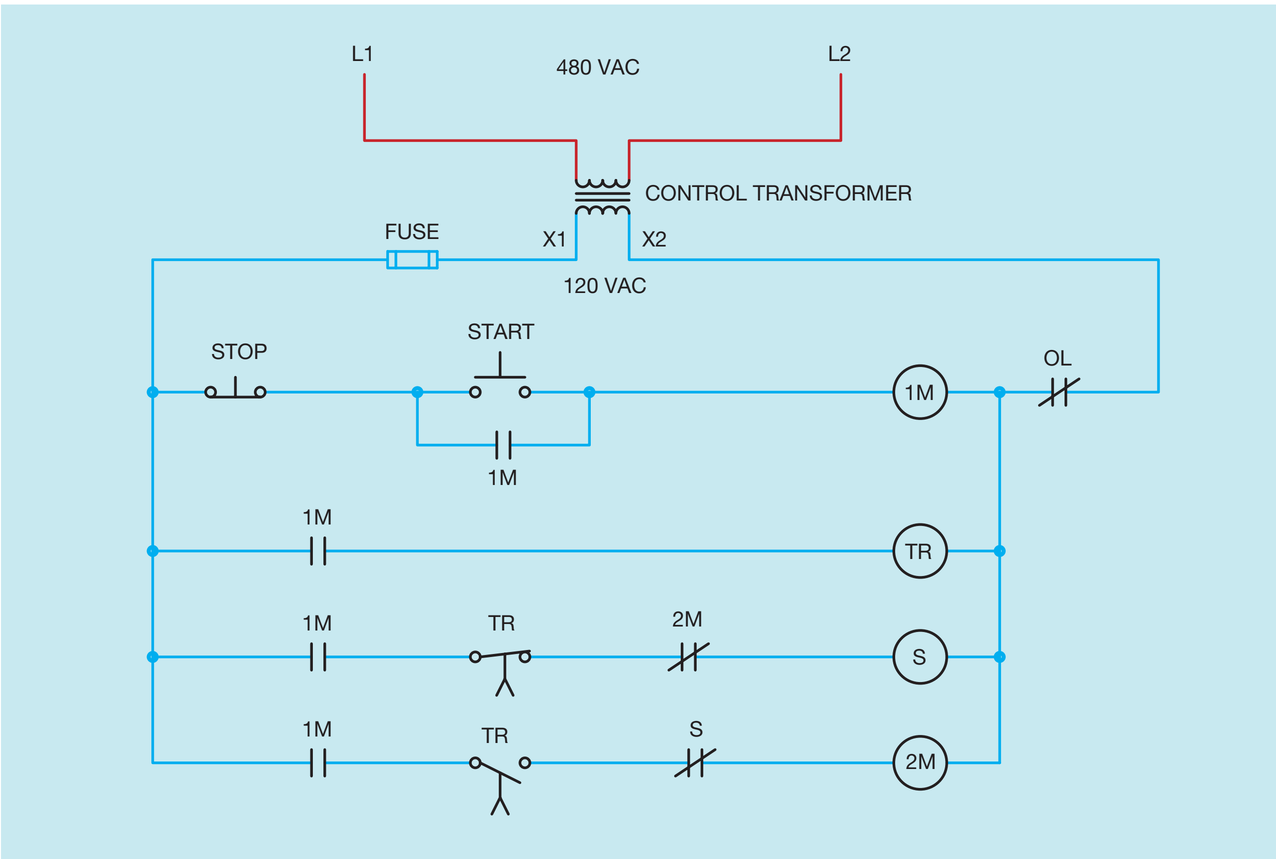


Figure 52–6 Basic control circuit for a wye-delta starter.

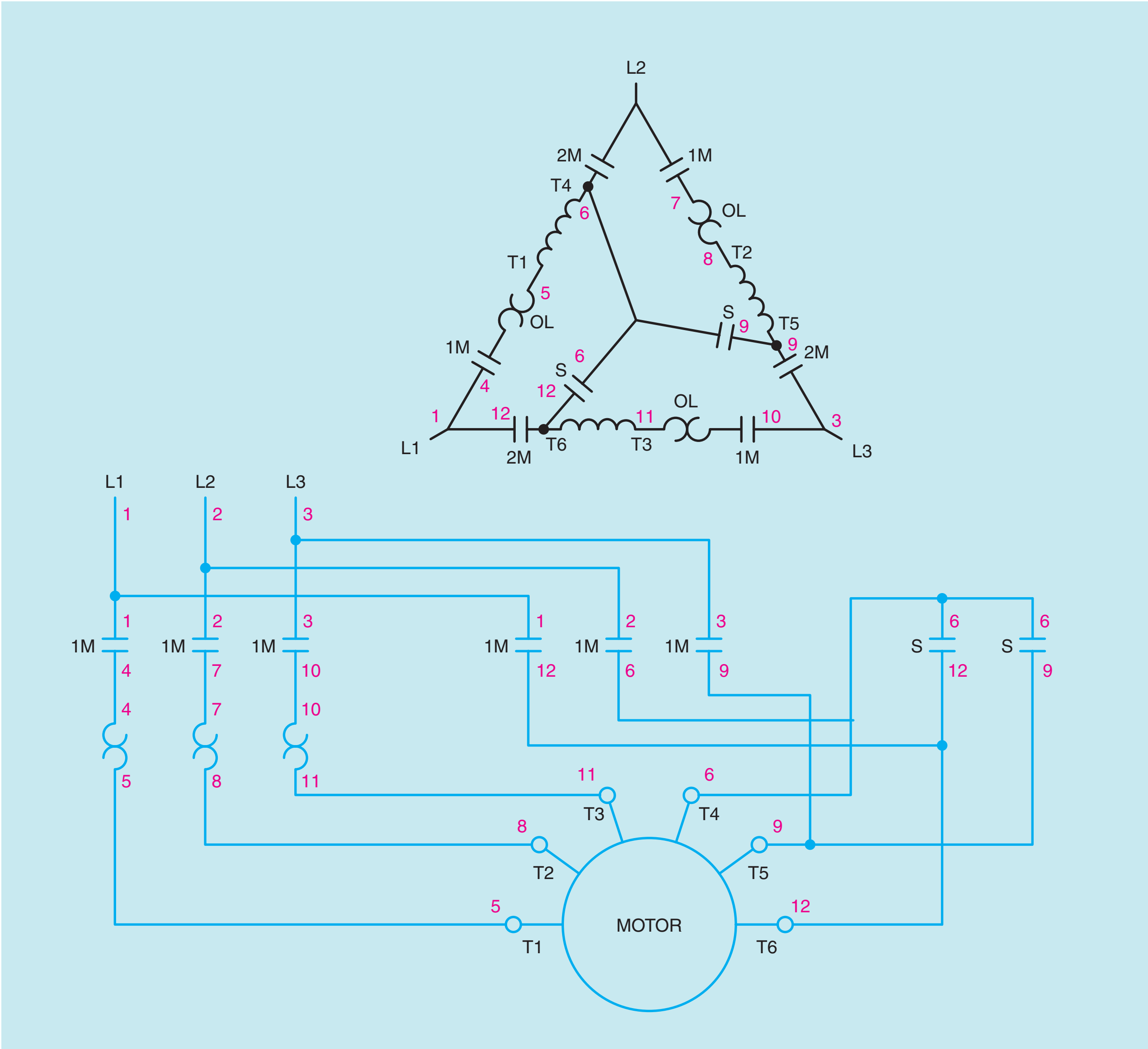


Figure 52–7 Load circuit connection for wye-delta starter.

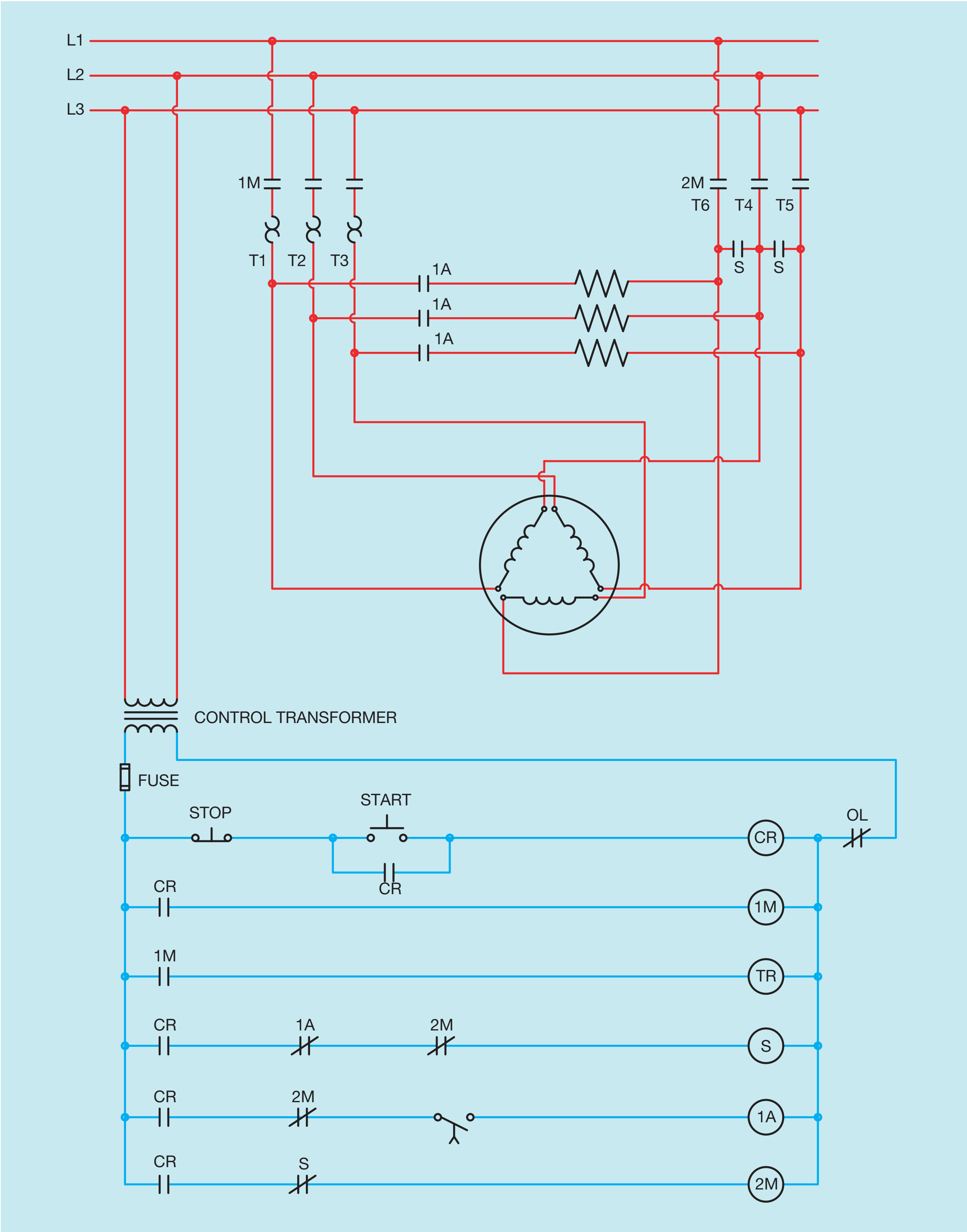
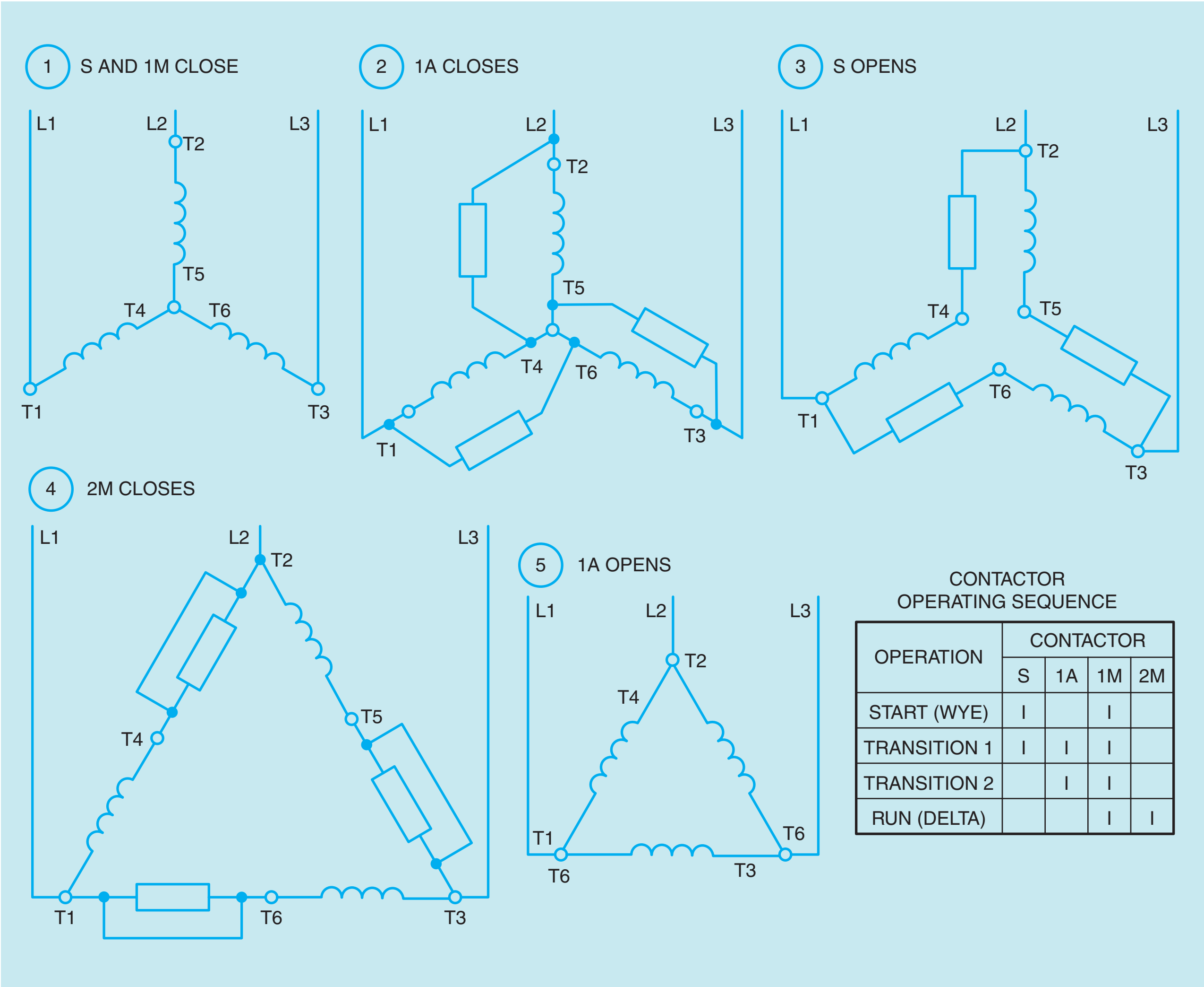


Figure 52–8 Basic schematic diagram of sizes 1, 2, 3, 4, and 5 wye-delta starters with closed transition starting.

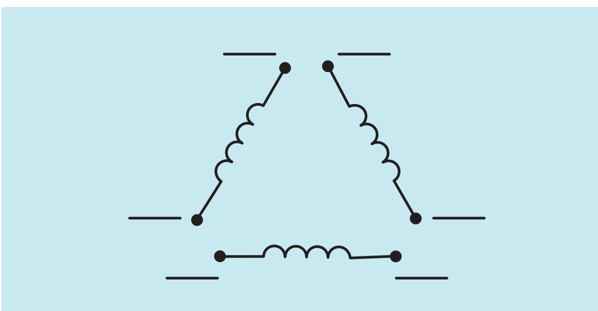


OPERATION	CONTACTOR			
	S	1A	1M	2M
START (WYE)	I		I	
TRANSITION 1	I	I	I	
TRANSITION 2		I	I	
RUN (DELTA)			I	I

Figure 52–9 Motor connection and operation sequence for star-delta closed transition starting.

Review Questions

1. Indicate the correct terminal markings for a star-delta motor on the diagram below.



2. What is the principal reason for using star-delta motors?
3. In Figure 52–6, which contactor closes the transition?
4. The closed transition contactor is energized only on transfer from star to delta. How is this accomplished?
5. If a delta-connected, six-lead motor nameplate reads "Full Load Current 170 Amperes," upon what current rating should the overload relay setting, or the selection of the heater elements be based?

UNIT 53

CONSEQUENT POLE MOTOR CONTROL

OBJECTIVES

After studying this unit, the student will be able to:

- Identify terminal markings for two-speed, one-winding motors and controllers.
- Describe the purpose and function of two-speed, one-winding motor starters and motors.
- Connect two-speed, one-winding controllers and motors.
- Connect a two-speed starter with reversing controls.
- Recommend solutions for troubleshooting these motors and controllers.

Certain applications require the use of a squirrel cage motor having a winding arranged so that the number of poles can be changed by reversing some of the currents. If the number of poles is doubled, the speed of the motor is cut approximately in half.

The number of poles can be cut in half by changing the polarity of alternate pairs of poles (Figure 53–1). The polarity of half the poles can be changed by reversing the current in half the coils (Figure 53–2).

If a stator field is laid flat (as in Figure 53–1) the established stator field must move the rotor twice as far in B as in A and in the same amount of time. As a result, the rotor must travel faster. The fewer the number of poles established in the stator, the greater is the speed in rpm of the rotor.

A three-phase squirrel cage motor can be wound so that six leads are brought out (Figure 53–3). By making suitable connections with these leads, the windings

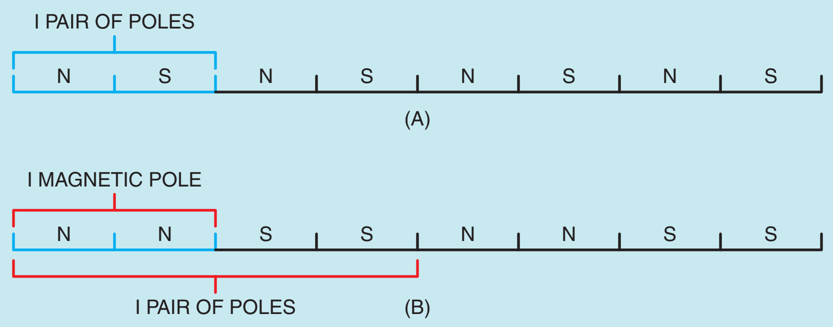


Figure 53–1 (A) Eight poles for low speed. (B) Four poles for high speed.

can be connected in series delta or parallel wye (Figure 53–4). If the winding is such that the series delta connection gives the high speed and the parallel wye connection gives the low speed, the horsepower rating is the same at both speeds. If the winding is such that the series delta connection gives the low speed and the parallel wye connection gives the high speed, the torque rating is the same at both speeds.

Consequent pole motors have a single winding for two speeds. Extra taps can be brought from the winding to permit reconnection for a different number of stator poles. The speed range is limited to a 1:2 ratio, such as 600–1200 rpm or 900–1800 rpm.

Two-speed, consequent pole motors have one reconnectable winding. However, three-speed, consequent pole motors have two windings, one of which is

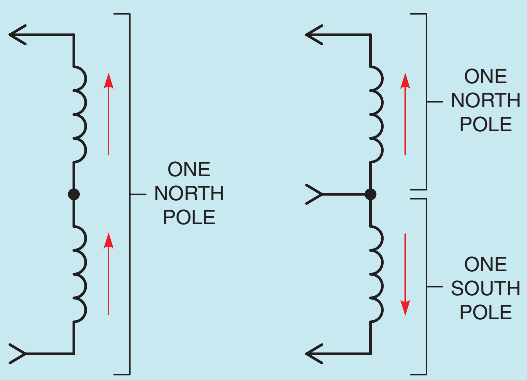
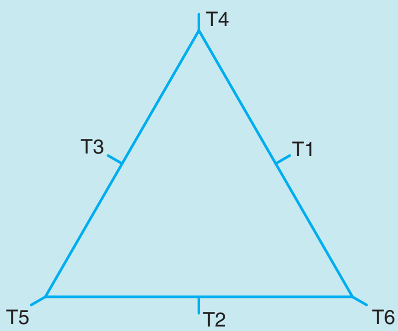


Figure 53–2 The number of poles is doubled by reversing current through half a phase. Two speeds are obtained by producing twice as many consequent poles for low-speed operation as for high speed.



SPEED	L1	L2	L3	OPEN	TOGETHER
LOW	T1	T2	T3	———	T4,T5,T6
HIGH	T4	T5	T6	ALL OTHERS	———

Figure 53–3 Connection table for a three-phase, two-speed, one-winding, constant horsepower motor.

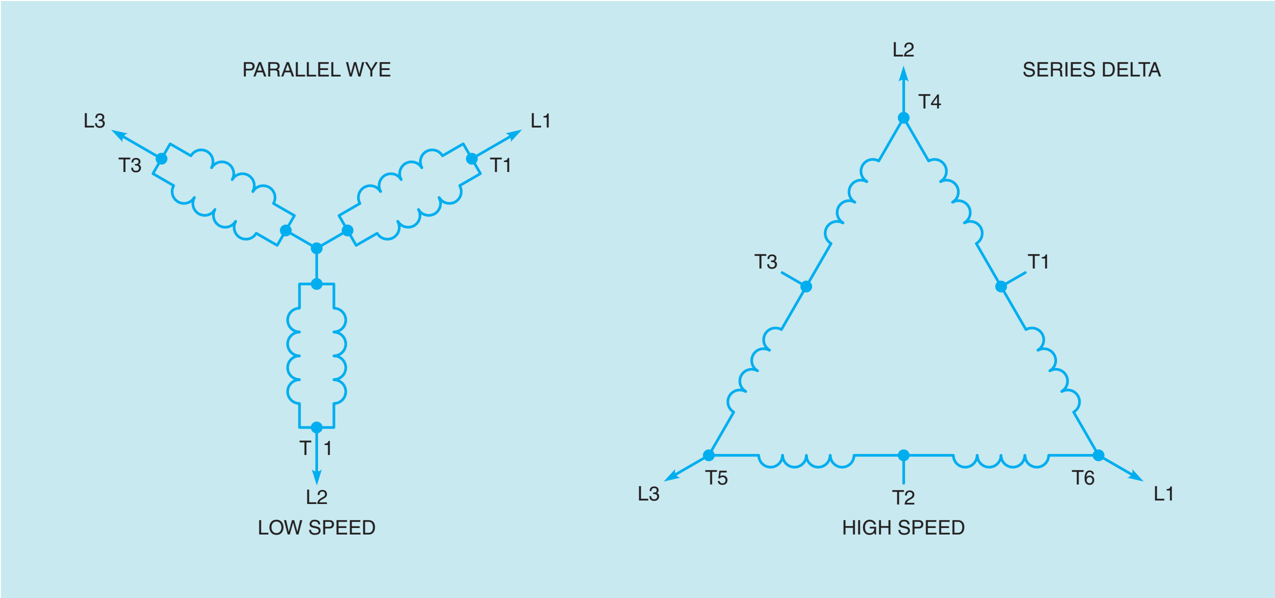


Figure 53–4 Three-phase, two-speed, one-winding, constant horsepower motor connections made by motor controller.

reconnectable. Four-speed consequent pole motors have two reconnectable windings.

Referring back to the motor connection table in Figure 53–3, note that for low speed operation, T1 is connected to L1; T2 to L2; T3 to L3; and T4, T5, and T6 are connected together. For high speed operation, T6 is connected to L1; T4 to L2; T5 to L3; and all other motor leads are open.

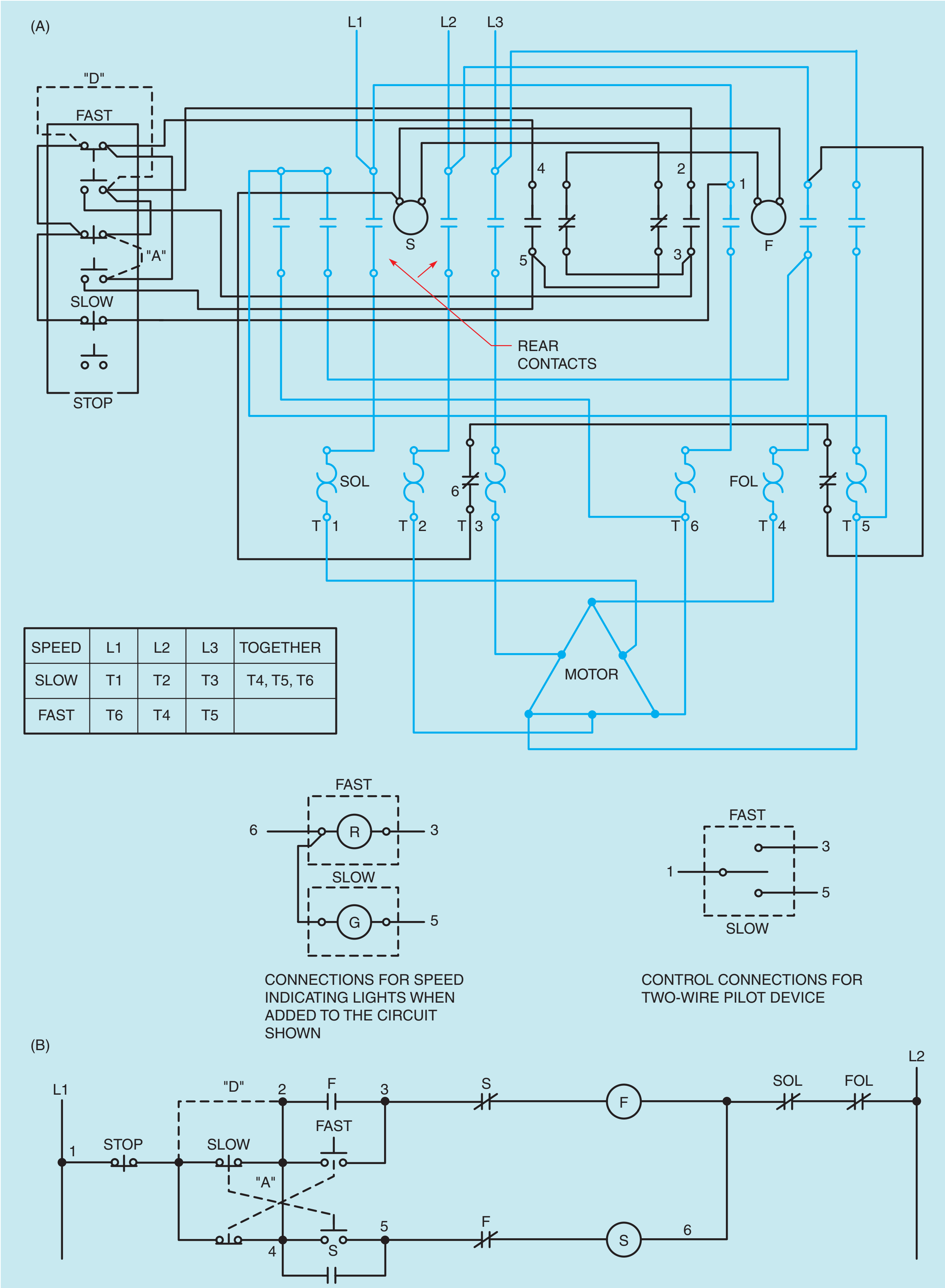
Figure 53–5 illustrates the circuit for a Size 1, selective multispeed starter connected for operation with a reconnectable, constant horsepower motor. The control station is a three-element, fast-slow-stop station connected for starting at either the fast or slow speed. The speed can be changed from fast to slow or slow to fast without pressing the STOP button between changes. If equipment considerations make it desirable to stop the motor before changing speeds, this feature can be added to the control circuit by making connections "D" and "A", shown in Figure 53–5 by the dashed lines. Adding these jumper wires eliminates push-button interlocking in favor of stopping the motor between speed changes. This feature may be desirable for some applications.

Connections for the addition of indicating lights or a two-wire pilot device instead of the control shown are also given.

A compelling-type control scheme is shown in Figure 53–6. These connections mean that the operator must start the motor at the slow speed. This controller cannot be switched to the fast speed until after the motor is running.

When the SLOW button is pressed, the slow-speed starter S and the control relay FR are energized. Once the motor is running, pressing the FAST button causes the slow-speed starter to drop out. The high-speed starter is picked up through the normally closed interlock contacts S of the slow-speed starter and through the normally open contacts of control relay FR. The normally open contacts of control relay FR will now close.

If the FAST button is pressed in an attempt to start the motor, nothing will happen because the normally open contacts of control relay FR will prevent the high-



SPEED	L1	L2	L3	TOGETHER
SLOW	T1	T2	T3	T4, T5, T6
FAST	T6	T4	T5	

Figure 53–5 Wiring diagram (A) and line diagram (B) of an ac, full voltage, two-speed magnetic starter for single-winding (reconnectable pole) motors.

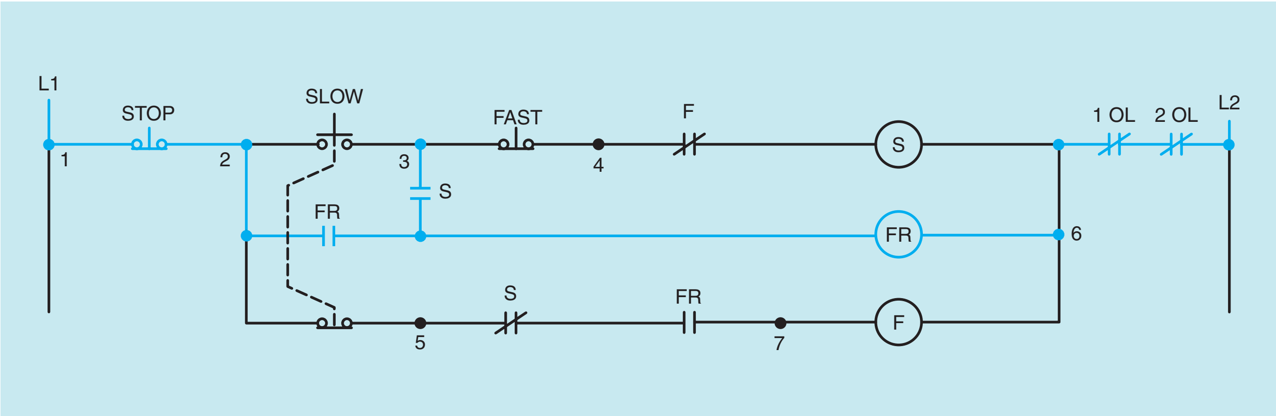


Figure 53–6 Two-speed control circuit using a compelling relay.

speed starter from energizing. When the FAST button is pressed, it breaks a circuit but does not make a circuit. This scheme is another form of sequence starting.

Mistaken Reversal Caution

When multispeed controllers are installed, the electrician should check carefully to insure that the phases between the high- and low-speed windings are not accidentally reversed. Such a phase reverse will also reverse the direction of motor rotation. The driven machine should remain disconnected from the motor until an operational inspection is completed. The upper oil inspection plugs (pressure plugs) in large gear reduction boxes should be removed. Failure to remove these plugs may create broken casings if the motor is reversed accidentally.

Machines can be damaged if the direction of rotation is changed from that for which they are designed. In general, the correct rotational direction is indicated by arrows on the driven machine.

Two-Speed Starter With Reversing Controls

Figure 53–7 is an elementary diagram of a two-speed, reversing controller. The desired speed, either high or low, is determined with a two-position selector switch. The direction of rotation is selected with either the FORWARD or REVERSE push buttons. When the power contacts (F) or (R) are closed, current is supplied for the "high-low" controls. Assuming that the selector switch is in the HIGH position, contactor L is energized to start the motor in low speed. At the same moment, timing relay coil TR is energized. When the normally closed delay-in-opening contact TR opens after a preset time delay, normally open contact (TR) closes at the same time. This operation drops out contactor L, and the normally closed interlock L energizes contactor H. The motor is now at high speed.

The motor may be started in low speed in either direction before it is transferred to high speed. If the low speed is to be maintained, the selector switch is turned to LOW in order to open the circuit supplying the timing relay coil TR. (This coil would normally transfer the control to high-speed operation.) Typical motor terminal connections are shown in Figure 53–8.

Three-Speed Consequent Pole Motors

Consequent pole motors that are intended to operate with three speeds contain two separate stator windings. One winding is reconnectable like the winding in a two-speed motor. The second winding is wound for a certain number of poles and is not reconnectable. If one

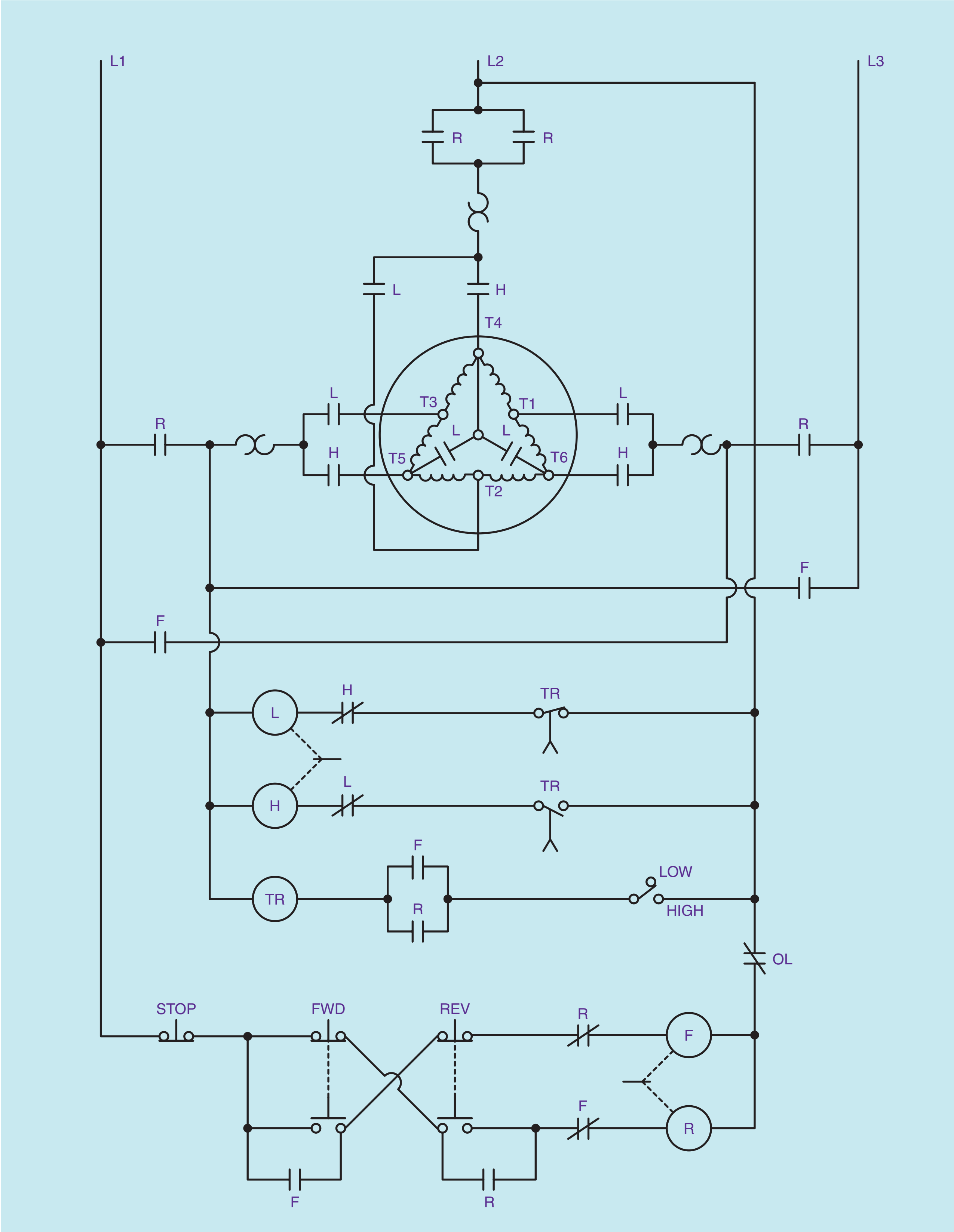
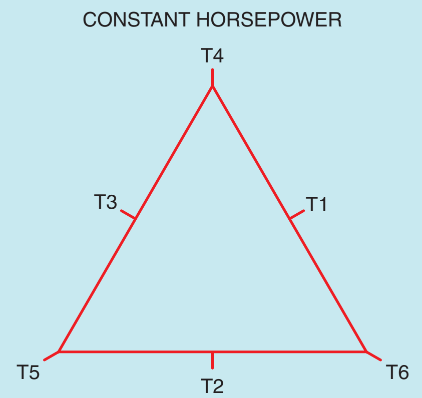
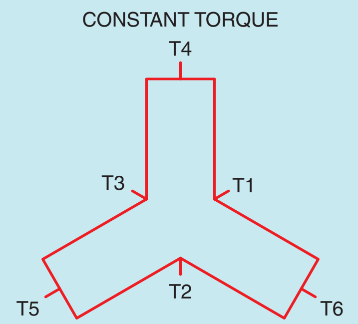


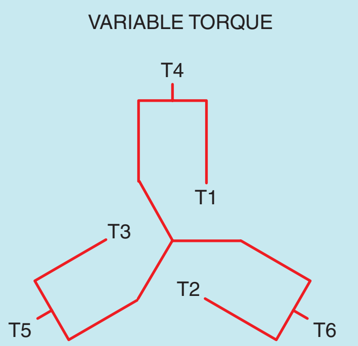
Figure 53–7 Two-speed reversing controller.



SPEED	L1	L2	L3	OPEN	TOGETHER
LOW	T1	T2	T3	————	T4,T5,T6
HIGH	T6	T4	T5	ALL OTHERS	————



SPEED	L1	L2	L3	OPEN	TOGETHER
LOW	T1	T2	T3	ALL OTHERS	————
HIGH	T6	T4	T5	————	T1,T2,T3



SPEED	L1	L2	L3	OPEN	TOGETHER
LOW	T1	T2	T3	ALL OTHERS	————
HIGH	T6	T4	T5	————	T1,T2,T3

Figure 53–8 Typical motor connection arrangement for three-phase, two-speed, one-winding motors. These connections conform to NEMA and ASA standards. (All possible arrangements are not shown.)

stator winding were wound with six poles and the second were reconnectable for two or four poles, the motor would develop synchronous speeds of 3600 RPM, 1800 RPM, or 1200 RPM when connected to a 60 Hz line. If the reconnectable winding were to be wound for four or eight pole connection, the motor would develop synchronous speeds of 1800 RPM, 1200 RPM, or 900 RPM. Three-speed consequent pole motors can be wound to produce constant horsepower, constant torque, or variable torque. Examples of different connection diagrams for three-speed, two-winding consequent pole motors are shown in Figures 53–9A through 53–9I.

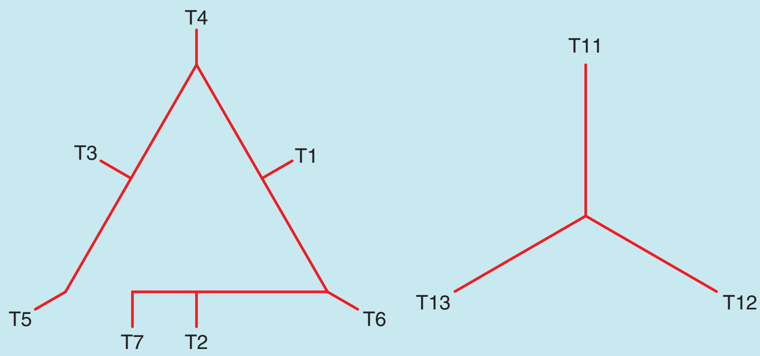
Four-Speed Consequent Pole Motors

Consequent pole motors intended to operate with four speeds use two reconnectable windings. Like two-speed or three-speed motors, four-speed motors can be wound to operate at constant horsepower, constant torque, or variable torque. Some examples of winding connections for four-speed, two-winding three-phase consequent pole motors are shown in Figures 53–10A through 53–10F.

A circuit for controlling a four-speed, three-phase consequent pole motor is shown in Figure 53–11. The control permits any speed to be selected by pushing the button that initiates that particular speed. In this circuit, stacked pushbuttons are used to break the circuit to any other speed before the starter that controls the selected speed is energized. Electrical interlocks are also used to ensure that two speeds cannot be energized at the same time. Eleven-pin control relays are used to provide interlock protection because they each contain three sets of contacts.

The load contact connection is also shown in Figure 53–11. The circuit assumes the connection diagram for the motor is the same as the diagram illustrated in Figure 53–10F. The circuit also assumes that the starters and contactors each contain three load contacts. Note that 3RD speed and HIGH speed require the use of two contactors to supply the necessary number of load contacts.

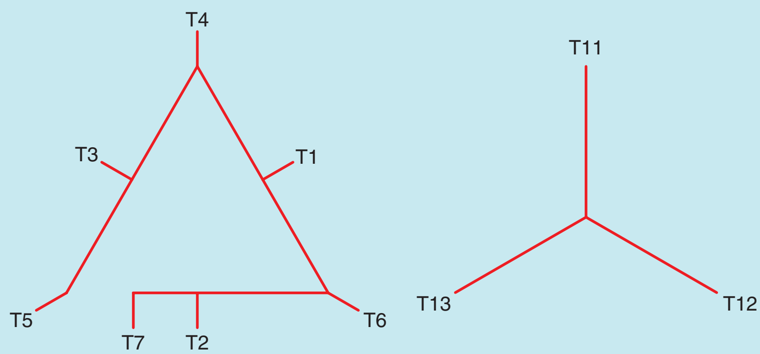
A two-speed, two-winding motor controller and a two-speed, one-winding motor controller are shown in Figure 53–12 and Figure 53–13.



WINDING ARRANGEMENT FOR 3 SPEED 2 WINDING
CONSEQUENT POLE 3 PHASE MOTORS

SPEED	L1	L2	L3	OPEN	TOGETHER
LOW	T1	T2	T3	ALL OTHERS	T4, T5, T6, T7
2ND	T6	T4	T5, T7	ALL OTHERS	————
HIGH	T11	T12	T13	ALL OTHERS	————

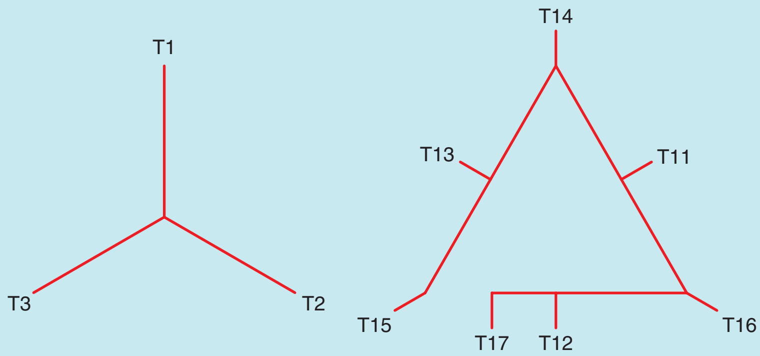
Figure 53–9A Constant horsepower.



WINDING ARRANGEMENT FOR 3 SPEED 2 WINDING
CONSEQUENT POLE 3 PHASE MOTORS

SPEED	L1	L2	L3	OPEN	TOGETHER
LOW	T1	T2	T3	ALL OTHERS	T4, T5, T6, T7
2ND	T11	T12	T13	ALL OTHERS	————
HIGH	T6	T4	T5, T7	ALL OTHERS	————

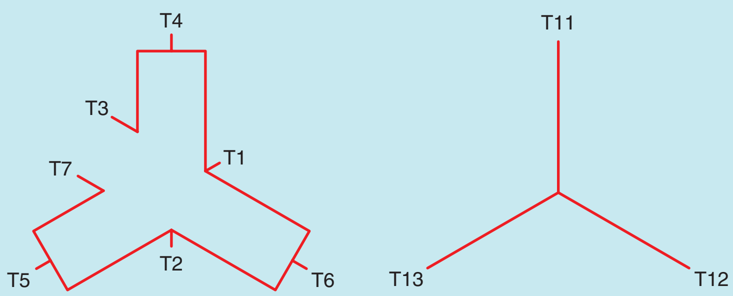
Figure 53–9B Constant horsepower.



WINDING ARRANGEMENT FOR 3 SPEED 2 WINDING
CONSEQUENT POLE 3 PHASE MOTORS

SPEED	L1	L2	L3	OPEN	TOGETHER
LOW	T1	T2	T3	ALL OTHERS	————
2ND	T11	T12	T13	ALL OTHERS	T14, T15, T16, T17
HIGH	T16	T14	T15, T17	ALL OTHERS	————

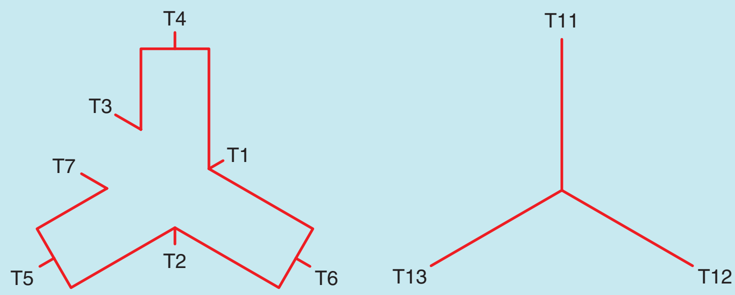
Figure 53–9C Constant horsepower.



WINDING ARRANGEMENT FOR 3 SPEED 2 WINDING
CONSEQUENT POLE 3 PHASE MOTORS

SPEED	L1	L2	L3	OPEN	TOGETHER
LOW	T1	T2	T3, T7	ALL OTHERS	————
2ND	T6	T4	T5	ALL OTHERS	T1, T2, T3, T7
HIGH	T11	T12	T13	ALL OTHERS	————

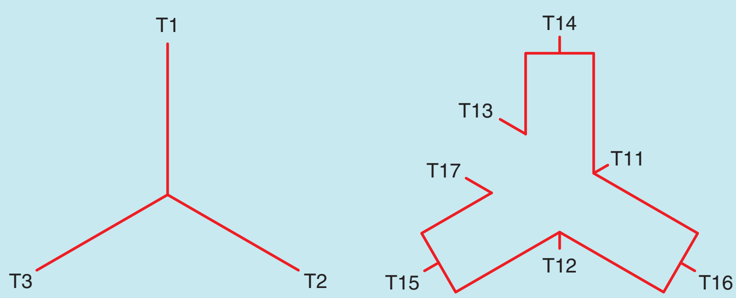
Figure 53–9D Constant torque.



WINDING ARRANGEMENT FOR 3 SPEED 2 WINDING
CONSEQUENT POLE 3 PHASE MOTORS

SPEED	L1	L2	L3	OPEN	TOGETHER
LOW	T1	T2	T3, T7	ALL OTHERS	————
2ND	T11	T12	T13	ALL OTHERS	————
HIGH	T6	T4	T5	ALL OTHERS	T1, T2, T3, T7

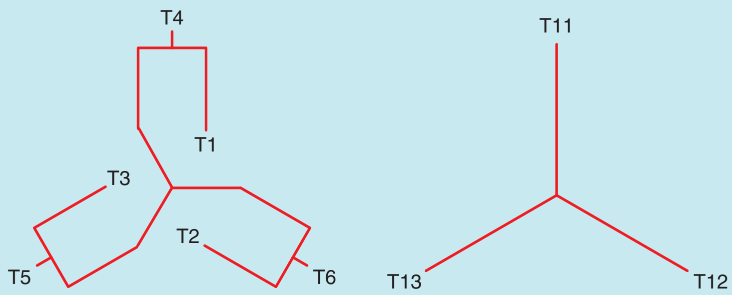
Figure 53–9E Constant torque.



WINDING ARRANGEMENT FOR 3 SPEED 2 WINDING
CONSEQUENT POLE 3 PHASE MOTORS

SPEED	L1	L2	L3	OPEN	TOGETHER
LOW	T1	T2	T3	ALL OTHERS	————
2ND	T11	T12	T13, T17	ALL OTHERS	————
HIGH	T16	T14	T15	ALL OTHERS	T11, T12, T13, T17

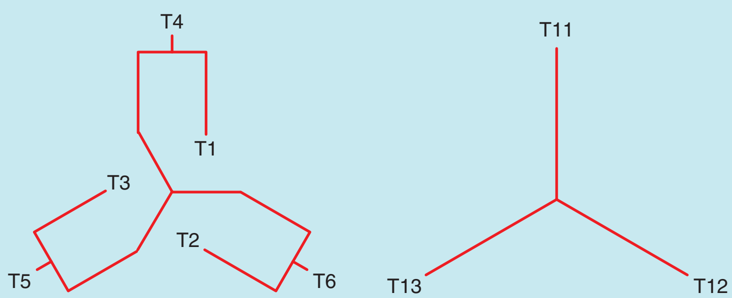
Figure 53–9F Constant torque.



WINDING ARRANGEMENT FOR 3 SPEED 2 WINDING
CONSEQUENT POLE 3 PHASE MOTORS

SPEED	L1	L2	L3	OPEN	TOGETHER
LOW	T1	T2	T3	ALL OTHERS	————
2ND	T11	T12	T13	ALL OTHERS	————
HIGH	T6	T4	T5	ALL OTHERS	T1, T2, T3

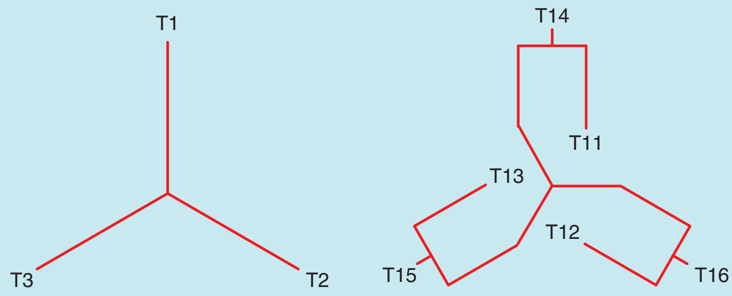
Figure 53–9G Variable torque.



WINDING ARRANGEMENT FOR 3 SPEED 2 WINDING
CONSEQUENT POLE 3 PHASE MOTORS

SPEED	L1	L2	L3	OPEN	TOGETHER
LOW	T1	T2	T3	ALL OTHERS	————
2ND	T6	T4	T5	ALL OTHERS	T1, T2, T3
HIGH	T11	T12	T13	ALL OTHERS	————

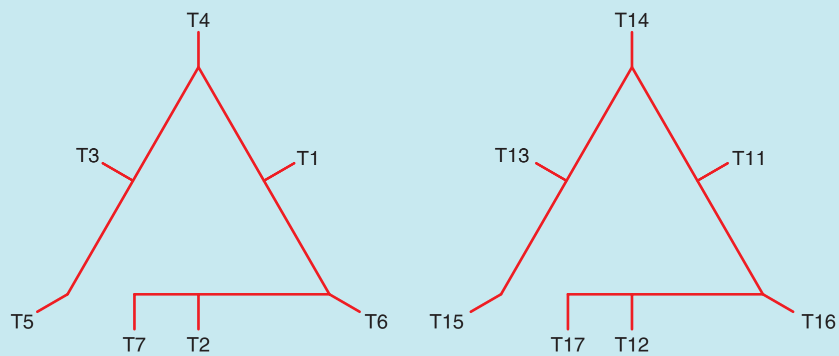
Figure 53–9H Variable torque.



WINDING ARRANGEMENT FOR 3 SPEED 2 WINDING
CONSEQUENT POLE 3 PHASE MOTORS

SPEED	L1	L2	L3	OPEN	TOGETHER
LOW	T1	T2	T3	ALL OTHERS	————
2ND	T11	T12	T13	ALL OTHERS	————
HIGH	T16	T14	T15	ALL OTHERS	T11, T12, T13

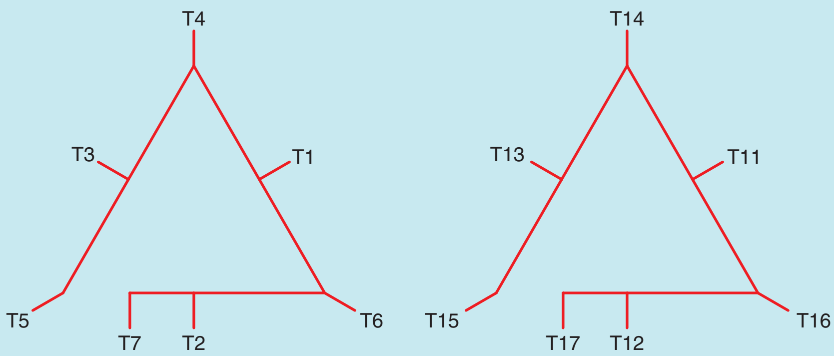
Figure 53–9I Variable torque.



WINDING ARRANGEMENT FOR 4 SPEED 2 WINDING
CONSEQUENT POLE 3 PHASE MOTOR

SPEED	L1	L2	L3	OPEN	TOGETHER
LOW	T1	T2	T3	ALL OTHERS	T4, T5, T6, T7
2ND	T6	T4	T5, T7	ALL OTHERS	————
3RD	T11	T12	T13	ALL OTHERS	T14, T15, T16, T17
HIGH	T16	T14	T15, T17	ALL OTHERS	————

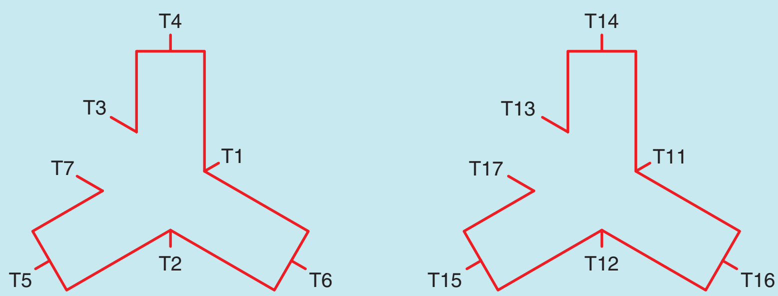
Figure 53–10A Constant horsepower.



WINDING ARRANGEMENT FOR 4 SPEED 2 WINDING
CONSEQUENT POLE 3 PHASE MOTOR

SPEED	L1	L2	L3	OPEN	TOGETHER
LOW	T1	T2	T3	ALL OTHERS	T4, T5, T6, T7
2ND	T11	T12	T13	ALL OTHERS	T14, T15, T16, T17
3RD	T6	T4	T5, T7	ALL OTHERS	————
HIGH	T16	T14	T15, T17	ALL OTHERS	————

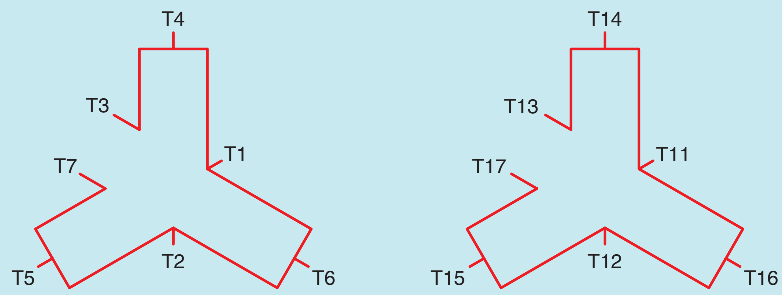
Figure 53–10B Constant horsepower.



WINDING ARRANGEMENT FOR 4 SPEED 2 WINDING
CONSEQUENT POLE 3 PHASE MOTOR

SPEED	L1	L2	L3	OPEN	TOGETHER
LOW	T1	T2	T3, T7	ALL OTHERS	————
2ND	T6	T4	T5	ALL OTHERS	T1, T2, T3, T7
3RD	T11	T12	T13, T17	ALL OTHERS	————
HIGH	T16	T14	T15	ALL OTHERS	T11, T12, T13, T17

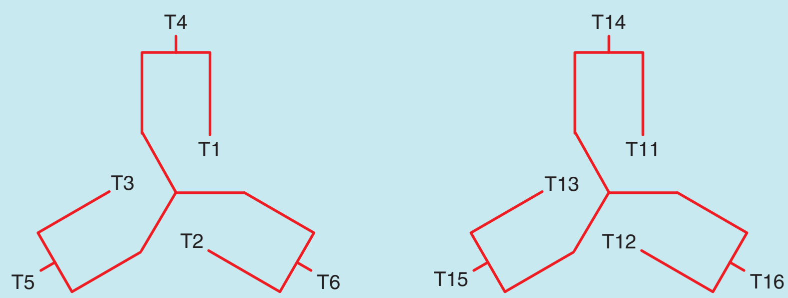
Figure 53–10C Constant torque.



WINDING ARRANGEMENT FOR 4 SPEED 2 WINDING
CONSEQUENT POLE 3 PHASE MOTOR

SPEED	L1	L2	L3	OPEN	TOGETHER
LOW	T1	T2	T3, T7	ALL OTHERS	————
2ND	T11	T12	T13, T17	ALL OTHERS	————
3RD	T6	T4	T5	ALL OTHERS	T1, T2, T3, T7
HIGH	T16	T14	T15	ALL OTHERS	T11, T12, T13, T17

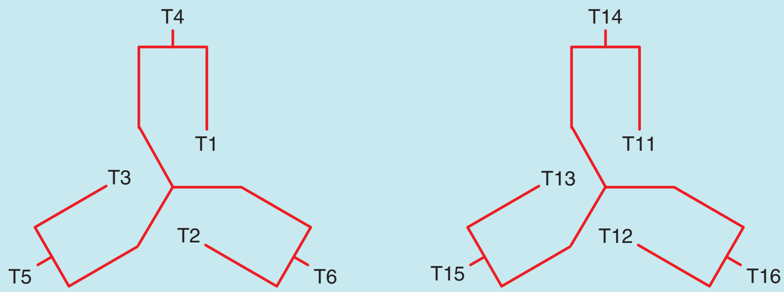
Figure 53–10D Constant torque.



WINDING ARRANGEMENT FOR 4 SPEED 2 WINDING
CONSEQUENT POLE 3 PHASE MOTOR

SPEED	L1	L2	L3	OPEN	TOGETHER
LOW	T1	T2	T3	ALL OTHERS	————
2ND	T6	T4	T5	ALL OTHERS	T1, T2, T3
3RD	T11	T12	T13	ALL OTHERS	————
HIGH	T16	T14	T15	ALL OTHERS	T11, T12, T13

Figure 53–10E Variable torque.



WINDING ARRANGEMENT FOR 4 SPEED 2 WINDING
CONSEQUENT POLE 3 PHASE MOTOR

SPEED	L1	L2	L3	OPEN	TOGETHER
LOW	T1	T2	T3	ALL OTHERS	————
2ND	T11	T12	T13	ALL OTHERS	————
3RD	T6	T4	T5	ALL OTHERS	T1, T2, T3
HIGH	T16	T14	T15	ALL OTHERS	T11, T12, T13

Figure 53–10F Variable torque.

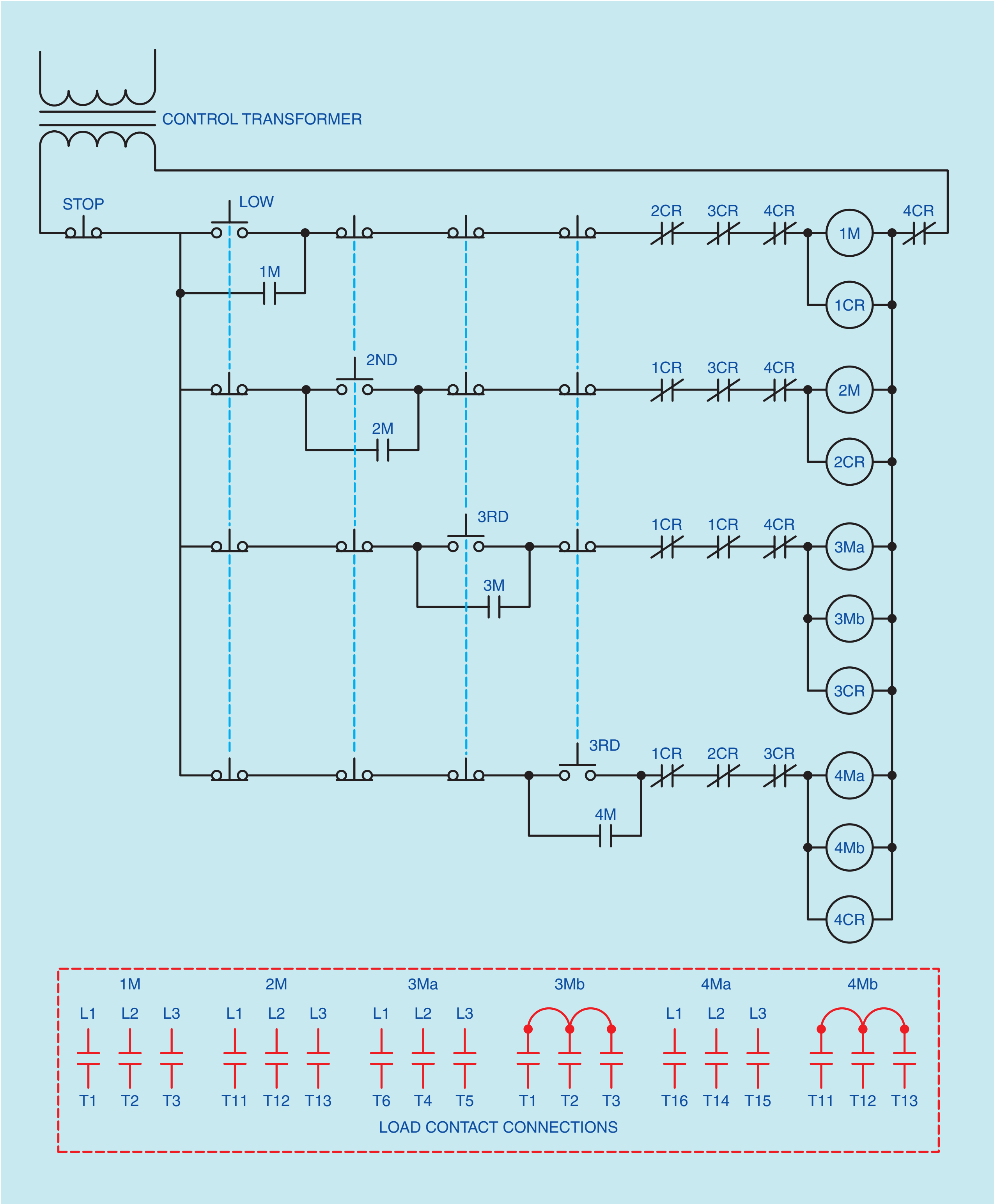


Figure 53–11 Pushbutton control for a four-speed, consequent pole three-phase motor.

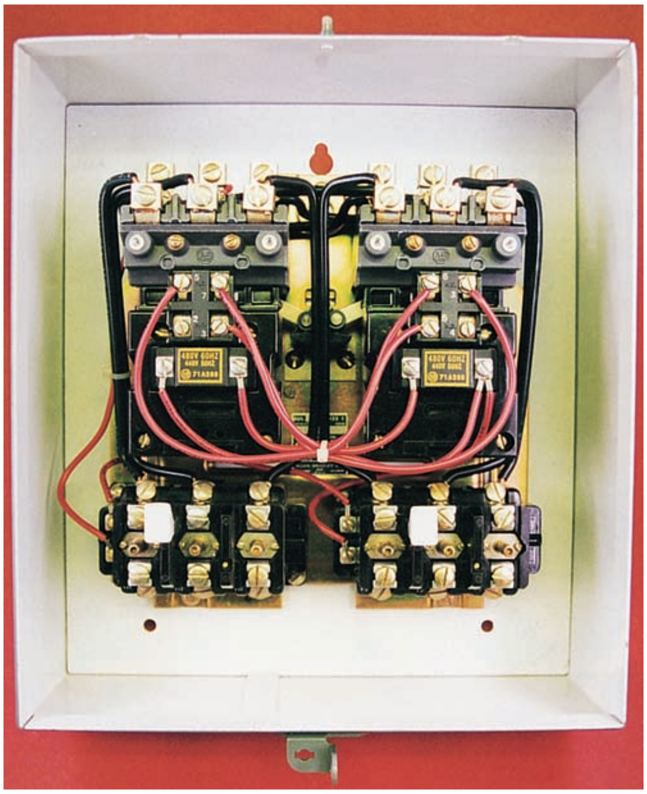


Figure 53–12 Two-speed, two-winding motor controller mounted in cabinet.

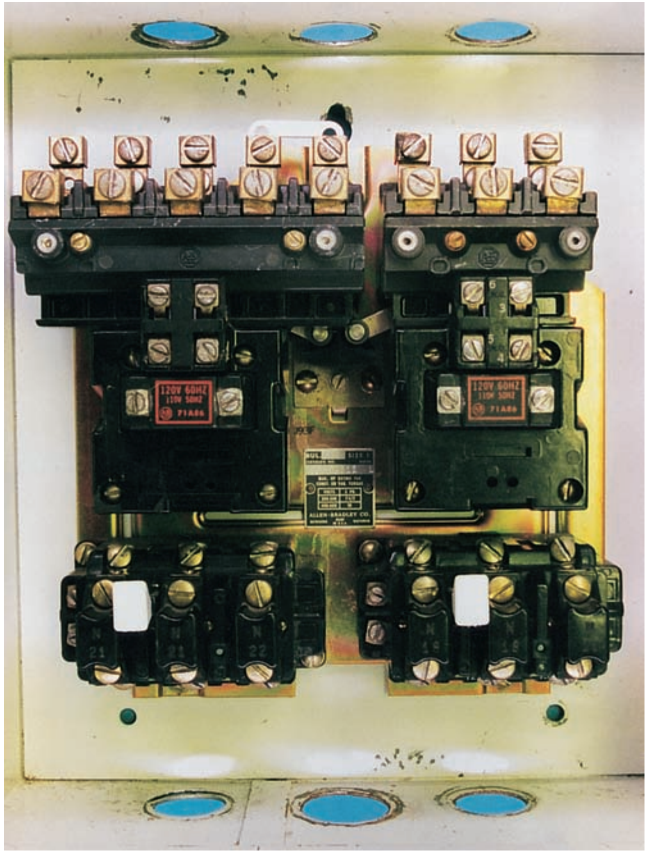


Figure 53–13 Two-speed, one-winding motor controller mounted in cabinet.

Review Questions

1. The rotating magnetic field of a two-pole motor travels 360 electrical degrees. How many mechanical degrees does the rotor travel?
2. How can two speeds be obtained from a one-winding motor?
3. What will happen if terminals T5 and T6 in Figure 53–3 are interchanged on high speed?
4. Is the motor operating at high speed or low speed when it is connected in series delta? In parallel wye?
5. Describe the operation of the line diagram in Figure 53–5(B) by adding jumper “D” only.
6. Describe the operation of Figure 53–5(B) by adding jumper wire “A” to the original circuit.
7. In Figure 53–6, the motor cannot be started in high speed. Why?
8. Draw a schematic diagram of a two-speed control circuit, using a standard duty selector switch for the high and low speeds. Add a red pilot light for fast speed and a green pilot light for low speed. Omit “A” and “D” jumper wires.
9. A three-speed consequent pole motor has two separate stator windings. How many are reconnectable and how many are not?
10. A four-speed consequent pole motor has two separate stator windings. How many are reconnectable and how many are not?
11. Refer to the control circuit shown in Figure 53–11. Assume that the coil of control relay 1CR is open. Explain how the circuit will operate.

UNIT 54

WOUND ROTOR MOTORS AND MANUAL SPEED CONTROL

OBJECTIVES

After studying this unit, the student will be able to:

- Identify terminal markings for wound rotor (slip ring) motors and controllers.
- Describe the purpose and function of manual speed control and wound rotor motor applications.
- Explain the difference between two-wire and three-wire control for wound rotor motors.
- Connect wound rotor motors with manual speed controllers.
- Recommend solutions to troubleshoot problems with these motors.

The ac three-phase wound rotor, or slip ring, induction motor was the first alternating-current motor that successfully provided speed control characteristics. This type of motor was an important factor in successfully adapting alternating current for industrial power applications. Because of their flexibility in specialized applications, wound rotor motors and controls are widely used throughout industry to drive conveyors for moving materials, hoists, grinders, mixers, pumps, variable speed fans, saws, and crushers. Advantages of this type of motor include maximum utilization of driven equipment, better coordination with the overall power system, and reduced wear on mechanical equipment. The wound rotor motor has the added features of high starting torque and low starting current. These features give the motor better operating characteristics for applications requiring a large motor or where the motor must start under load. This motor is especially desirable where its size is large with respect to the capacity of the transformers or power lines.

The phrase "wound rotor" actually describes the construction of the rotor. In other words, it is wound with wire. When the rotor is installed in a motor, three leads are brought out from the rotor winding to solid conducting slip rings (Figure 54–1). Carbon brushes ride on these rings and carry the rotor winding circuit out of the motor to a controller. Unlike the squirrel cage motor, the induced current can be varied in the wound rotor motor. As a result, the motor speed can also be varied (Figure 54–2). (Wound rotor motors have stator

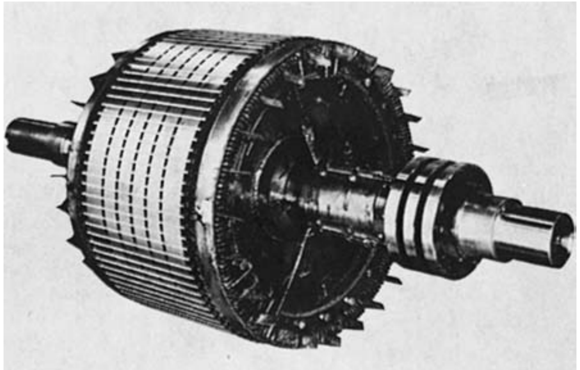


Figure 54–1 Rotor of an 800-hp, wound rotor induction motor. (Courtesy Electric Machinery Mfg. Co.).

windings identical to those used in squirrel cage motors.) The controller varies the resistance (and thus the current), in the rotor circuit to control the acceleration and speed of the rotor once it is operating.

Resistance is introduced into the rotor circuit when the motor is started or when it is operating at slow speed. As the external resistance is eliminated by the controller, the motor accelerates.

Generally, wound rotor motors are not started under load with their slip rings shunted or shorted together. If a wound rotor motor is started in this manner, the starting resistance is so low that starting current is too high to be acceptable. In addition, the amount of starting torque per ampere of starting current is much less than if resistance is connected in the circuit during the starting period. To better understand this concept, consider that there are three factors that determine the amount of torque developed by an induction motor.

a. The strength of the magnetic field of the stator winding.

b. The strength of the magnetic field of the rotor.

c. The phase angle difference between the rotor and stator magnetic fields. (Maximum starting torque is developed if the rotor and stator currents are in phase with each other.)

The amount of current flow in the stator and rotor determine the strength of the magnetic field in each. The phase angle difference, however, is determined by the amount of inductance as compared to the amount of resistance in the circuit. If the motor is started with the slip rings shorted together, the rotor current is limited primarily by the inductive reactance of the rotor. This causes the rotor current to lag behind the stator current by almost 90°, producing a very low starting torque for the amount of starting current. If resistance is added to the rotor circuit during starting, rotor current becomes much more in phase with stator current. This results in the rotor and stator magnetic field being more in phase and the amount of starting torque per ampere of starting current is increased.

A control for a wound rotor motor consists of two separate elements: (1) a means of connecting the primary or stator winding to the power lines, and (2) a mechanism for controlling the resistance in the secondary or rotor circuit. For this reason, wound rotor motor controllers are often called *secondary resistor starters.*

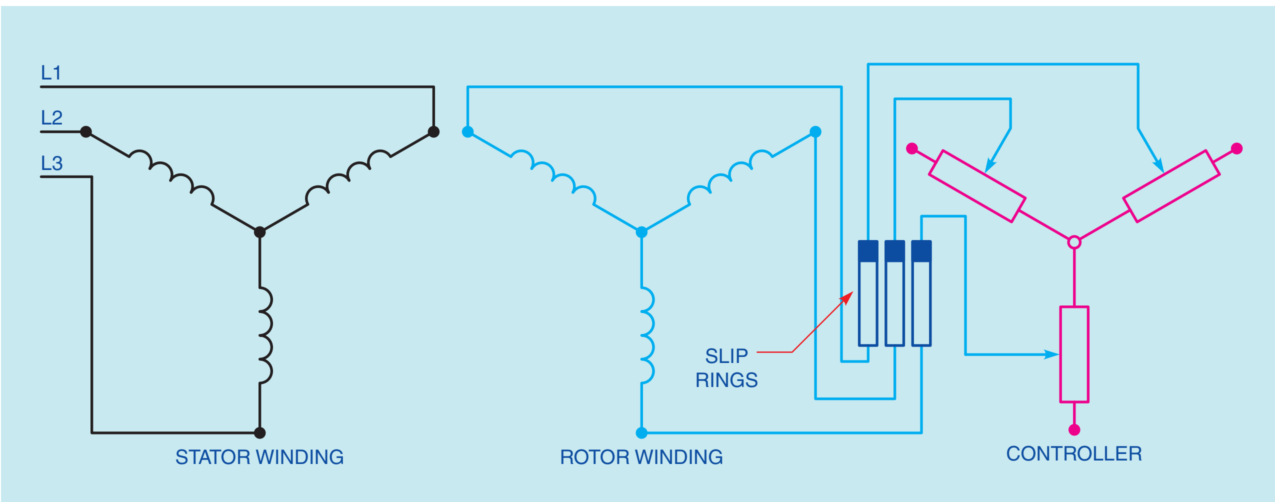


Figure 54–2 Stator, rotor, and controller.

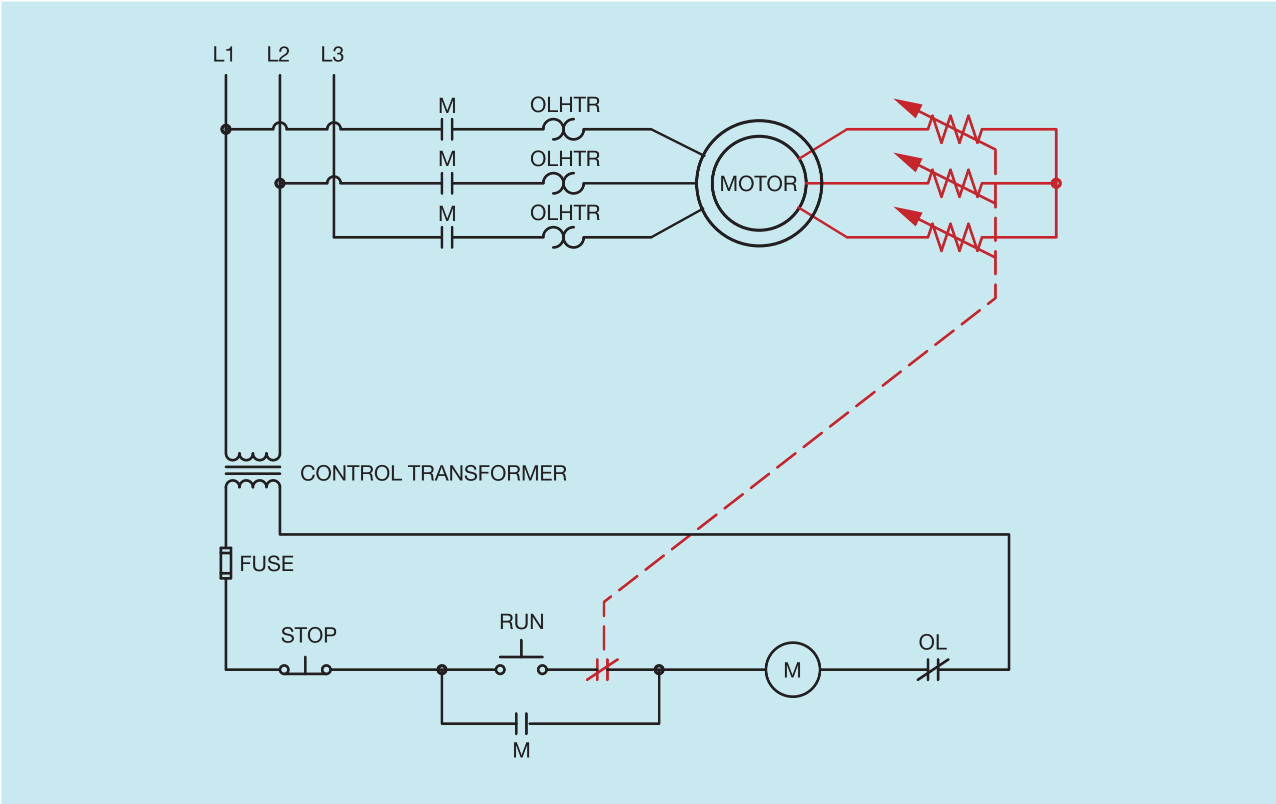


Figure 54–3 Diagram of a basic manual speed regulator interlocked with magnetic starter for a wound rotor induction motor (three-wire control).

Basically, there are two types of manual controllers, *starters* and *regulators*. The resistors used in *starters* are designed for starting duty only. This means that the operating lever must be moved to the full *ON* position. The lever must *not* be left in any intermediate position. The resistors used in *regulators* are designed for continuous duty. As a result, the operating lever in regulators can be left in any speed position.

When wound rotor motors are used as adjustable speed drives, they are operated on a continuous basis with resistance in the rotor circuit. In this case, the speed regulation of the motor is changed, and the motor operates at less than the full-load speed.

The use of three-wire control for starting (normally closed control contact, Figure 54–3), means that low-voltage protection is provided. The motor is disconnected from the line in the event of voltage failure. To restart the motor when the voltage returns to its normal value, the normal starting procedure must be followed. To reverse the motor, any two of the three-phase motor leads may be interchanged.

Review Questions

1. What characteristic of wound rotor motors led to their wide use for industrial applications?
2. By what means is the rotor coupled to the stator?
3. What other name is given to the wound rotor motor?
4. Does increased resistance in the rotor circuit produce low or high speed?
5. What two separate elements are used to control a wound rotor motor?
6. What is the difference between a manual starter and a manual regulator?

UNIT 55

AUTOMATIC ACCELERATION FOR WOUND ROTOR MOTORS

OBJECTIVES

After studying this unit, the student will be able to:

- State the advantages of using controllers to provide automatic acceleration of wound rotor motors.
- Identify terminal markings for automatic acceleration controllers used with wound rotor motors.
- Describe the process of automatic acceleration using reversing control.
- Describe the process of automatic acceleration using frequency relays.
- Connect wound rotor motor and automatic acceleration and reversal controllers using push buttons and limit switches.
- Recommend troubleshooting solutions for these problems.

Secondary resistor starters used for the automatic acceleration of wound rotor motors consist of (1) an across-the-line starter for connecting the primary circuit to the line and (2) one or more accelerating contactors to shunt out resistance in the secondary circuit as the rotor speed increases. The secondary resistance consists of banks of three uniform wye sections. Each section is to be connected to the slip rings of the motor. The wiring of the accelerating starters and the design of the resistor sections are meant for starting duty only. This type of controller cannot be used for speed regulation. The current inrush on starters with two steps of acceleration is limited by the secondary resistors to a value of approximately 250 percent at the point of the initial acceleration. Resistors on starters with three or more steps of acceleration limit the current inrush to 150 percent at the point of initial acceleration. Resistors for acceleration generally are designed to withstand one 10-second accelerating period in each 80 seconds of elapsed time, for a duration of one hour without damage.

The operation of accelerating contactors is controlled by a timing device. This device provides timed acceleration in a manner similar to the operation of primary resistor starters. Normally, the timing of the steps of acceleration is controlled by adjustable

accelerating relays. When these timing relays are properly adjusted, all starting periods are the same regardless of variations in the starting load. This automatic timing feature eliminates the danger of an improper startup sequence by an inexperienced machine operator.

When the START button is pressed, motor starter M energizes and causes all M contacts to close. The three M load contacts connect the stator winding of the motor to the power line. The M auxiliary contact connected in parallel with the START button closes to maintain the circuit when the START button is released, and the M auxiliary contact connected in series with time delay relay TR1 closes and provides power to coil TR1. The motor is now connected to the power line with all resistance connected in the rotor circuit, causing the motor to start in its lowest speed.

When the time delay setting of TR1 is completed, contact TR1 closes and connects contactor S1 to the power line, causing all S1 contacts to close. The two S1 load contacts close and shunt out the first set of rotor circuit resistors. Since less resistance is now connected in the rotor circuit, the motor accelerates to its second speed. The normally open S1 auxiliary contact connected in series with coil TR2 closes and starts the timing action for timer TR2.

When the time delay setting of TR2 is completed, contact TR2 closes and energizes the coil of contactor S2. This causes S2 load contacts to close and shunt out the remaining resistance in the rotor circuit. The motor is now operating at its highest speed.

Automatic Acceleration with Reversing Control

Automatic acceleration can be obtained in either direction by adding the necessary contactor and push buttons as shown in Figure 55–2. The wound rotor induction motor can be reversed in the same manner as a squirrel cage induction motor, by reversing any two of the stator winding leads. This causes a reversal of the rotating magnetic field in the stator. This reversal of direction has no effect on the resistors connected in the rotor circuit. Note that in the circuit shown in Figure 55–2, a normally open auxiliary R contact has been connected in parallel with a normally open F contact. This permits timer TR1 to be energized if either direction of rotation is chosen. The acceleration control is identical to the circuit shown in Figure 55–1.

As is the case with almost all reversing controllers, interlocking is employed to prevent the possibility of the forward and reverse contactors from being energized at the same time. The normally closed F and R contacts connected in series with the coils of contactors F and R provide this protection as well as a mechanical interlock. The FORWARD and REVERSE push buttons are double acting in this circuit, meaning that both a normally open and normally closed section is used for each button. This arrangement permits the motor to be stopped without having to push the STOP push button if a change of direction is desired. If the motor is operating in the forward direction and the REVERSE push button is pressed, the normally closed section of the REVERSE push button opens to disconnect the coil of contactor F from the line, causing the F load contacts to open and disconnect the motor from the line, and the normally closed F contact connected in series with the coil of contactor R to close. When the normally open section of the REVERSE push button closes, a circuit is completed to the coil of contactor R, causing all R contacts to change position. The motor will now restart in the reverse direction. Notice that the motor must restart at the lowest speed and accelerate to its highest speed each time the direction of rotation is changed.

Automatic Acceleration Using Frequency Relays

Definite timers or compensated timers may be used to control the acceleration of wound rotor motors. Definite timers, which usually consist of pneumatic or electronic relays, are set for the highest load current and remain at the same setting regardless of the load. The operation of a compensated timer is based on the applied load. In other words, the motor will be allowed to accelerate faster for a light load and slower for a heavy load. The frequency relay is one type of compensating timer. This relay uses the principle of electrical resonance in its operation.

When a 60-hertz ac, wound rotor motor is accelerated, the frequency induced in the secondary circuit decreases from 60 hertz at zero speed to two or three

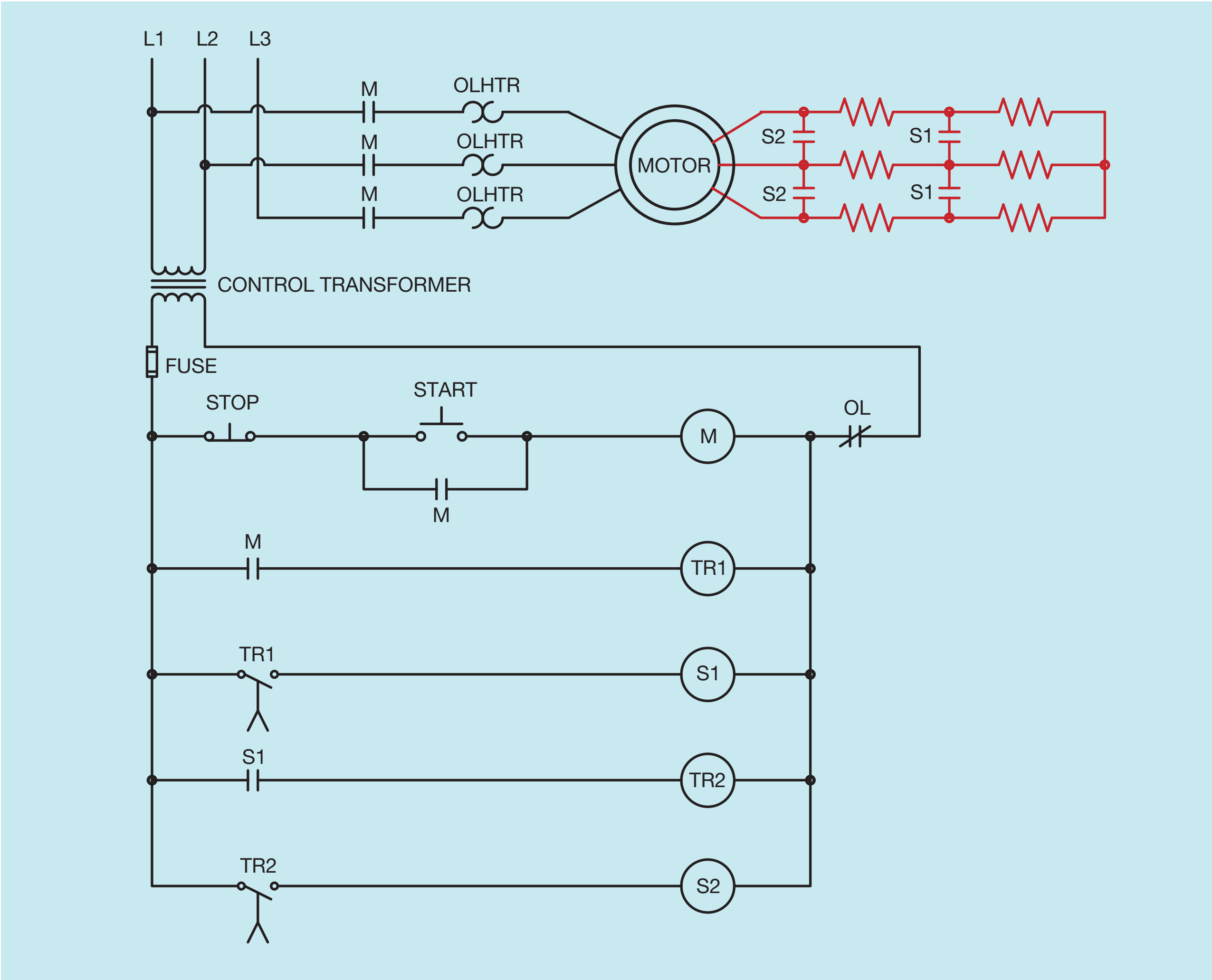


Figure 55–1 Typical elementary diagram of wound rotor motor starter with three steps of acceleration.

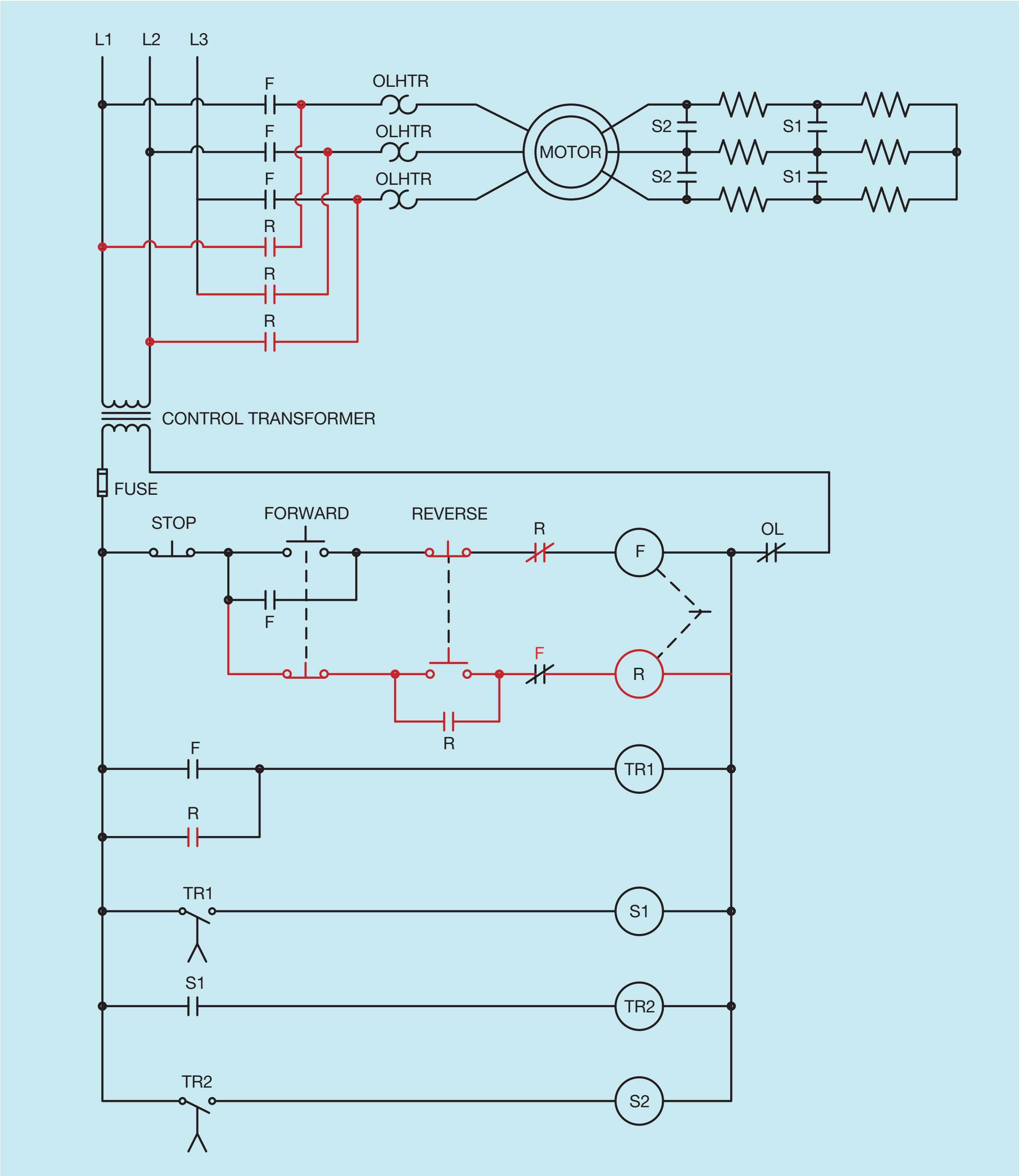


Figure 55–2 Wound rotor motor control with three steps of starting with the addition of forward-reverse control.

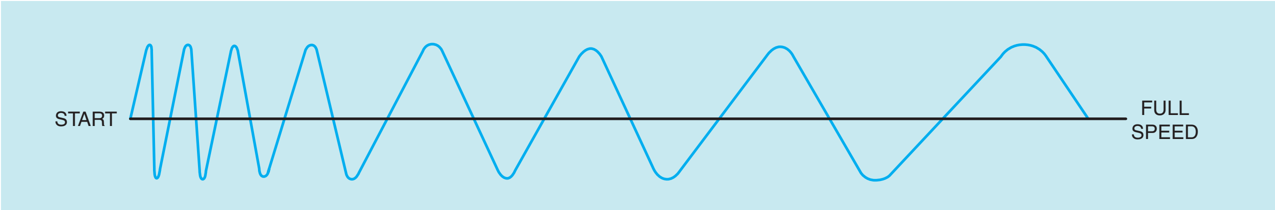


Figure 55–3 Rotor frequency decreases as the motor approaches full speed.

hertz at full speed (Figure 55–3). The voltage between the phases of the secondary circuit decreases in the same proportion from zero speed to full-speed operation. At zero speed, the voltage induced in the rotor is determined by the ratio of the stator and rotor turns. This action is similar to the operation of a transformer. The frequency, however, is the same as that of the line supply. As the rotor accelerates, the magnetic fields induced in it almost match the rotating magnetic field of the stator. As a result, the number of lines of force cut by the rotor is decreased, causing a decrease in the frequency and voltage of the rotor. The rotor never becomes fully synchronized with the rotating field. This is due to the slip necessary to achieve the relative motion required for induction and the operation of the rotor. The percentage of slip determines the value of the secondary frequency and voltage. If the slip is 5%, then the secondary frequency and voltage are 5% of normal.

Figure 55–4 illustrates a simplified frequency relay system operated by push-button starting. This system has two contactor coils connected in parallel (A and B) and a capacitor connected in series with coil B. A three-step automatic acceleration results from this arrangement. When the motor starts, full voltage is produced across coils A and B, causing normally closed contacts A and B to open. The full resistance is connected across the secondary of the motor. As the motor accelerates, the secondary frequency decreases. This means that coil B drops out and contacts B close to decrease the resistance in the rotor circuit, resulting in continued acceleration of the motor. The capacitor depends upon the frequency of an alternating current. As the motor continues to accelerate, coil A drops out and closes contacts A, accelerating the motor further. Because the normally closed contacts are used, the secondary of the motor cannot be shunted out completely. If the secondary could be completely removed from the circuit, the electron flow would take the path of least resistance, resulting in no energy being delivered to coils A and B upon starting.

The controllers for large crane hoists have a resistance, capacitance, and inductance control circuit network that is independent of the secondary rotor resistors.

Frequency relays have a number of advantages, including:

(1) positive response

(2) operating current drops sharply as the frequency drops below the point of resonance

(3) accuracy is maintained because this type of relay operates in a resonant circuit

(4) simple circuit

(5) changes in temperature and variations in line voltage do not affect the relay

(6) an increase in motor load prolongs the starting time.

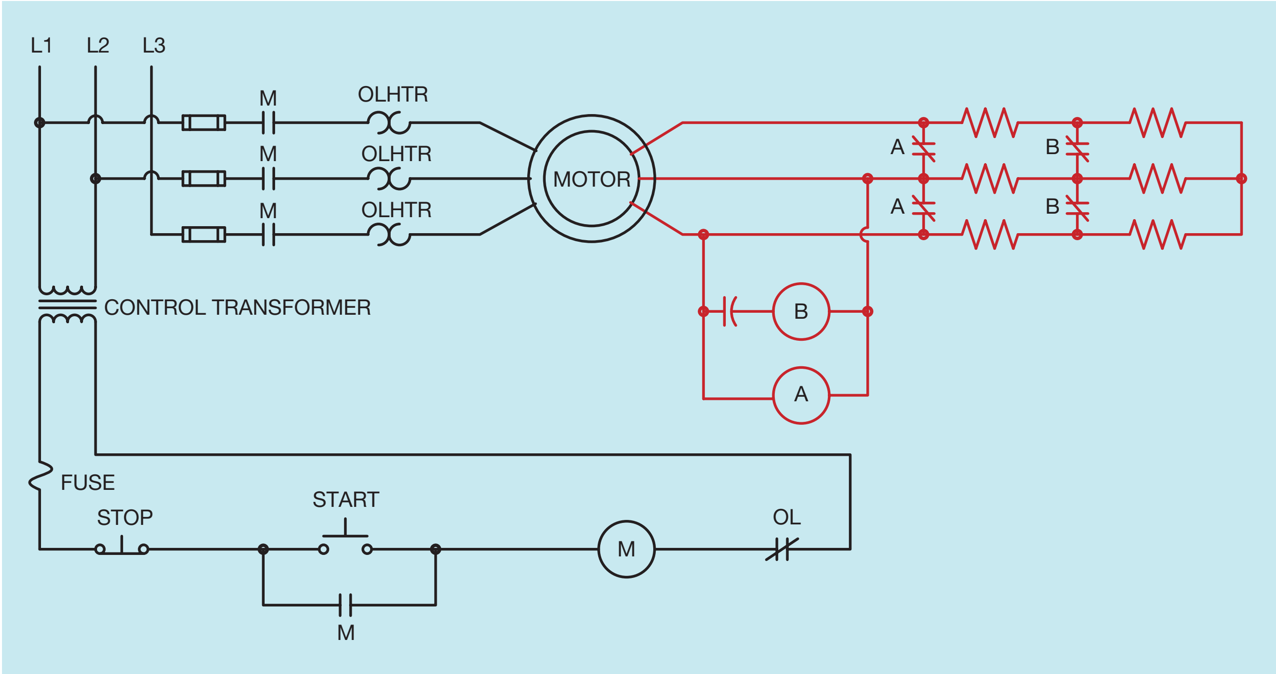


Figure 55–4 Automatic acceleration of wound rotor motor using simplified frequency relay system.

Review Questions

1. Are the secondary resistors connected in three uniform wye or delta sections?
2. Do secondary resistors on starters with three or more steps of acceleration have more or less current inrush than those with two steps of acceleration?
3. Does reversing the secondary rotor leads mean that the direction of rotation will reverse?
4. If one of the secondary resistor contacts (S2) fails in Figure 55–1, what will happen?
5. In Figure 55–2, how many different interlocking conditions exist? Name them.
6. Referring to Figure 55–4, why isn't it possible to remove all of the resistance from the secondary circuit?
7. If frequency relays are used on starting, why is the starting cycle prolonged with an increase in motor load?
8. If there is a locked rotor in the secondary circuit, what will be the value of the frequency?
9. In Figure 55–1, assume timer TR1 became defective and had to be replaced. Also assume that TR1 was mistakenly replaced with an off-delay timer instead of an on-delay timer. What will be the action of the circuit when the START button is pressed?
10. Refer to Figure 55–2. If the FORWARD push button is pressed, the motor starts in its lowest speed, and then accelerates normally to second speed and then to high speed. If the REVERSE push button is pressed, the motor starts in the reverse direction in its lowest speed, but never accelerates to second or high speed. What could cause this condition? Explain your answer.

UNIT 56
SYNCHRONOUS MOTOR OPERATION

OBJECTIVES

After studying this unit, the student will be able to:

- Describe the operation and applications of a synchronous motor.
- Describe lagging and leading power factor and the causes of each.
- Describe how the use of a synchronous motor improves the efficiency of an electrical system having a lagging power factor.
- Identify a brushless synchronous motor.

One of the distinguishing features of the synchronous motor is that it runs without slip at a speed determined by the frequency of the connected power source and the number of poles it contains. This type of motor sets up a rotating field through stator coils energized by alternating current. (This action is similar to the principle of an induction motor.) An independent field is established by a rotor energized by direct current through slip rings mounted on the shaft. The rotor has the same number of coils as the stator. At running speed, these fields (north and south) lock into one another magnetically so that the speed of the rotor is in step with the rotating magnetic field of the stator. In other words, the rotor turns at the synchronous speed. Variations in the connected load do not cause a corresponding change in speed, as they would with the induction motor.

The rotor (Figure 56–1), is excited by a source of direct current so that it produces alternate north and south poles. These poles are then attracted by the rotating magnetic field in the stator. The rotor must have the same number of poles as the stator winding. Every rotor pole, north and south, has an alternate stator pole, south and north, with which it can synchronize.

The rotor has dc field windings to which direct current is supplied through collector rings (slip rings). The current is provided from either an external source or a small dc generator connected to the end of the rotor shaft.

The magnetic fields of the rotor poles are locked into step with—and pulled around by—the revolving field of the stator. Assuming that the rotor and stator have the same number of poles, the rotor moves at the stator frequency (in hertz) actually produced by the generator supplying the motor.

Synchronous motors are constructed almost exactly like alternators. They differ only in those features of

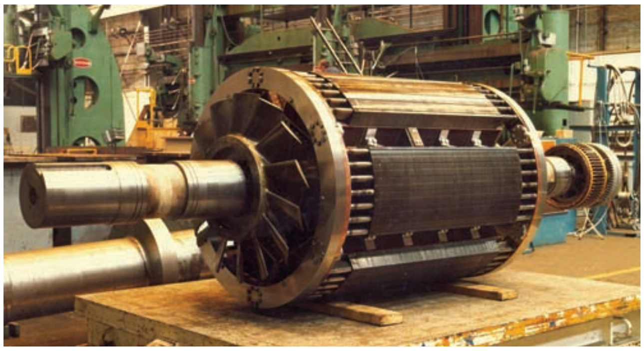


Figure 56–1 Synchronous motor rotor with amortisseur winding. (Courtesy of G.E. Industrial Systems, Fort Wayne, IN.)

design that may make the motor better adapted to its particular purpose.

A synchronous motor cannot start without help because the dc rotor poles at rest are alternately attracted and repelled by the revolving stator field. Therefore, an induction squirrel cage, or starting, winding is embedded in the pole faces of the rotor. This is called an *amortisseur* (ah-more-ti-sir) winding.

This starting winding resembles a squirrel cage winding. The induction effect of the starting winding provides the starting, accelerating, and pull-up torques required. The winding is designed to be used only for starting and for damping oscillations during running. It cannot be used like the winding of the conventional squirrel cage motor. It has a relatively small cross-sectional area and will overheat if the motor is used as a squirrel cage induction motor.

The slip is equal to 100 percent at the moment of starting. Thus, when the ac rotating magnetic field of the stator cuts the rotor windings, which are stationary at startup, the induced voltages produced may be high enough to damage the insulation if precautions are not taken.

If the dc rotor field is either connected as a closed circuit or connected to a discharge resistor during the starting period, the resulting current produces a voltage drop that is opposed to the generated voltage. Thus, the induced voltage at the field terminals is reduced. The squirrel cage winding is used to *start* the synchronous motor in the same way it is used in the squirrel cage induction motor. When the rotor reaches the maximum speed to which it can be accelerated as a squirrel cage motor (about 95 percent or more of the synchronous speed), direct current is applied to the rotor field coils to establish north and south rotor poles. These poles then are attracted by the poles on the stator. The rotor then accelerates until it locks into synchronous motion with the stator field.

Synchronous motors are used for applications involving large, slow-speed machines with steady loads and constant speeds. Such applications include compressors, fans and pumps, many types of crushers and grinders, and pulp, paper, rubber, chemical, flour, and metal rolling mills (Figure 56–2).

Power Factor Correction By Synchronous Motor

A synchronous motor converts alternating-current electrical energy into mechanical power. In addition, it also provides power factor correction. It can operate at a

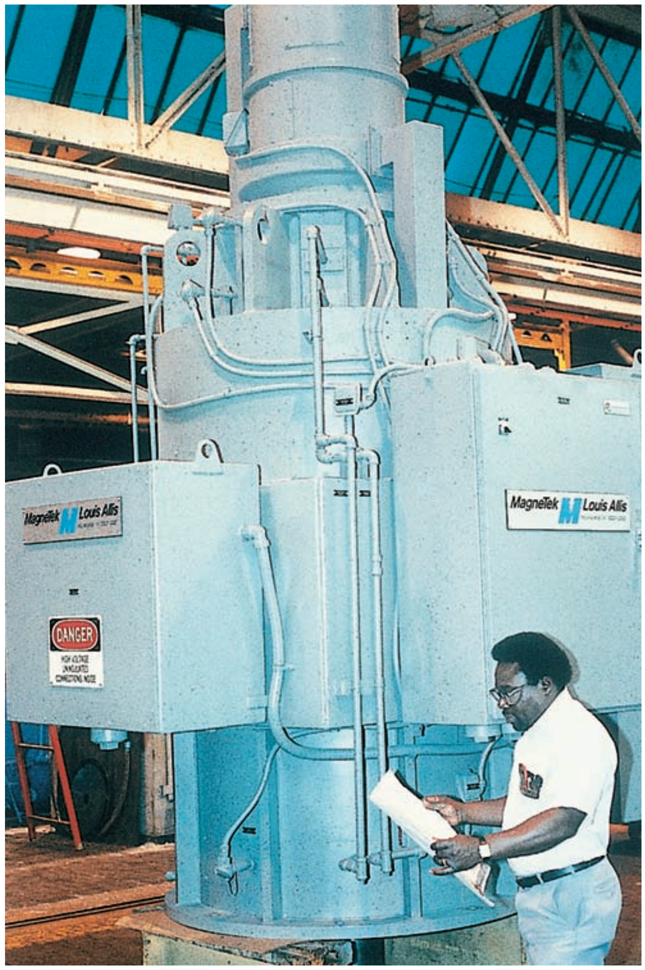


Figure 56–2 A 2500 hp synchronous motor driving a water circulating pump. (Courtesy MagneTek Louis Allis).

leading power factor or at unity. In very rare occasions, it can operate at a lagging power factor.

The power factor is of great concern to industrial users of electricity with respect to energy conservation. Power factor is the ratio of the actual power being used in a circuit, expressed in watts or kilowatts, to the power apparently being drawn from the line, expressed in volt-amperes or kilo volt-amperes (kVA). The kVA value is obtained by multiplying a voltmeter reading and an ammeter reading of the same circuit or equipment. Inductance within the circuit will cause the current to lag the voltage.

When the values of the apparent and actual power are equal or in phase, the ratio of these values is 1 : 1. In other words, when the voltage and amperage are in phase, the ratio of these values is 1 : 1. This is the case of pure resistive loads. The unity power factor value is the highest power factor that can be obtained. The higher the power factor, the greater is the efficiency of the electrical equipment.

Ac loads generally have a lagging power factor. As a result, these loads burden the power system with a large reactive load. Refer to the induction motor in Figure 56–3. A synchronous motor with an overexcited dc field may be used to offset the low power factor of the other loads on the same electrical system. An overexcited synchronous motor means that it is operating at more than the unity power factor. Therefore, it is working to improve the power factor of the power system.

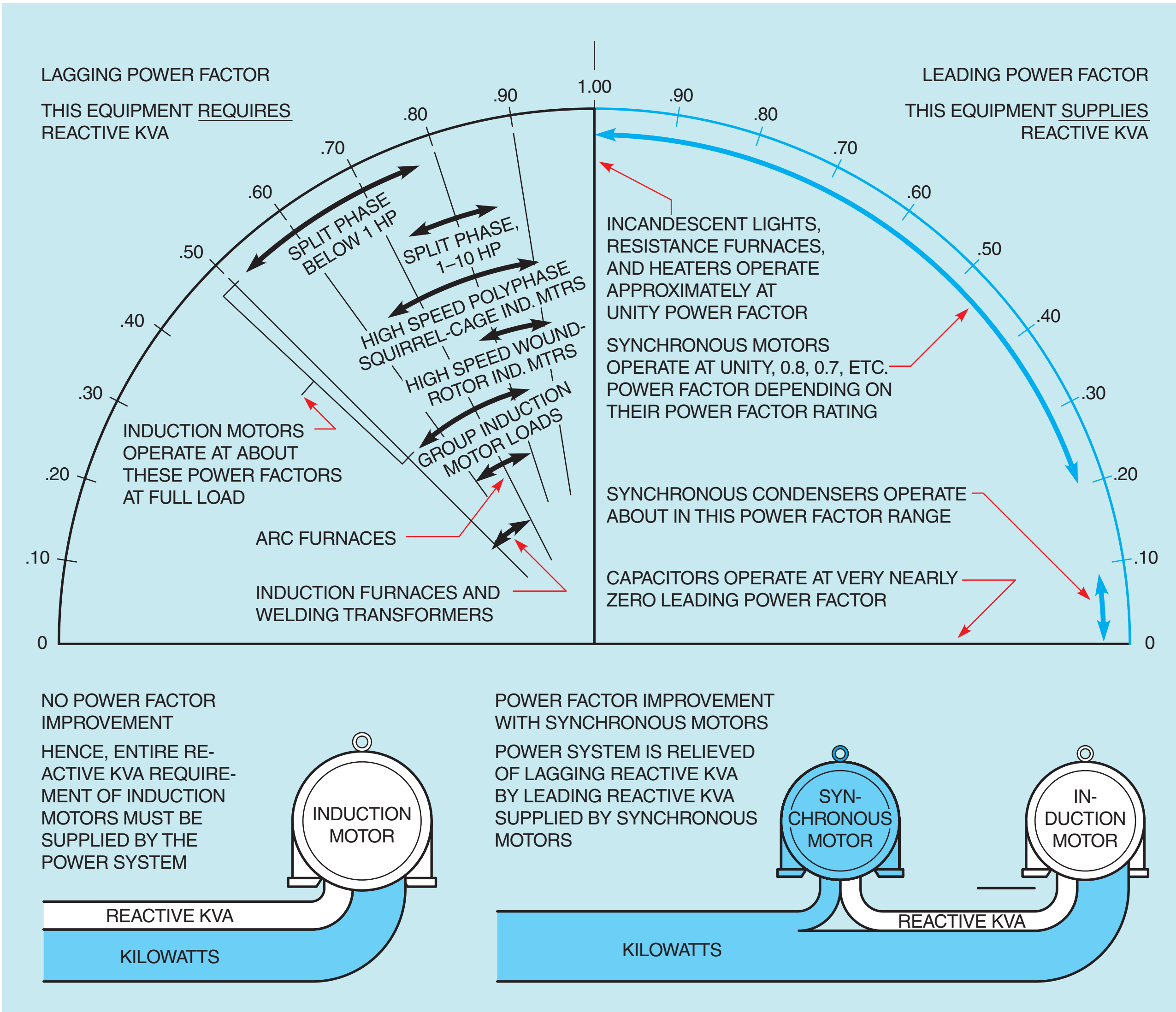


Figure 56–3 Power factor operation of various devices may be improved through the use of a synchronous motor. (Courtesy Electric Machinery Mfg. Co.)

Brushless Synchronous Motors

Solid-state technology has brought about the use of brushless synchronous motors. The dc field excitation for such a motor is provided by a special ac generator mounted on the main motor shaft. The excitation is converted to direct current by a rotating rectifier assembly.

The operating characteristics are the same as those of synchronous motors with brushes. However, elimination of the collector rings, brushes, commutator, and some control contactors gives the brushless motor several outstanding advantages:

- Brush sparking is eliminated, reducing safety hazards in some areas.
- Field control and excitation are provided by a static system, requiring much less maintenance.
- Field excitation is automatically removed whenever the motor is out of step. Automatic resynchronization can be achieved whenever it is practical.

Review Questions

1. Why is it necessary that the rotor and stator have an equal number of poles?
2. What is the effect of the starting winding of the synchronous motor on the running speed?
3. What are typical applications of synchronous motors?
4. Explain how the rotor magnetic field is established.
5. A loaded synchronous motor cannot operate continuously without dc excitation on the rotor. Why?
6. Why must a discharge resistor be connected in the field circuit for starting?
7. What is meant when a synchronous motor is called overexcited?
8. Depending on their power factor ratings, what is the range of the leading power factor at which synchronous motors operate?
9. At what power factor do incandescent lights operate?
10. At what power factor do high-speed, wound rotor motors operate?

Select the *best* answer for the following items.

11. The speed of a synchronous motor is fixed by the
    a. rotor winding
    b. amortisseur winding
    c. supply voltage
    d. frequency of power supply and number of poles
12. Varying the dc voltage to the rotor field changes the
    a. motor speed
    b. power factor
    c. phase excitation
    d. slip
13. Amortisseur windings are located
    a. in the stator pole faces
    b. in the rotor pole faces
    c. in the controller
    d. leading the power factor
14. Dc excitation is applied to the
    a. starting winding
    b. stator winding
    c. rotor winding
    d. amortisseur winding
15. Induction motors and welding transformers require magnetizing current which causes
    a. lagging power factor
    b. leading power factor
    c. unity power factor
    d. zero power factor
16. A synchronous motor can be used to increase the power factor of an electrical system by
    a. reducing the speed
    b. overexciting the stator field
    c. overexciting the rotor field
    d. applying direct current to the stator field

UNIT 57

SYNCHRONOUS AUTOMATIC MOTOR STARTER

OBJECTIVES

After studying this unit, the student will be able to:

- Describe how an out-of-step relay protects the starting winding of a synchronous motor.
- Describe the action of a polarized field frequency relay in applying and removing dc field excitation on a synchronous motor.
- Connect synchronous motors and controllers which use out-of-step relays and polarized field frequency relays to achieve automatic motor synchronization.
- Recommend troubleshooting solutions for problems.

An automatic synchronous motor starter can be used with a synchronous motor to provide automatic control of the startup sequence. That is, the controller automatically sequences the operation of the motor so that the rotor field is synchronized with the revolving magnetic field of the stator.

There are two basic methods of starting synchronous motors automatically. In the first method, full voltage is applied to the stator winding. In the second method, the starting voltage is reduced. A commonly used method of starting synchronous motors is the across-the-line connection. In this method, the stator of the synchronous motor is connected directly to the plant distribution system at full voltage. A magnetic starter is used in this method of starting.

A polarized field frequency relay can be used for the automatic application of field excitation to a synchronous motor.

Rotor Control Equipment

Field Contactor

The field contactor opens both lines to the source of excitation (Figure 57–1). During starting, the contactor also provides a closed field circuit through a discharge resistor. A solenoid-operated field contactor is similar in appearance to the standard dc contactor. However, for this dc operated contactor, the center pole is normally closed. It is

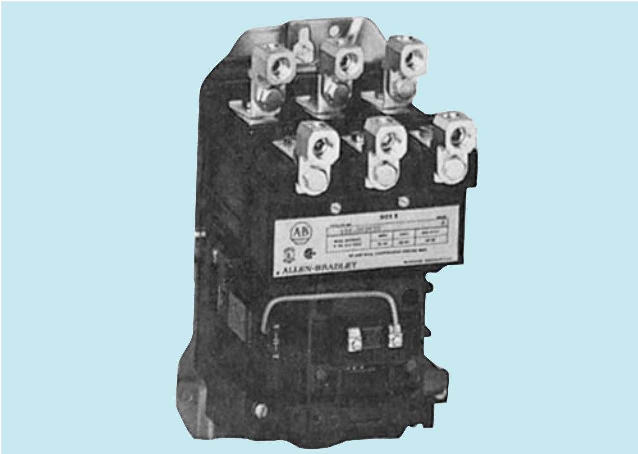


Figure 57–1 Magnetic mor starter used on synchronous motor starters for field control. (Courtesy Allen-Bradley Co.)

designed to provide a positive overlap between the normally closed contact and the two normally open contacts. This overlap is an important feature because it means that the field winding is never open. The field winding of the motor must always be short-circuited through a discharge resistor or connected to the dc line. The coil of the field contactor is operated from the same direct-current source that provides excitation for the synchronous motor field.

Out-of-Step Relay

The squirrel cage winding, or starting (amortisseur) winding will not overheat if a synchronous motor starts, accelerates, and reaches synchronous speed within a time interval determined to be normal for the motor. In addition, the motor must continue to operate at synchronous speed. Under these conditions, adequate protection for the entire motor is provided by three overload relays in the stator winding. The squirrel cage winding, however, is designed for starting only. If the motor operates at subsynchronous speed, the squirrel cage winding may overheat and be damaged. It is not unusual for some synchronous motors to with stand a maximum locked rotor interval of only five to seven seconds.

An out-of-step relay (OSR) (Figure 57–2), is provided on automatic synchronous starters to protect the starting winding. The normally closed contacts of the relay will open to de-energize the line contactor under the following conditions:

1. the motor does not accelerate and reach the synchronizing point after a preset time delay.

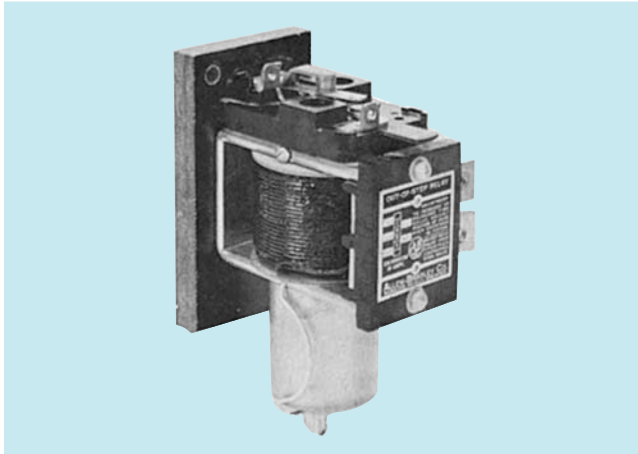


Figure 57–2 Out-of-step relay used on synchronous motor starters. (Courtesy Allen-Bradley Co.)

2. the motor does not return to a synchronized state after leaving it.
3. the amount of current induced in the field winding exceeds a value determined by the core setting of the out-of-step relay.

As a result, power is removed from the stator circuit before the motor overheats.

Polarized Field Frequency Relay

A synchronous motor is started by accelerating the motor to as high a speed as possible from the squirrel cage winding and then applying the dc field excitation. The components responsible for correctly and dependably applying and removing the field excitation are a *polarized field frequency relay* and a reactor (Figure 57–3).

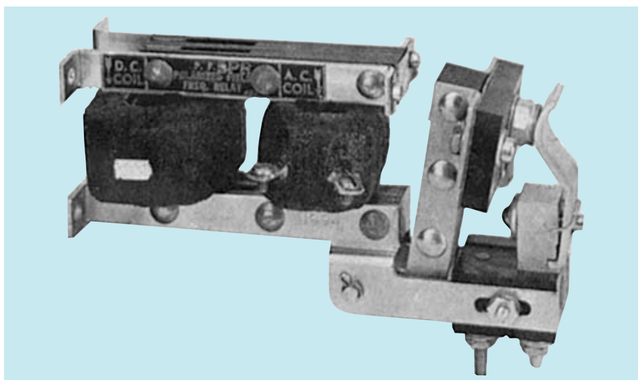


Figure 57–3 Polarized field frequency relay used on synchronous motor staters (Courtesy Allen-Bradley Co.)

The operation of the frequency relay is shown in Figure 57–4. The magnetic core of the relay has a direct-current coil (C), an induced field-current coil (B), and a pivoted armature (A) to which contact (S) is attached. Coil C is connected to the source of dc excitation. This coil establishes a constant magnetic flux in the relay core. This flux causes the relay to be polarized. Superimposed on this magnetic flux in the relay core is the alternating magnetic flux produced by the alternating induced rotor field current flowing in coil B. The flux through armature A depends on the flux produced by ac coil B and dc coil C. Coil B produces an alternating flux of equal positive and negative magnitude each half-cycle. Thus, the combined flux flowing through armature A is much larger when the flux from coil B opposes that from coil C. In Figure 57–4(A), the flux from coil B opposes the flux from dc coil C, resulting in a strong flux being forced through armature A of the relay. This condition is shown by the lower shaded loops of Figure 57–4(C). One-half cycle later, the flux produced by coil B reverses and less flux flows through armature A. This is due to the fact that the flux from coil B no longer forces as much flux from coil C to take the longer path through armature A. The resultant flux is weak and is illustrated by the small, upper shaded loops of Figure 57–4(C). The relay armature opens only during the period of the induced field current wave, which is represented by the small, upper loops of the relay armature flux.

As the motor reaches synchronous speed, the induced rotor field current in relay coil B decreases in amplitude. A value of relay armature flux (upper shaded loop) is reached at which the relay armature A no longer stays closed. The relay then opens to establish contact S. Dc excitation is then applied at the point indicated on the induced field current wave.

Excitation is applied in the direction shown by the arrow. The excitation is opposite in polarity to that of the induced field current at the point of application. This requirement is necessary to compensate for the time needed to build up excitation. The time interval results from the magnetic inertia of the motor field winding. Because of the inertia, the dc excitation does not become effective until the induced current reverses (point 0 on the wave) to the same polarity as the direct current. The excitation continues to build up until the motor is synchronized as shown by point M on the curve.

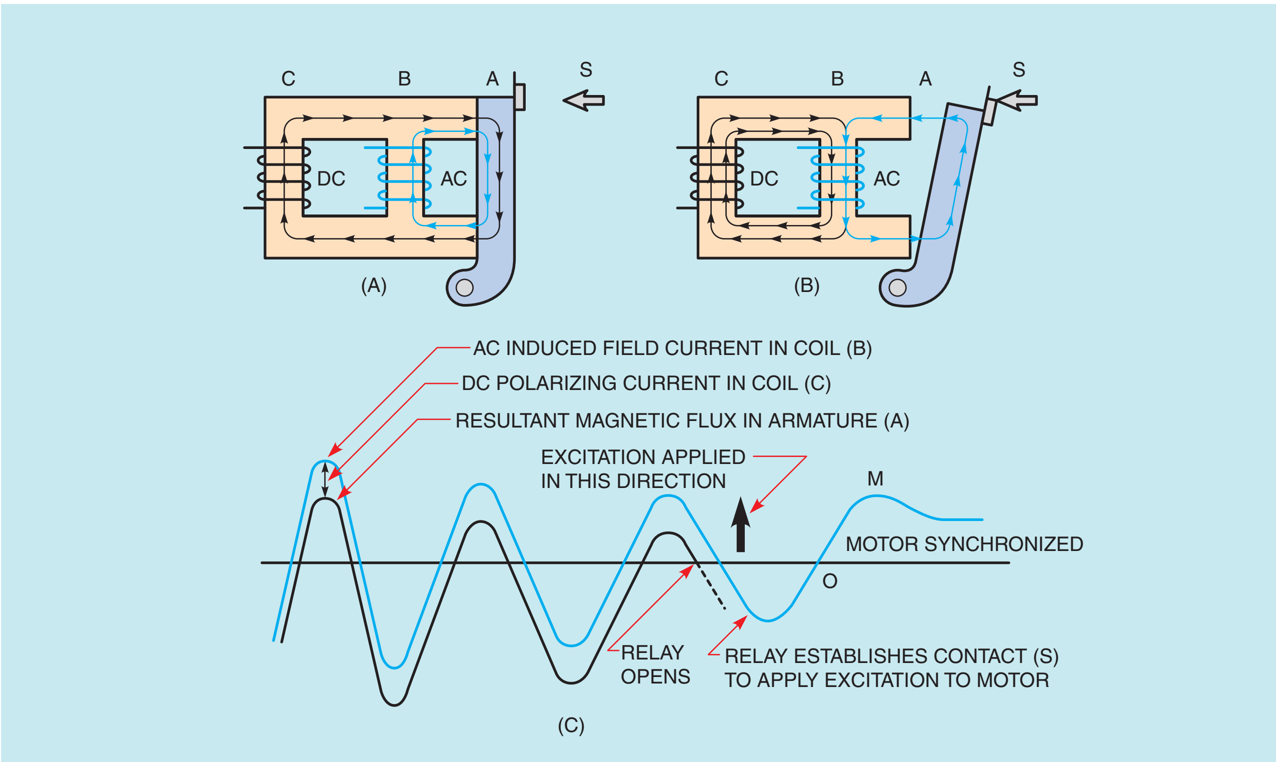


Figure 57–4 Polarized field frequency relay operation. (Courtesy Electric Machinery Mfg. Co.)

Figure 57–5 indicates the normal operation of the frequency relay. Dc excitation is applied to the coil of the relay at the instant the synchronous motor is started. When the stator winding is energized, using either full voltage or reduced voltage methods, line current is allowed to flow through the three overload relays and the stator winding. Line frequency currents are induced in the two electrically independent circuits of the rotor: (1) the squirrel cage or starting windings and (2) the field windings. The current induced in the field windings flows through the reactor. This device shunts part of the current through the ac coil of the frequency relay, the coil of the out-of-step relay, the field discharge resistor, and finally to the normally closed contact of the field contactor. The flux established in the frequency relay core pulls the armature against the spacer and opens the normally closed relay contacts (Figure 57–5). As the motor accelerates to the synchronous speed, the frequency of the induced currents in the field windings diminishes. There is, however, sufficient magnetic flux in the relay core to hold the armature against the core. This flux is due to a considerable amount of induced current forced through the ac coil of the frequency relay by the impedance of the reactor at high slip frequency.

At the point where the motor reaches its synchronizing speed (usually 92 to 97 percent of the synchronous speed) the frequency of the induced field current is at a very low value. The reactor impedance also is greatly reduced at this low frequency. Thus, the amount of current shunted to the ac coil is reduced to the point where the resultant core flux is no longer strong enough to hold the armature against the spacer. At the moment that the rotor speed and the frequency and polarity of the induced currents are most favorable for synchronization, the armature is released, the relay contacts close, and the control circuit is completed to the operating coil of the field contactor. Dc excitation is applied to the motor field winding (Figure 57–5B). At the same time, the out-of-step relay and discharge resistor are deenergized by the normally closed contacts of the field contactor.

An overload or voltage fluctuation may cause the motor to pull out of synchronism. In this case, a current at the slip frequency is induced in the field windings. Part of this current flows through the ac coil of the polarized field frequency relay, opens the relay contact, and removes the dc field excitation. The motor automatically resynchronizes if the line voltage and load conditions return to normal within a preset time interval, and the motor has enough pull-in torque. However, if the overload and low-voltage conditions continue so that the motor cannot resynchronize, then either the out-of-step relay or the overload relays activate to protect the motor from overheating.

Summary of Automatic Starter Operation

The line diagram in Figure 57–6 shows the automatic operation of a synchronous motor. For starting, the motor field winding is connected through the normally closed power contact of the field contactor (F), the discharge resistor, the coil of the out-of-step relay, and the reactor. When the start button is pressed, the circuit is completed to the control relay coil (CR1) through the control fuse, the stop button, and contacts of the over load and out-of-step relays. The closing of CR1 energizes the line contactor M which applies full voltage at the motor terminals with the overload relays in the circuit. A normally open contact on CR1 and a normally open interlock on line contactor M provide the hold-in, or maintaining circuit. The starting and running current drawn by the motor is indicated by an ammeter with a current transformer.

At the moment the motor starts, the polarized field frequency relay (PFR) opens its normally closed contact and maintains an open circuit to the field contactor (F) until the motor accelerates to the proper speed for synchronizing. When the motor reaches a speed equal to 92 to 97 percent of its synchronous speed, and the rotor is in the correct position, the contact of the polarized field frequency relay closes to energize field contactor F through an interlock on line contactor M. The closing of field contactor F applies the dc excitation to the field winding and causes the motor to synchronize. After the rotor field circuit is established through the normally open power contacts of the field contactor, the normally closed contact on this contactor opens the discharge circuit. The motor is now operating at the synchronous speed. If the stop button is pressed, or if either magnetic overload relay is tripped, the starter is de-energized and disconnects the motor from the line.

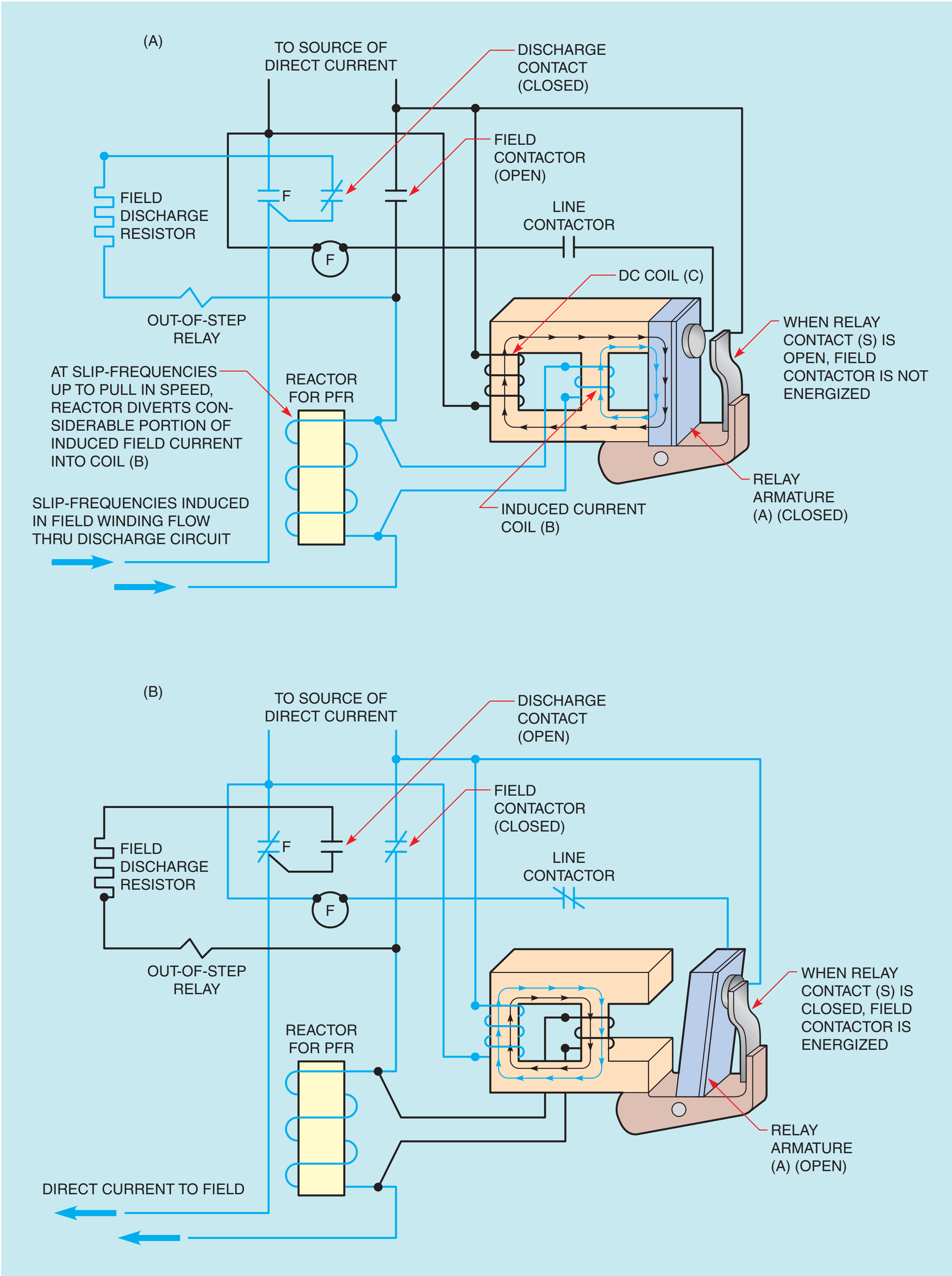


Figure 57–5 Wiring connections and operation of a polarized field frequency relay. (Courtesy Electric Machinery Mfg. Co.)

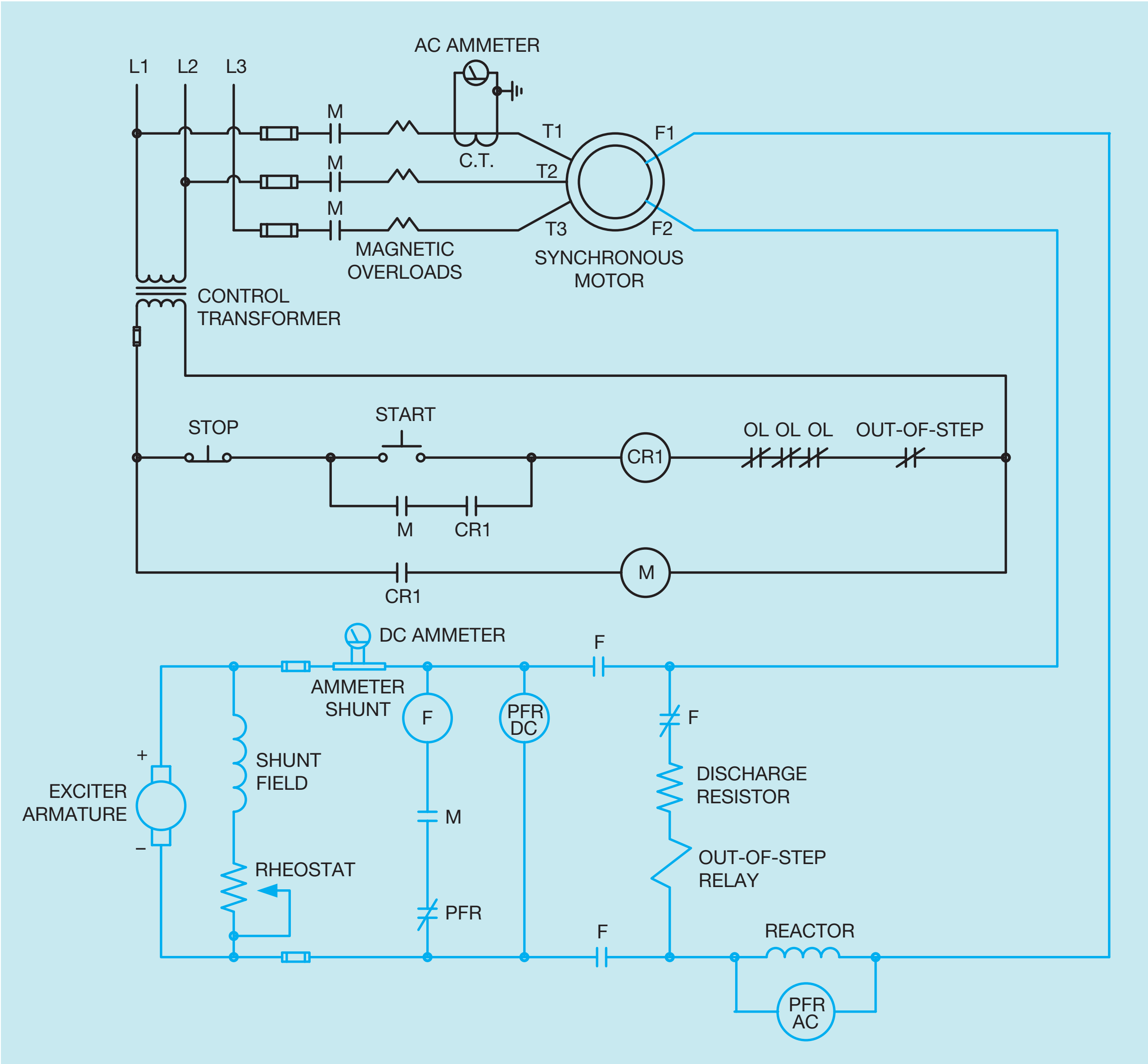


Figure 57–6 Line diagram for automatic operation of a synchronous motor using polarized field frequency relay.

Review Questions

1. What are the two basic methods of automatically starting a synchronous motor?
2. What is an out-of-step relay?
3. Why is an out-of-step relay used on automatic synchronous starters?
4. Under what conditions will the out-of-step relay trip out the control circuit?
5. What is the last control contact which closes on a starting and synchronizing operation?
6. What influence do both of the polarized field frequency relay (PFR) coils exert on the normally closed contact?
7. Why is the PFR polarized with a dc coil?
8. Approximately how much time (in terms of electrical cycles) elapses from the moment the PFR opens to the moment the motor actually synchronizes?
9. How does the ac coil of the PFR receive the induced field current without receiving the full field current strength?
10. Why is a control relay (CR1) used in Figure 57–6?

UNIT 58

VARIABLE SPEED AC MOTOR CONTROL

OBJECTIVES

After studying this unit, the student will be able to:

- Discuss different methods of changing the speed of ac induction motors.
- Discuss how an alternator is used to provide variable frequency motor control.
- Discuss electronic methods of variable frequency control.

Two factors determine the speed of the rotating magnetic field of an ac induction motor:

1. Number of stator poles
2. Frequency

If either of these factors is changed, the speed of the motor can be changed.

In Unit 53, the operation of the consequent pole motor was discussed. The speed of the consequent pole motor can be changed by changing the number of stator poles. This method of speed control causes the speed to change in steps and does not permit control over a wide range of speed. For example, the synchronous speed of the rotating magnetic field in a two-pole motor is 3600 rpm when connected to a 60 Hz line. If this motor is changed to a four-pole motor, the synchronous speed will change to 1800 rpm. Notice that this method of speed control permits the motor to operate with a synchronous field speed of 3600 rpm or 1800 rpm. The motor cannot be operated with a synchronous speed between 3600 rpm and 1800 rpm.

Variable Voltage Speed Control

Another method of controlling the speed of some ac induction motors is by reducing the applied voltage to the stator. This method does not change the synchronous speed of the rotating magnetic field, but it does cause the magnetic field of the stator to become weaker. As the magnetic field of the stator becomes weaker, the rotor slip becomes greater and, therefore, causes a reduction in rotor speed.

Variable voltage speed control is used with fractional horsepower motors that operate light loads such as fans or blowers. Motors that are intended to be

operated with variable voltage are designed with high resistance rotors, such as the type "A" rotor, to help limit the amount of current induced into the rotor at low speed. Induction motors that use a centrifugal switch cannot be used with variable voltage control. This limits the types of induction motors that can be used to shaded pole motors or capacitor start-capacitor run motors.

There are several methods used to control the voltage supplied to the motor. One method is to use a triac with a phase shift network similar to the circuit shown in Figure 58–1. When triac circuits are used with inductive loads, care must be taken to insure that both halves of the ac wave form are conducted. Only triac controllers intended to be used with inductive loads should be used for motor control. Triac circuits intended to control incandescent lamp loads will often begin conducting on one half of the ac cycle and not the other. For example, assume the triac in Figure 58–1 begins conducting on the positive half cycle of voltage before it conducts the negative half cycle. A waveform similar to the one shown in Figure 58–2 could be produced across the load. Since only positive voltage pulses are being conducted, the voltage applied to the load is dc. A dc voltage applied to a resistive load such as an incandescent lamp will not cause any harm, but a great deal of harm can be done if a dc voltage is applied to an inductive load such as the stator winding of a motor. A variable speed control using a triac is shown in Figure 58–3.

Another device used to control the voltage applied to a small induction motor is the autotransformer (Figure 58–4). In this circuit, a rotary switch is used to connect the motor to different taps on the transformer winding. This permits the motor to be operated at any one of several different speeds.

A tapped inductor can also be used to control motor speed (Figure 58–5). In this circuit, the inductor is not used to control the voltage applied to the motor, but is used to control the impedance of the circuit. If more of the inductor is connected in series with the motor, the total impedance of the circuit is increased and, therefore, the current flow through the motor is decreased. As current flow is decreased, the magnetic field of the stator becomes weaker and the increase in rotor slip causes the motor speed to slow down. The motor speed can be adjusted by changing the tap with the rotary switch to insert more or less of the inductor winding in series with the motor.

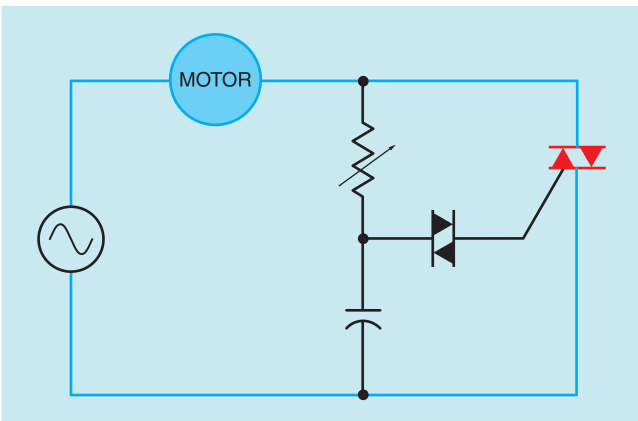


Figure 58–1 Triac used to control motor speed.

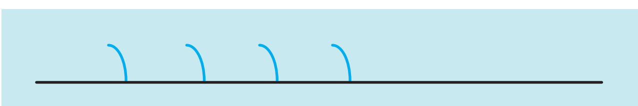


Figure 58–2 Triac conducts only the positive half of the waveform.

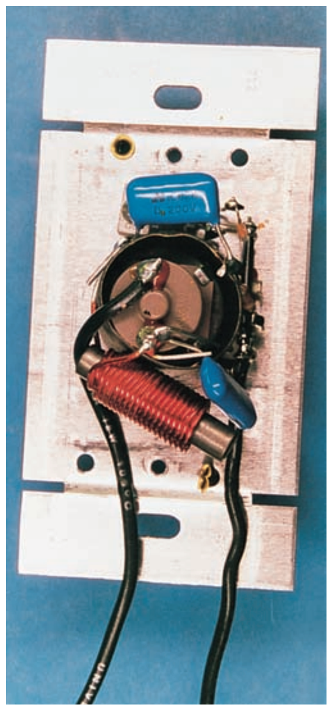


Figure 58–3 Variable speed control using a triac to control the voltage applied to the motor.

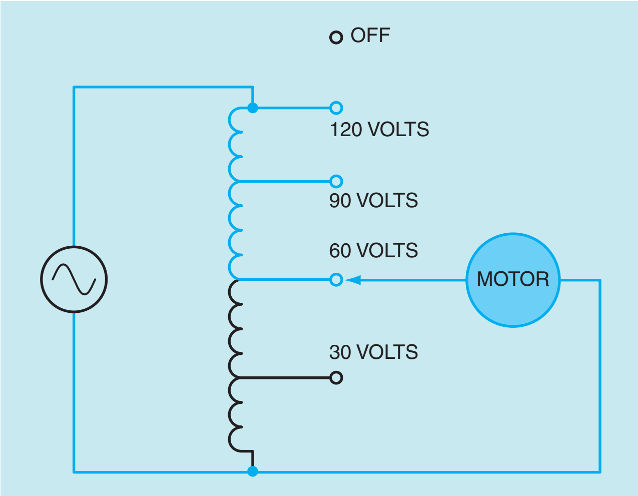


Figure 58–4 Autotransformer controls motor voltage.

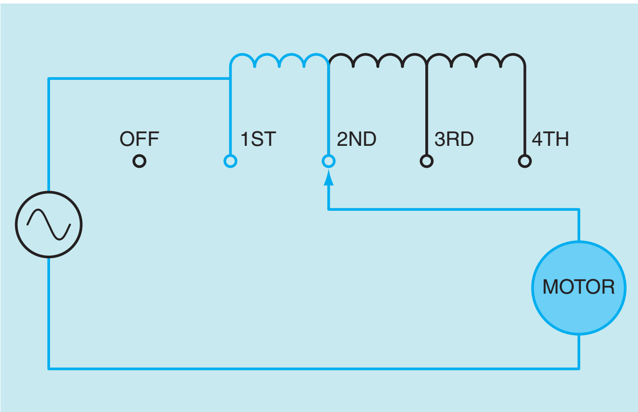


Figure 58–5 Series inductor changes impedance of circuit.

Variable Frequency Control

One of the factors that determines the speed of the rotating magnetic field of an induction motor is the frequency of the applied voltage. If the frequency is changed, the speed of the rotating magnetic field changes also. For example, a four-pole stator connected to a 60 Hz line will have a synchronous speed of 1800 rpm. If the frequency is lowered to 30 Hz, the synchronous field speed falls to 900 rpm.

When the frequency is lowered, care must be taken not to damage the stator winding. The current flow through the winding is limited to a great extent by inductive reactance. When the frequency is lowered, inductive reactance is lowered also ($X_L = 2\pi FL$). For this reason, variable frequency motor controllers must have some method of reducing the applied voltage to the stator as frequency is reduced.

Alternator Control

One method of producing variable frequencies for operating induction motors is with the use of an alternator (Figure 58–6). In this arrangement some type of variable speed drive, such as dc motor, is used to turn the shaft of the alternator. The speed of the alternator determines the frequency of the voltage applied to the induction motors. The alternator can furnish power to as many induction motors as desired provided the power rating of the alternator is not exceeded.

Since the output voltage of the alternator is controlled by the amount of dc excitation current applied

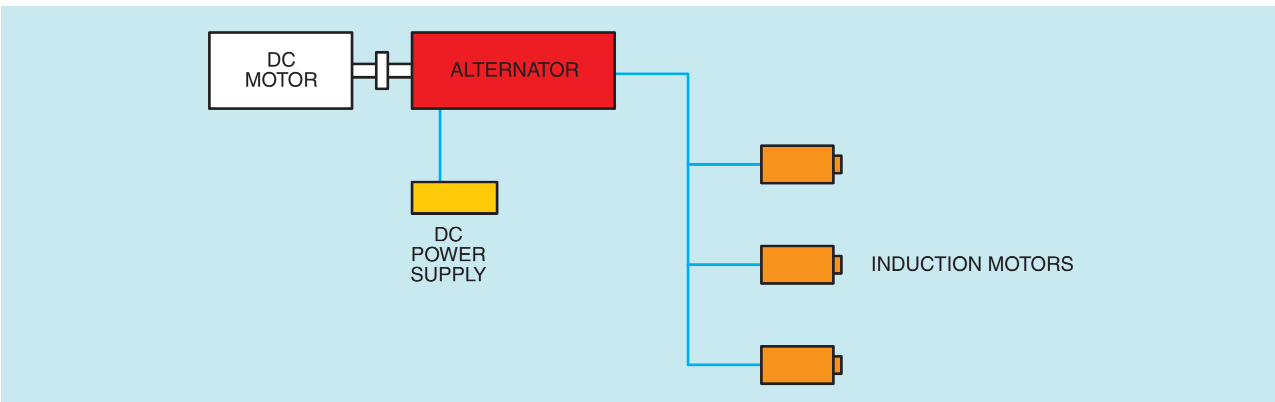


Figure 58–6 Tapped inductor used to control motor speed by connecting it in series with the motor winding.

Figure 58–7A Inside of a variable frequency AC motor drive. (Courtesy Square D Company.)

to the rotor, a variable voltage dc power supply is used to determine the output voltage of the alternator. As frequency is reduced, the output voltage must also be reduced to prevent excessive current flow in the windings of the induction motors. This method of speed control is frequently used on conveyor systems where it is desirable to have a large number of motors controlled from one source.

Solid-State Control

Most solid-state variable frequency drives operate by first changing the ac voltage to dc, and then changing the dc voltage back to ac at the desired frequency. A variable frequency controller is shown in Figure 58–7A and Figure 58–7B. The circuit shown in Figure 58–8 uses a three-phase bridge rectifier to convert three-phase ac voltage into dc voltage. A phase shift unit controls the output voltage of the rectifier. This permits the voltage applied to the motor to be decreased as the frequency is decreased.

A choke coil and capacitor bank are used to filter the output voltage of the rectifier before transistors Q1 through Q6 change the dc voltage back to ac. An electronic control unit is connected to the bases of transistors Q1 through Q6. The electronic control unit converts the dc voltage back into three-phase alternating current by turning transistors on or off at the proper

Figure 58–7B 2 hp variable frequency motor controller. (Courtesy Toshiba International Corp.)

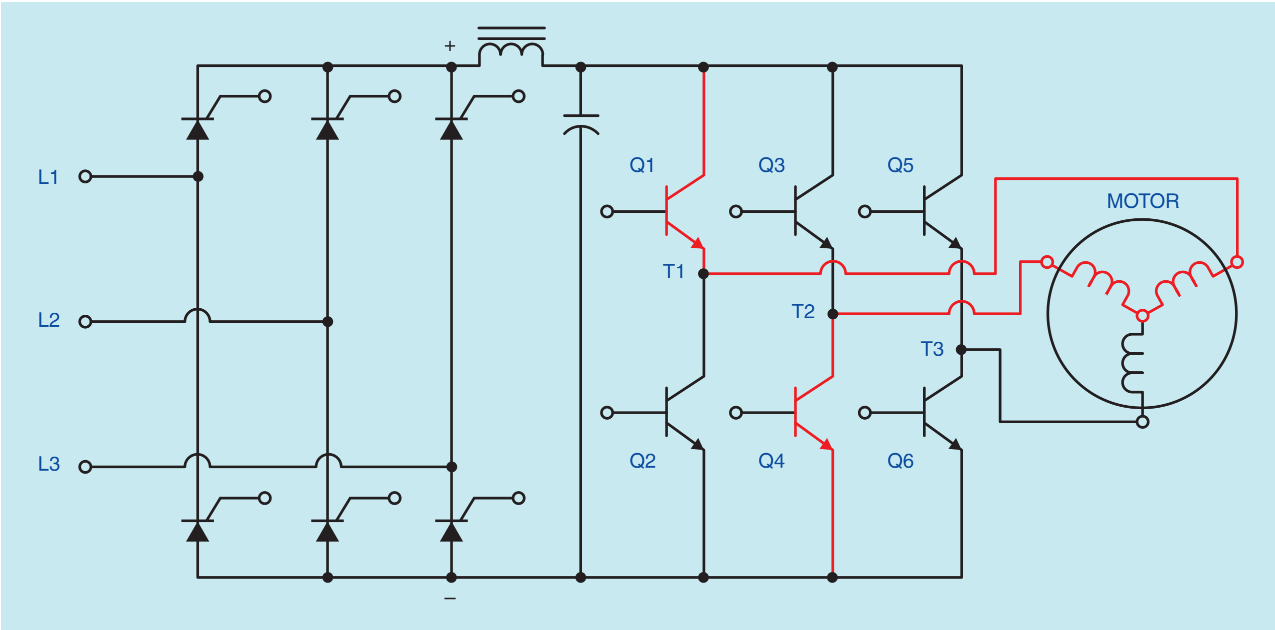


Figure 58–8 Solid-state variable frequency control.

time and in the proper sequence. For example, assume that transistors Q1 and Q4 are switched on at the same time. This permits T1 to be positive at the same time T2 is negative. If conventional current flow is assumed, current will flow through transistor Q1 to T1, from T1 through the motor winding to T2, and then through transistor Q4 to negative. Now assume that transistors Q1 and Q4 have been turned off, and transistors Q3 and Q6 have been turned on. Current can now flow through transistor Q3 to T2, from T2 through the motor to T3, and through transistor Q6 to negative.

Since the transistors are turned completely on or completely off, the waveform produced is a square wave instead of a sine wave (Figure 58–9). Induction motors will operate on a square waveform without any problem. Some manufacturers design units that will produce a stepped waveform as shown in Figure 58–10. This stepped waveform is used because it is similar to a sine wave. Several sizes of AC drives are shown in Figure 58–11.

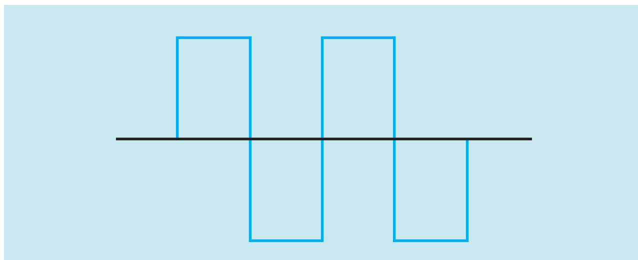


Figure 58–9 Square wave.

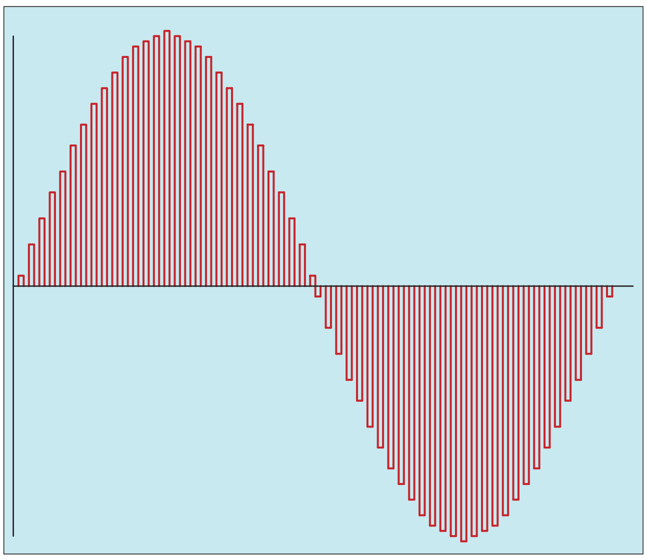


Figure 58–10 Stepped wave.

Control Using SCRs

Because of their ability to handle large amounts of power, SCRs are often used for converting direct current into alternating current. An example of this type of circuit is shown in Figure 58–12. In this circuit, the

Figure 58–11 Variable frequency AC drives can be obtained in different sizes depending on the horsepower and voltage of the motor they are to control. (Courtesy Square D Company.)

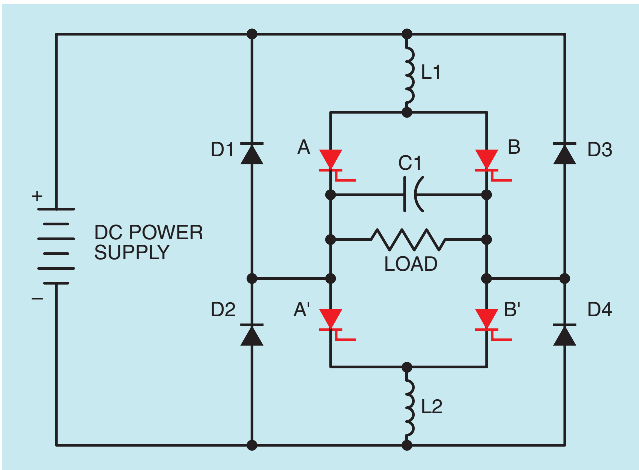


Figure 58–12 Changing dc into ac using SCRs.

SCRs are connected to a control unit which controls the sequence and rate at which the SCRs are gated on. The circuit is constructed so that SCRs A and A′ are gated on at the same time and SCRs B and B′ are gated on at the same time. Inductors L_1 and L_2 are used for filtering and wave shaping. Diodes D1 through D4 are clamping diodes and are used to prevent the output voltage from becoming excessive. Capacitor C_1 is used to turn one set of SCRs off when the other set is gated on. This capacitor must be a true ac capacitor because it will be charged to the alternate polarity each half cycle. In a converter intended to handle large amounts of power, capacitor C_1 will be a bank of capacitors. To understand the operation of this circuit, assume that SCRs A and A′ are gated on at the same time. Current will flow through the circuit as shown in Figure 58–13. Notice the direction of current flow through the load and that capacitor C_1 has been charged to the polarity shown. Recall that when an SCR has been turned on by the gate, it can only be turned off by permitting the current flow through the anode-cathode section to drop below the holding current level. Now assume that SCRs B and B′ are gated on. Because SCRs A and A′ are still turned on, two separate current paths now exist through the circuit. The negative charge on capacitor C_1, however, causes the positive current to see a path more negative than the one through SCRs A and A′. The current now flows through SCRs B and B′ to charge capacitor C_1 to the opposite polarity as shown in Figure 58–14.

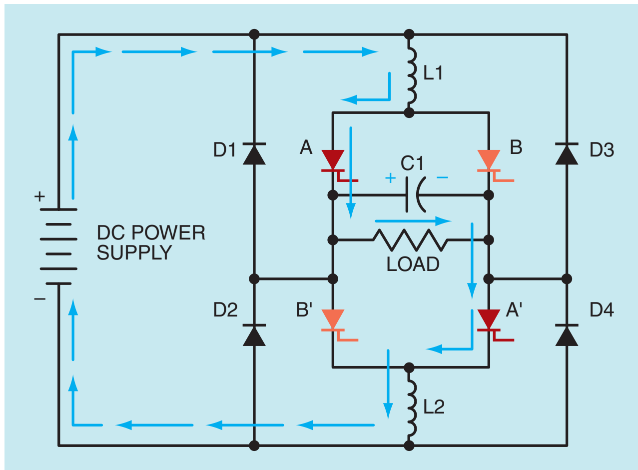


Figure 58–13 Current flows through SCRs A and A′.

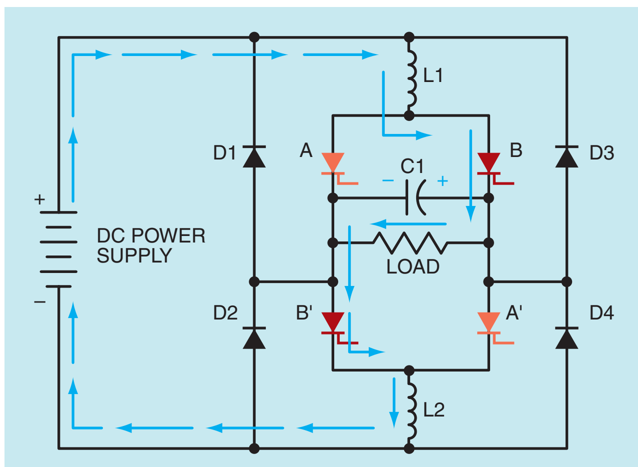


Figure 58–14 Current flows through SCRs B and B′.

Because current now flows through SCRs B and B′, SCRs A and A′ turn off. Notice that the current flows through the load in the opposite direction, which produces alternating current through the load, and that capacitor C_1 has been charged to the opposite polarity.

To produce the next half cycle of ac current, SCRs A and A′ are gated on again. The negatively charged side of capacitor C_1 will now cause the current to stop flowing through SCRs B and B′ and begin flowing through SCRs A and A′ as shown in Figure 58–13. The frequency of the circuit is determined by the rate at which the SCRs are gated on.

Features of Variable Frequency Control

Although the primary purpose of a variable frequency drive is to provide speed control for an ac motor, most drives provide functions that other types of controls do not. Many variable frequency drives can provide the low speed torque characteristic that is so desirable in dc motors. It is this feature that permits ac squirrel cage motors to replace dc motors for many applications.

Many variable frequency drives also provide current limit and automatic speed regulation for the motor. Current limit is generally accomplished by connecting current transformers to the input of the drive and sensing the increase in current as load is added. Speed regulation is accomplished by sensing the speed of the motor and feeding this information back to the drive (Figure 58–15).

Another feature of variable frequency drives is acceleration and deceleration control, sometimes called *ramping*. Ramping is used to accelerate or decelerate a motor over some period of time. Ramping permits the motor to bring the load up to speed slowly as opposed to simply connecting the motor directly to the line. Even if the speed control is set in the maximum position when the start button is pressed, ramping permits the motor to accelerate the load from zero to its maximum rpm over several seconds This feature can be a real advantage for some types of loads, especially gear drive loads. The amount of acceleration and deceleration time can generally be adjusted by setting potentiometers on the main control board.

Some other adjustments that can usually be set by changing potentiometers are as follows:

Current Limit: This controls the maximum amount of current the drive is permitted to deliver to the motor.

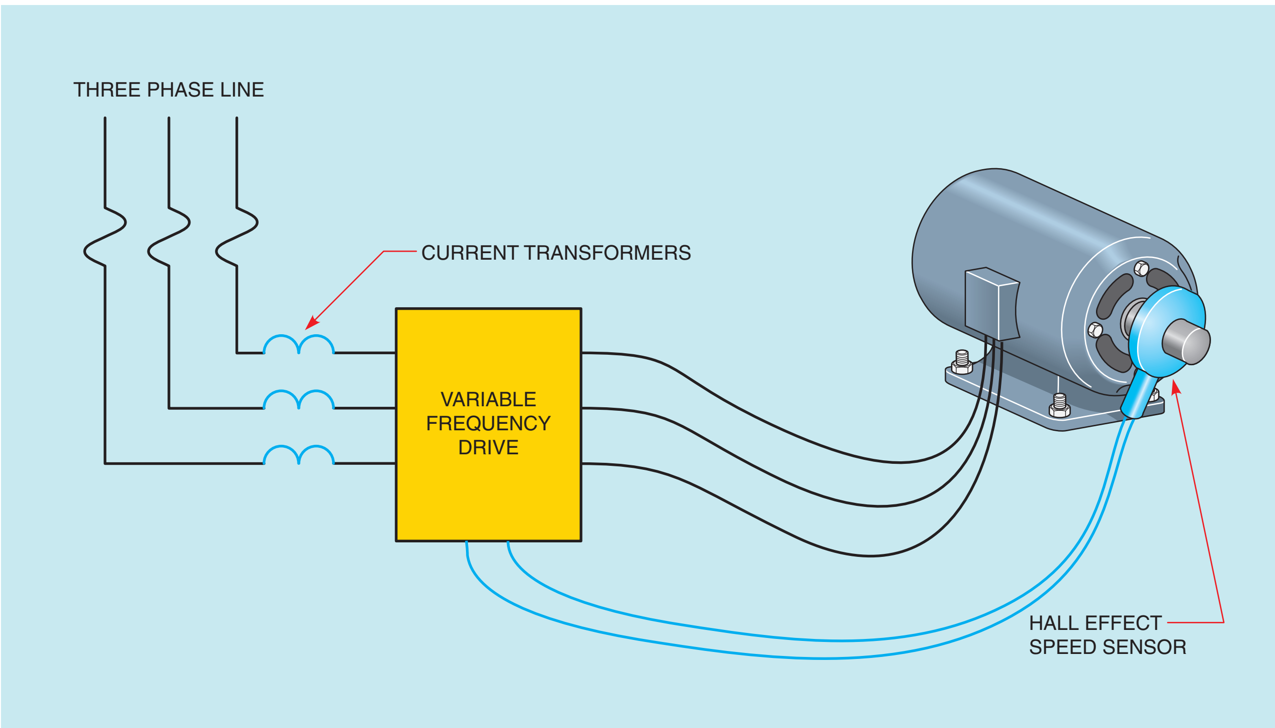


Figure 58–15 Many variable frequency drives provide current limit and speed regulation.

Volts per Hertz: This sets the ratio by which the voltage increases as frequency increases or decreases as frequency decreases.

Maximum Hz: This controls the maximum speed of the motor.

Minimum Hz: This sets the minimum speed the motor is permitted to run.

Review Questions

1. What two factors determine the synchronous speed of the rotating magnetic field of an induction motor?
2. What method of speed control that is often used with small motors does not involve changing the speed of the rotating magnetic field?
3. Name two devices commonly used to control the voltage applied to the motor.
4. Name the two types of motors most often used when speed control is accomplished by reducing the voltage applied to the motor.
5. Why are these two motors generally used for this type of speed control?
6. What type of rotor is generally used with motors designed to be controlled by variable voltage?
7. What determines the output frequency of an alternator?
8. What determines the output voltage of an alternator?
9. In the circuit shown in Figure 58–8, why are SCRs used to form the three-phase bridge rectifier instead of diodes?
10. Why must the voltage applied to an induction motor be reduced when frequency is reduced?

UNIT 59

MAGNETIC CLUTCH AND MAGNETIC DRIVE

OBJECTIVES

After studying this unit, the student will be able to:

- State several advantages of the use of a clutch in a drive.
- Describe the operating principles of magnetic clutches and drives.
- Distinguish between single and multiple-face clutches.
- Connect magnetic clutch and magnetic drive controls.
- Recommend troubleshooting solutions for magnetic clutch and drive problems.

Electrically Controlled Magnetic Clutches

Machinery clutches were originally designed to engage very large motors to their loads after the motors had reached running speeds (Figure 59–1). Clutches provide smooth starts for operations in which the material being processed might be damaged by abrupt starts (Figure 59–2). Clutches are also used to start high-inertia loads, since the starting may be difficult for a motor that is sized to handle the running load. When starting conditions are severe, a clutch inserted between the motor and the load means that the motor can run within its load capacity. The motor will take longer to bring the load up to speed, but the motor and load will not be damaged.

As more automatic cycling and faster cycling rates are being required in industrial production, electrically controlled clutches are being used more often.

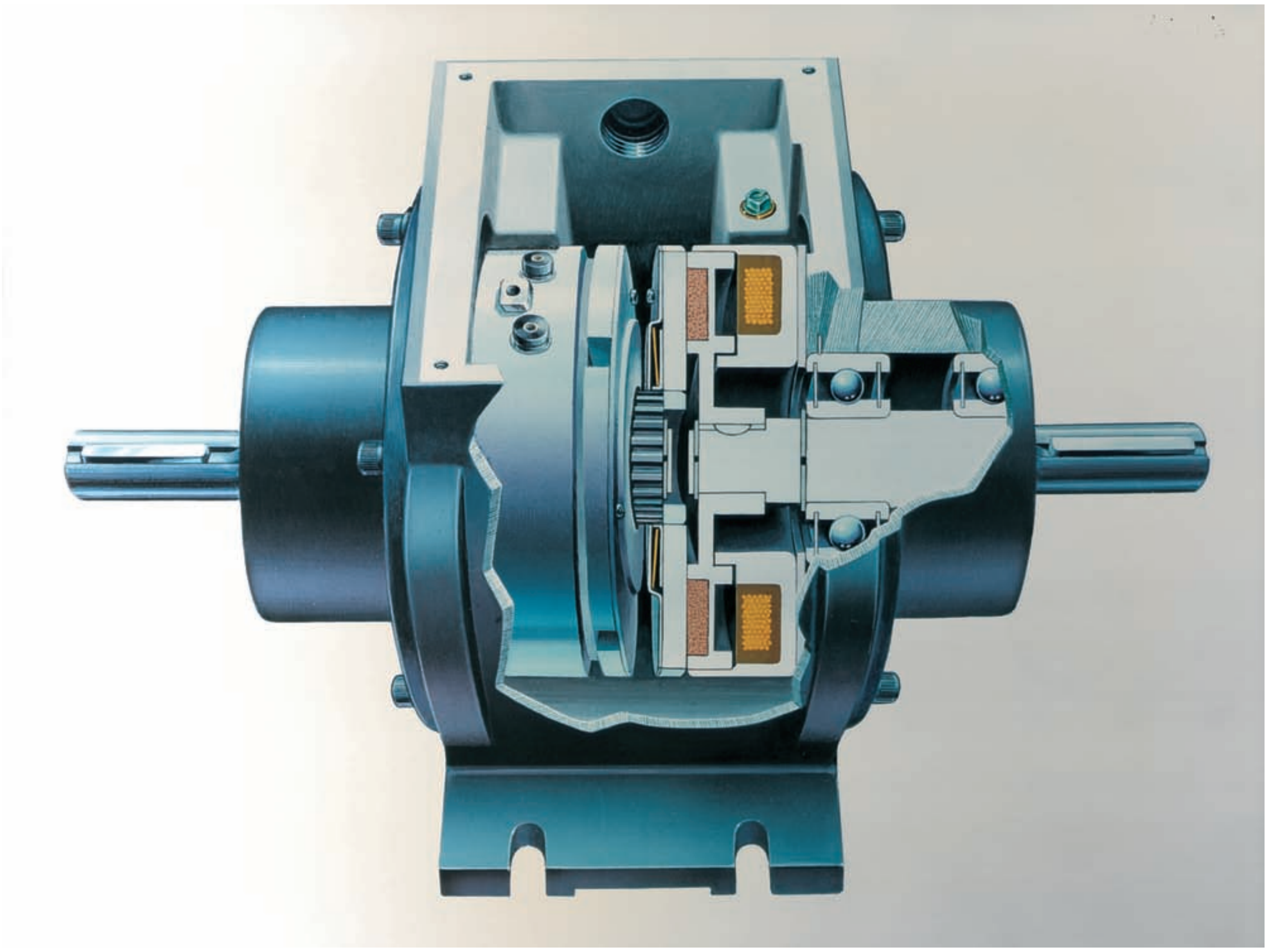


Figure 59–1 Cut-away view of a magnetic clutch. (Courtesy Warner Electric, South Beloit, Illinois.)

Single-face Clutch

The single-face clutch consists of two discs: one is the field member (electromagnet) and the other is the armature member. The operation of the clutch is similar to that of the electromagnet in a motor starter (Figure 59–3). When current is applied to the field winding disc through collector (slip) rings, the two discs are drawn together magnetically. The friction face of the field disc is held tightly against the armature disc to provide positive engagement between the rotating drives. When the current is removed, a spring action separates the faces to provide a definite clearance between the discs. In this manner, the motor is mechanically disconnected from the load.

Multiple-face Clutch

Multiple-face clutches are also available. In a double-face clutch, both the armature and field discs are mounted on a single hub with a double-faced friction lining supported between them. When the magnet of the field member is energized, the armature and field members are drawn together. They grip the lining

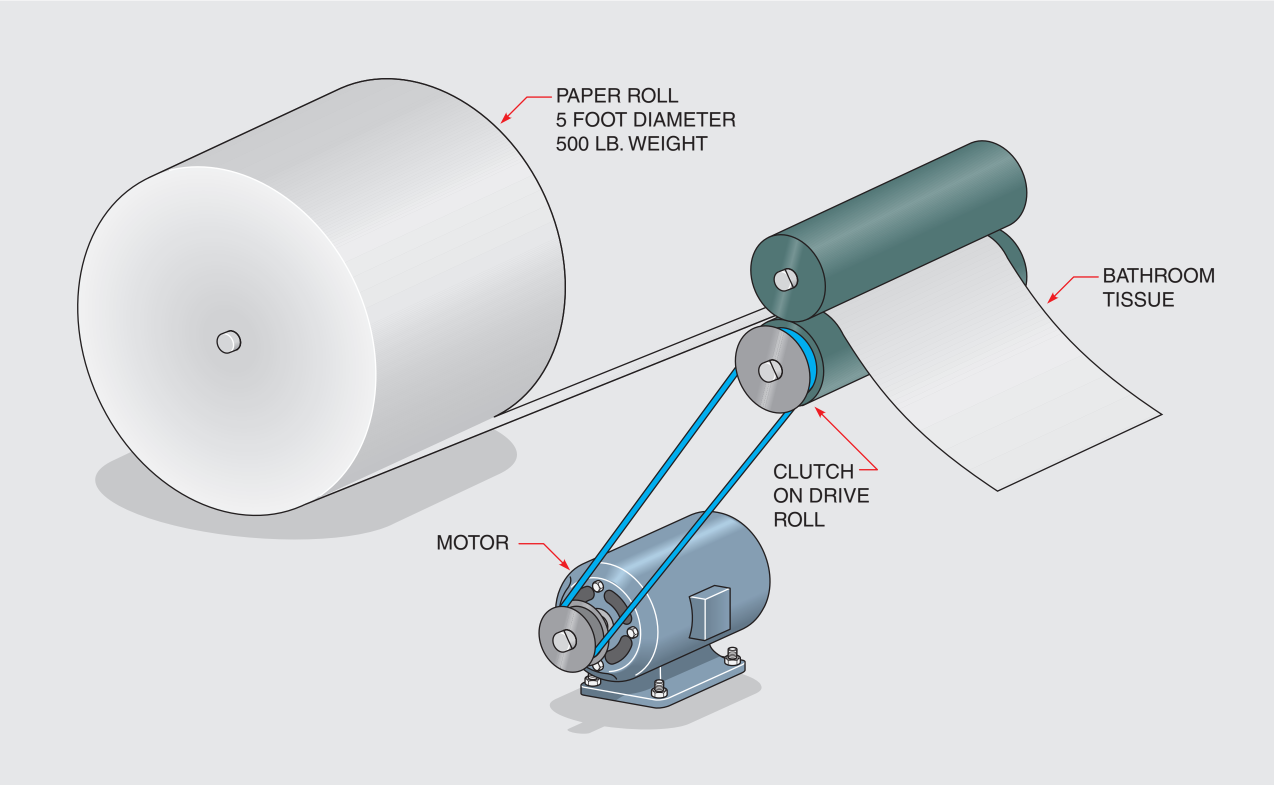


Figure 59–2 To prevent tearing, a cushioned start is required on drive roll that winds bathroom tissue of large roll. Roll is five feet in diameter and weighs 500 pounds when full. Pickup of thin tissue must be very gradual to avoid tearing. Application also can be used for filmstrip processing machine.

between them to provide the driving torque. When the magnet is de-energized, a spring separates the two members and they rotate independently of each other. Double-face clutches are available in sizes up to 78 inches in diameter.

A water-cooled magnetic clutch is available for applications that require a high degree of slippage between the input and output rotating members. Uses for this type of clutch include tension control (wind-up and payoff) and cycling (starting and stopping) operations in which large differences between the input and the output speeds are required. Flowing water removes the heat generated by the continued slippage within the clutch. A rotary water union mounted in the end of the rotor shaft means that the water-cooled clutch cannot be end-coupled directly to the prime mover. Chains or gears must be used.

A combination clutch and magnetic brake disconnects the load from the drive and simultaneously applies a brake to the load side of the drive. Magnetic clutches and brakes are often used as mechanical power-switching devices in module form. Figure 59–4 shows a combination electric clutch and an electric brake. An application of this arrangement is shown in Figure 59–5. Remember that the quicker the start or stop, the shorter the life of this equipment.

Magnetic clutches are used on automatic machines for starting, running, cycling, and torque-limiting. The combinations and variations of these functions are practically limitless.

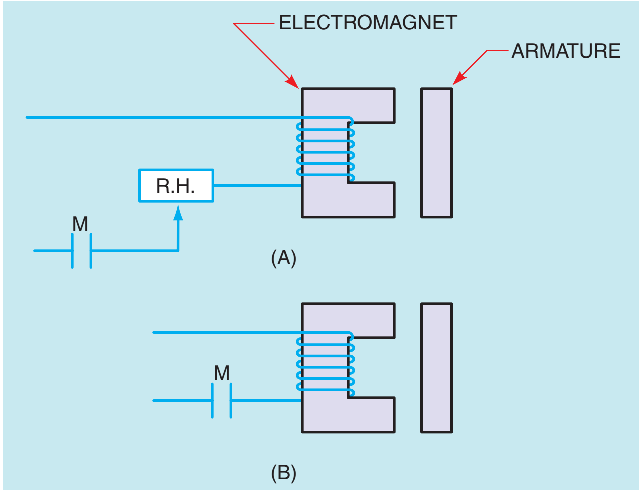


Figure 59–3 Principle of operation of electrically controlled clutches: (A) gradual clutch engagement; (B) more rapid clutch engagement.

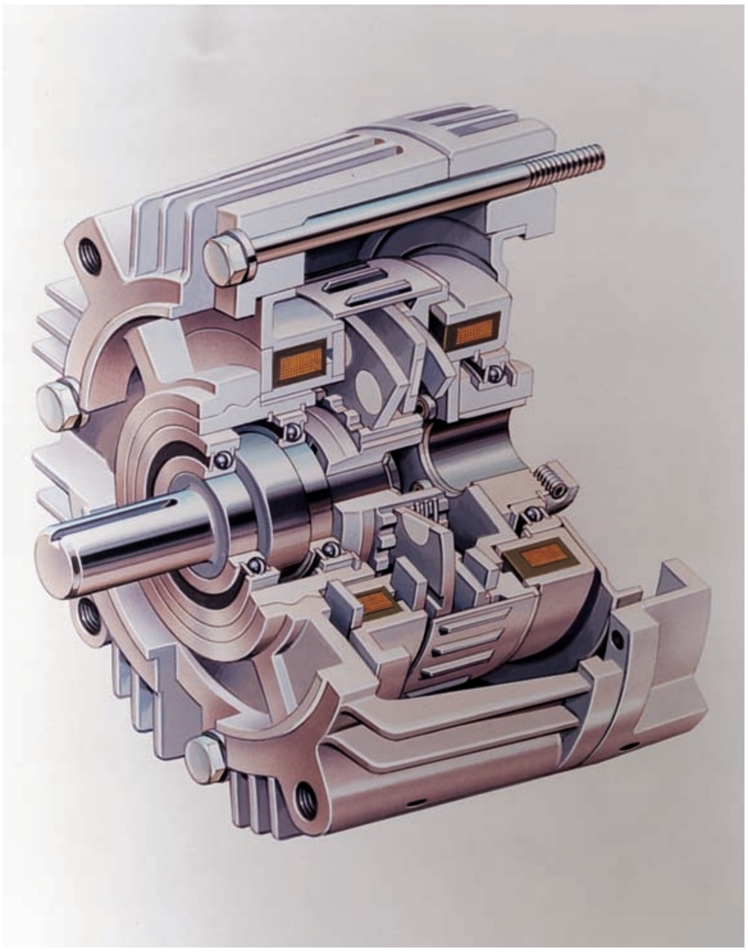


Figure 59–4 Cut-away view of a combination clutch and brake. (Courtesy of Warner Electric, South Beloit, Illinois.)

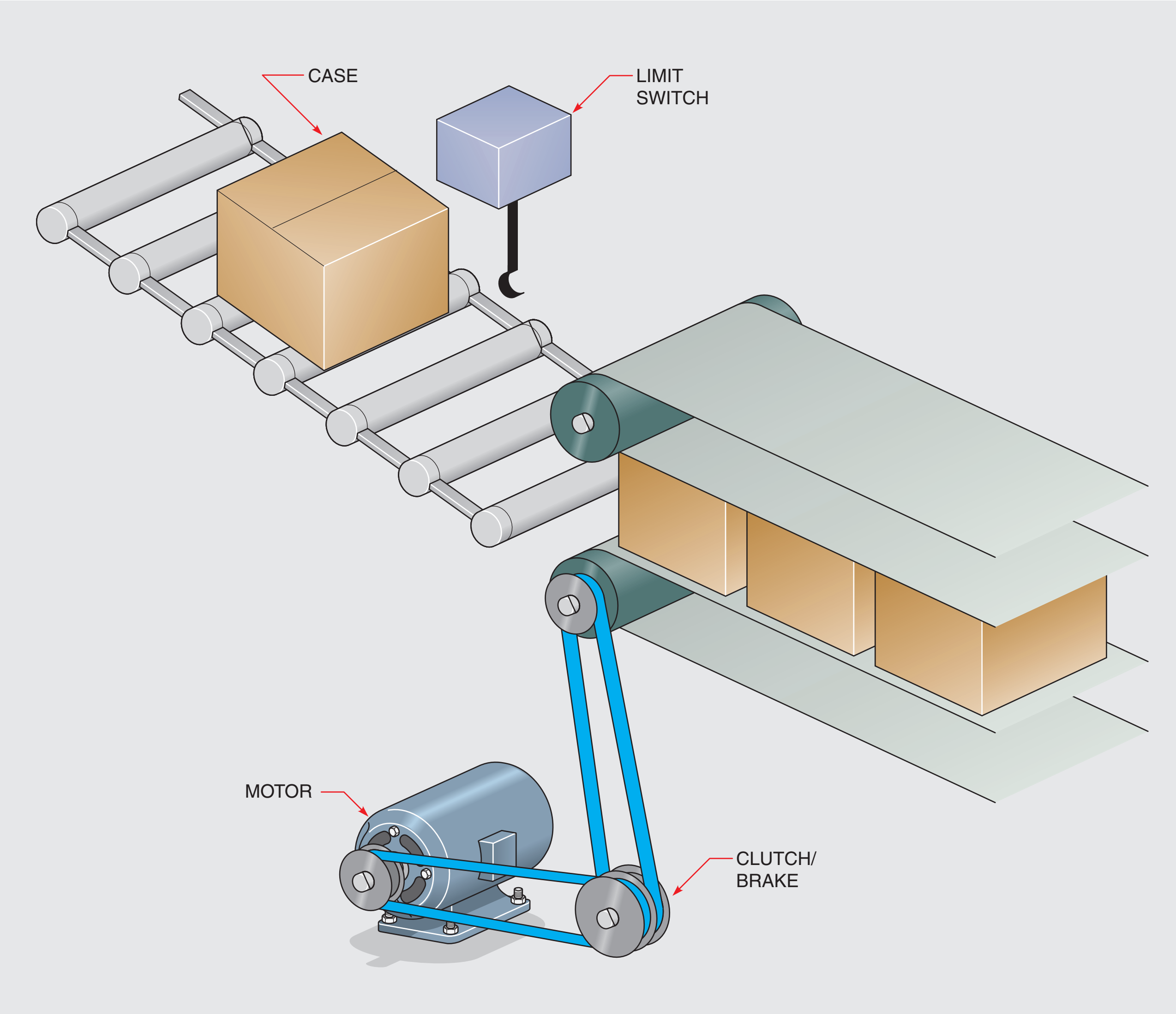


Figure 59–5 Case sealer is used to hold top of carton while glue is drying. In this application, cartons come down gravity conveyor and hit switch in front of sealer. Clutch on sealer drive is engaged, moving all cartons in sealer forward. When new carton passes trip switch, brake is engaged and clutch disengaged. Positioning provided even spacing of cartons, insuring that they are in the sealer for as long a time as possible.

Magnetic Drives

The magnetic drive couples the motor to the load magnetically. The magnetic drive can be used as a clutch and can be adapted to an adjustable speed drive.

The electromagnetic (or eddy current) coupling is one of the simpler ways to obtain an adjustable output speed from the constant input speed of squirrel cage motors.

There is no mechanical contact between the rotating members of the magnetic drive. Thus, there is no wear. Torque is transmitted between the two rotating units by an electromagnetic reaction created by an energized coil winding. The slip between the motor and load can be controlled continuously, with more precision, and over a wider range than is possible with the mechanical friction clutch.

As shown in Figure 59–6, the magnet rotates within the steel ring or drum. There is an air gap between the

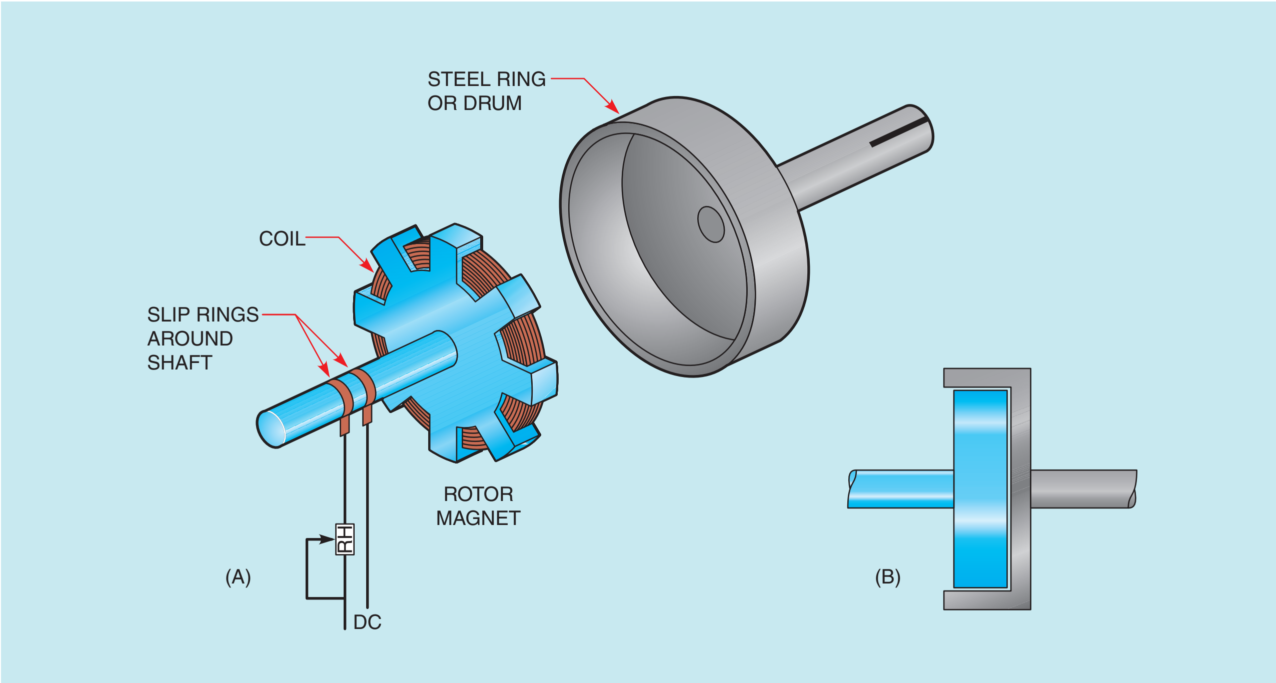


Figure 59–6 Diagram showing (A) open view of magnetic drive assembly; (B) spider rotor magnet rotates within ring.

ring and the magnet. The magnetic flux crosses the air gap and penetrates the iron ring. The rotation of the ring with relation to the magnet generates eddy currents and magnetic fields in the ring. Magnetic interaction between the two units transmits torque from the motor to the load. This torque is controlled with a rheostat which manually or automatically adjusts the direct current supplied to the electromagnet through the slip rings.

When the electromagnetic drive responds to an input or command voltage, a further refinement can be obtained in automatic control to regulate and maintain the output speed. The magnetic drive can be used with any type of actuating device or transducer that can provide an electrical signal. For example, electronic controls and sensors that detect liquid level, air and fluid pressure, temperature, and frequency can provide the input required.

A tachometer generator provides feedback speed control in that it generates a voltage that is proportional to its speed. Any changes in load condition will change the speed. The resulting generator voltage fluctuations are fed to a control circuit which increases or decreases the magnetic drive field excitation to hold the speed constant.

For applications where a magnetic drive meets the requirements, an adjustable speed is frequently a desirable choice. Magnetic drives are used for applications requiring an adjustable speed, such as cranes, hoists, fans, compressors, and pumps (Figure 59–7).

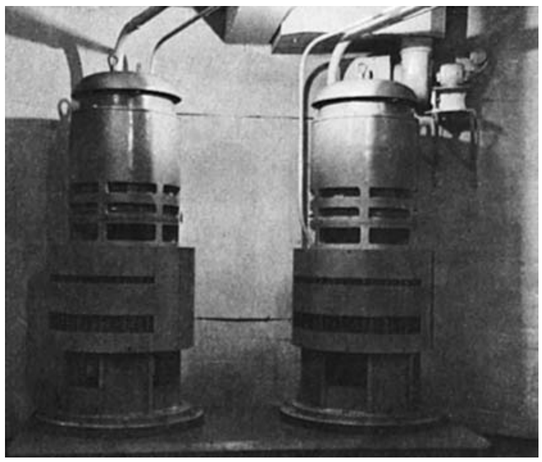


Figure 59–7 Three-phase motor attached to a magnetic variable speed drive, often referred to as an eddy current clutch. (Courtesy Electric Machinery Mfg. Co.)

Review Questions

1. How is the magnetic clutch engaged and disengaged?
2. What devices may be used to energize the magnetic clutch?
3. Which type of drive is best suited for maintaining large differences in the input and output speeds? Why?
4. What is meant by feedback speed control?
5. How is the magnetic drive used as an adjustable speed drive?

UNIT 60
MOTOR INSTALLATION

OBJECTIVES

After studying this unit, the student will be able to:

- Determine the full load current rating of different types of motors using the *National Electrical Code® (NEC®)*.
- Determine the conductor size for installing motors.
- Determine the overload size for different types of motors.
- Determine the size of the short-circuit protective device for individual motors and multi-motor connections.
- Select the proper size starter for a particular motor.

Determining Motor Current

There are different types of motors, such as direct current, single-phase ac, two-phase ac, and three-phase ac. Different tables from the *National Electrical Code® (NEC®)* are used to determine the running current for these different types of motors. *Table 430.247* (Figure 60–1) is used to determine the full-load running current for a direct current motor. *Table 430.248* (Figure 60–2) is used to determine the full-load running current for single-phase motors; *Table 430.249* (Figure 60–3) is used to determine the running current for two-phase motors; and *Table 430.250* (Figure 60–4) is used to determine the full-load running current for three-phase motors. Note that the tables list the amount of current that the motor is expected to draw under a full-load condition. The motor will exhibit less current draw if it is not under full load. These tables list the ampere rating of the motors according to horsepower and connected voltage. It should also be noted that *NEC® Section 430.6(A)(1)* states these tables, rather than the nameplate rating of the motor, are to be used to determine *conductor size, short-circuit protection size, and ground fault protection size.* The motor overload size, however, is to be determined by the nameplate rating of the motor.

DC Motors

Table 430.247 lists the full-load running currents for direct current motors. The horsepower rating of the

Table 430.247 Full-Load Current in Amperes, Direct-Current Motors

The following values of full-load currents* are for motors running at base speed.

Horsepower	Armature Voltage Rating* 90 Volts	120 Volts	180 Volts	240 Volts	500 Volts	550 Volts
1/4	4.0	3.1	2.0	1.6	—	—
1/3	5.2	4.1	2.6	2.0	—	—
1/2	6.8	5.4	3.4	2.7	—	—
3/4	9.6	7.6	4.8	3.8	—	—
1	12.2	9.5	6.1	4.7	—	—
1½	—	13.2	8.3	6.6	—	—
2	—	17	10.8	8.5	—	—
3	—	25	16	12.2	—	—
5	—	40	27	20	—	—
7½	—	58	—	29	13.6	12.2
10	—	76	—	38	18	16
15	—	—	—	55	27	24
20	—	—	—	72	34	31
25	—	—	—	89	43	38
30	—	—	—	106	51	46
40	—	—	—	140	67	61
50	—	—	—	173	83	75
60	—	—	—	206	99	90
75	—	—	—	255	123	111
100	—	—	—	341	164	148
125	—	—	—	425	205	185
150	—	—	—	506	246	222
200	—	—	—	675	330	294

*These are average dc quantities.

Figure 60–1 Table 430.247. (Reprinted with permission from NFPA 70-2005, *National Electrical Code*®, Copyright © 2005, National Fire Protection Association, Quincy, MA 02269.)

motor is given in the far left-hand column. Rated voltages are listed across the top of the table. The table shows that a 1 hp motor will have a full-load current of 12.2 A when connected to 90 V dc. If a 1 hp motor is designed to be connected to 240 V, it will have a current draw of 4.7 A.

Single-Phase AC Motors

The current ratings for single-phase ac motors are given in *Table 430.248*. Particular attention should be paid to the statement preceding the table. The table asserts that the values listed in this table are for motors that operate under normal speeds and torques. Motors especially designed for low speed and high torque, or multispeed motors, shall have their running current determined from the nameplate rating of the motor.

The voltages listed in the table are 115, 200, 208, and 230. The last sentence of the preceding statement states that the currents listed shall be permitted for voltages of 110 to 120 V and 220 to 240 V. This means that if the motor is connected to a 120 V line, it is permissible to use the currents listed in the 115 V column. If the

Table 430.248 Full-Load Currents in Amperes, Single-Phase Alternating-Current Motors

The following values of full-load currents are for motors running at usual speeds and motors with normal torque characteristics. Motors built for especially low speeds or high torques may have higher full-load currents, and multispeed motors will have full-load current varying with speed, in which case the nameplate current ratings shall be used.

The voltages listed are rated motor voltages. The currents listed shall be permitted for system voltage ranges of 110 to 120 and 220 to 240 volts.

Horsepower	115 Volts	200 Volts	208 Volts	230 Volts
1/6	4.4	2.5	2.4	2.2
1/4	5.8	3.3	3.2	2.9
1/3	7.2	4.1	4.0	3.6
1/2	9.8	5.6	5.4	4.9
3/4	13.8	7.9	7.6	6.9
1	16	9.2	8.8	8.0
1 1/2	20	11.5	11.0	10
2	24	13.8	13.2	12
3	34	19.6	18.7	17
5	56	32.2	30.8	28
7 1/2	80	46.0	44.0	40
10	100	57.5	55.0	50

Figure 60–2 Table 430.248. (Reprinted with permission from NFPA 70-2005, *National Electrical Code*®, Copyright © 2005, National Fire Protection Association, Quincy, MA 02269.)

motor is connected to a 220 V line, the 230 V column can be used.

EXAMPLE:

A 3 hp single-phase ac motor is connected to a 208 V line. What will be the full-load running current of this motor?

Locate 3 hp in the far left-hand column. Follow across to the 208 V column. The full-load current will be 18.7 A.

Two-Phase Motors

Although two-phase motors are seldom used, *Table 430.249* lists the full-load running currents for these motors. Like single-phase motors, two-phase motors, which are especially designed for low-speed, high-torque applications, and multispeed motors use the nameplate rating instead of the values shown in the table. When using a two-phase, three-wire system, the size of the neutral conductor must be increased by the square root of 2, or 1.414. The reason for this is that the voltages of a two-phase system are 90° out of phase with each other as shown in Figure 60–5. The principle of two-phase power generation is shown in Figure 60–6. In a two-phase alternator, the phase windings are arranged 90° apart. The magnet is the rotor of the alternator. When the rotor turns, it induces voltage into the phase windings, which are 90° apart. When one end of each phase winding is joined to form a common terminal, or neutral, the current in the neutral conductor will be greater than the current in either of the two phase conductors. An example of this is

Table 430.249 Full-Load Current, Two-Phase Alternating-Current Motors (4-Wire)

The following values of full-load current are for motors running at speeds usual for belted motors and motors with normal torque characteristics. Motors built for especially low speeds or high torques may require more running current, and multispeed motors will have full-load current varying with speed, in which case the nameplate current rating shall be used. Current in the common conductor of a 2-phase, 3-wire system will be 1.41 times the value given.

The voltages listed are rated motor voltages. The currents listed shall be permitted for system voltage ranges of 110 to 120, 220 to 240, 440 to 480, and 550 to 600 volts.

	Induction-Type Squirrel Cage and Wound Rotor (Amperes)				
Horsepower	115 Volts	230 Volts	460 Volts	575 Volts	2300 Volts
1/2	4.0	2.0	1.0	0.8	—
3/4	4.8	2.4	1.2	1.0	—
1	6.4	3.2	1.6	1.3	—
1 1/2	9.0	4.5	2.3	1.8	—
2	11.8	5.9	3.0	2.4	—
3	—	8.3	4.2	3.3	—
5	—	13.2	6.6	5.3	—
7 1/2	—	19	9.0	8.0	—
10	—	24	12	10	—
15	—	36	18	14	—
20	—	47	23	19	—
25	—	59	29	24	—
30	—	69	35	28	—
40	—	90	45	36	—
50	—	113	56	45	—
60	—	133	67	53	14
75	—	166	83	66	18
100	—	218	109	87	23
125	—	270	135	108	28
150	—	312	156	125	32
200	—	416	208	167	43

Figure 60–3 Table 430.249. (Reprinted with permission from NFPA 70-2005, *National Electrical Code®*, Copyright © 2005, National Fire Protection Association, Quincy, MA 02269.)

Table 430.250 Full-Load Current, Three-Phase Alternating-Current Motors

The following values of full-load currents are typical for motors running at speeds usual for belted motors and motors with normal torque characteristics.
Motors built for low speeds (1200 rpm or less) or high torques may require more running current, and multispeed motors will have full-load current varying with speed. In these cases, the nameplate current rating shall be used.
The voltages listed are rated motor voltages. The currents listed shall be permitted for system voltage ranges of 110 to 120, 220 to 240, 440 to 480, and 550 to 600 volts.

	Induction-Type Squirrel Cage and Wound Rotor (Amperes)							Synchronous-Type Unity Power Factor* (Amperes)			
Horsepower	**115 Volts**	**200 Volts**	**208 Volts**	**230 Volts**	**460 Volts**	**575 Volts**	**2300 Volts**	**230 Volts**	**460 Volts**	**575 Volts**	**2300 Volts**
1/2	4.4	2.5	2.4	2.2	1.1	0.9	—	—	—	—	—
3/4	6.4	3.7	3.5	3.2	1.6	1.3	—	—	—	—	—
1	8.4	4.8	4.6	4.2	2.1	1.7	—	—	—	—	—
1 1/2	12.0	6.9	6.6	6.0	3.0	2.4	—	—	—	—	—
2	13.6	7.8	7.5	6.8	3.4	2.7	—	—	—	—	—
3	—	11.0	10.6	9.6	4.8	3.9	—	—	—	—	—
5	—	17.5	16.7	15.2	7.6	6.1	—	—	—	—	—
7 1/2	—	25.3	24.2	22	11	9	—	—	—	—	—
10	—	32.2	30.8	28	14	11	—	—	—	—	—
15	—	48.3	46.2	42	21	17	—	—	—	—	—
20	—	62.1	59.4	54	27	22	—	—	—	—	—
25	—	78.2	74.8	68	34	27	—	53	26	21	—
30	—	92	88	80	40	32	—	63	32	26	—
40	—	120	114	104	52	41	—	83	41	33	—
50	—	150	143	130	65	52	—	104	52	42	—
60	—	177	169	154	77	62	16	123	61	49	12
75	—	221	211	192	96	77	20	155	78	62	15
100	—	285	273	248	124	99	26	202	101	81	20
125	—	359	343	312	156	125	31	253	126	101	25
150	—	414	396	360	180	144	37	302	151	121	30
200		552	528	480	240	192	49	400	201	161	40
250	—	—	—	—	302	242	60	—	—	—	—
300	—	—	—	—	361	289	72	—	—	—	—
350	—	—	—	—	414	336	83	—	—	—	—
400	—	—	—	—	477	382	95	—	—	—	—
450	—	—	—	—	515	412	103	—	—	—	—
500	—	—	—	—	590	472	118	—	—	—	—

*For 90 and 80 percent power factor, the figures shall be multiplied by 1.1 and 1.25, respectively.

Figure 60–4 Table 430.250. (Reprinted with permission from NFPA 70-2005, *National Electrical Code*®, Copyright © 2005, National Fire Protection Association, Quincy, MA 02269.)

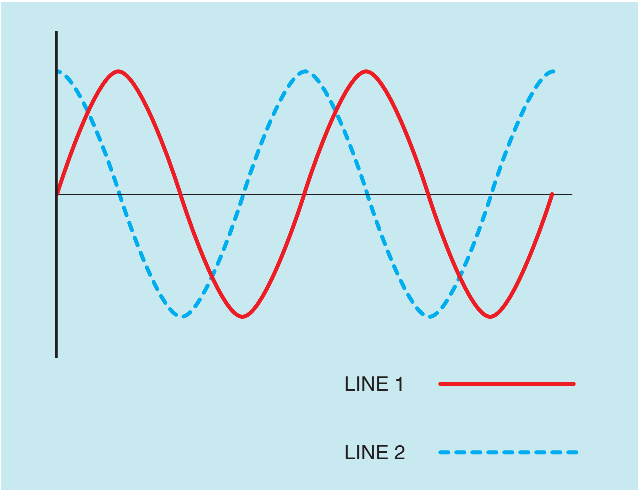


Figure 60–5 The voltages of a two-phase system are 90° out of phase with each other.

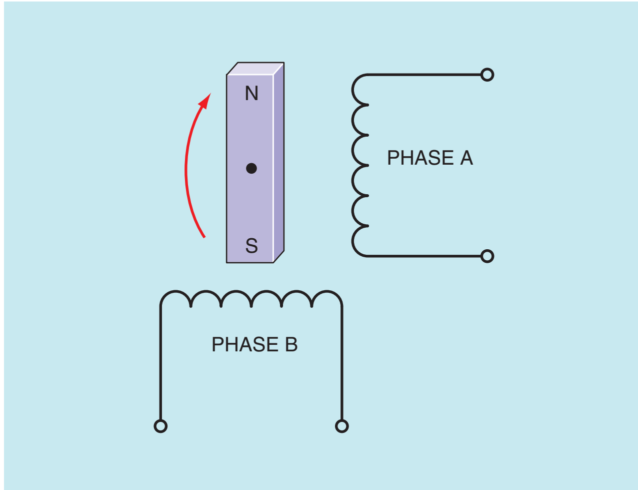


Figure 60–6 Two-phase alternator.

shown in Figure 60–7. In this example, a two-phase alternator is connected to a two-phase motor. The current draw on each of the phase windings is 10 A. The current flow in the neutral, however, is 1.414 times greater than the current flow in the phase windings, or 14.14 A.

EXAMPLE:

Compute the phase current and neutral current for a 60 hp, 460 V two-phase motor.
The phase current can be taken from *Table 430–149.*

Phase current = 67 A

The neutral current will be 1.414 times higher than the phase current.

Neutral current = 67 × 1.414
Neutral current = 94.574 A.

Three-Phase Motors

Table 430.250 is used to determine the full load current of three-phase motors. The notes at the top of the table are very similar to the notes of *Tables 430.248* and *430.249.* The full load current of low-speed, high-torque, and multispeed motors is to be determined from the nameplate rating instead of from the values listed in the table. *Table 430.250* has an extra note that deals with synchronous motors. Notice that the right side of *Table 430.250* is devoted to the full load currents of synchronous type motors. The currents listed are for synchronous type motors that are to be operated at unity or 100% power factor. Since synchronous motors are often made to have a leading power factor by overexcitation of the rotor current, the full-load current rating must be increased when this is done. If the motor is operated at 90% power factor, the rated full-load current in the table must be increased by 10%. If the motor is to be operated at 80% power factor, the full-load current is to be increased by 25%.

EXAMPLE:

A 150 hp, 460 V synchronous motor is to be operated at 80% power factor. What will be the full-load current rating of the motor?

The table indicates a current value of 151 A for this motor. To determine the running current at 80% power factor, multiply this current by 125% or 1.25. (Multiplying by 1.25 results in the same answer that would be obtained by dividing by 0.80.)

151 × 1.25 = 188.75 or 189 A

EXAMPLE:

A 200 hp, 2300 V synchronous motor is to be operated at 90% power factor. What will be the full-load current rating of this motor?

Locate 200 hp in the far left-hand column. Follow across to the 2300 V column listed under synchronous type motors. Increase this value by 10%.

40 × 1.10 = 44 A

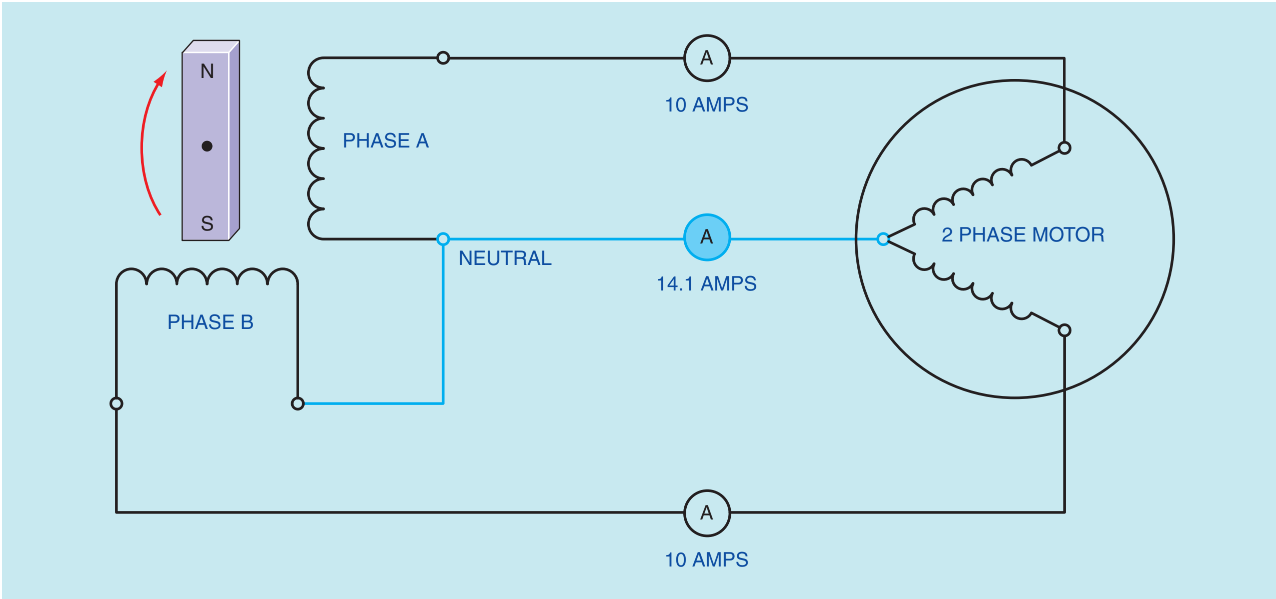


Figure 60–7 The neutral conductor must be larger than the phase conductors.

Determining Conductor Size For A Single Motor

NEC® Section 430.6(A)(1) states that the conductor for a motor connection shall be based on the values from *Tables 430.247, 430.248, 430.249,* and *430.250* instead of the motor nameplate current. *Section 430.22(A)* states that conductors supplying a single motor shall have an ampacity of not less than 125% of the motor full-load current. *NEC® Section 310* is used to select the conductor size after the ampacity has been determined. The exact table employed will be determined by the wiring conditions. Probably the most frequently used table is *Table 310.16* (Figure 60–8).

Termination Temperature

Another factor that must be taken into consideration when determining the conductor size is the temperature rating of the devices and terminals as specified in *NEC® Section 110.14(C).* This section states that the conductor is to be selected and coordinated as to not exceed the lowest temperature rating of any connected termination, any connected conductor, or any connected device. This means that regardless of the temperature rating of the conductor, the ampacity must be selected from a column that does not exceed the temperature rating of the termination. The conductors listed in the first column of *Table 310.16* have a temperature rating of 60°C, the conductors in the second column have a rating of 75°C, and the conductors in the third column have a rating of 90°C. The temperature ratings of devices such as circuit breakers, fuses, and terminals are found in the UL (Underwriters Laboratories) product directories. Occasionally, the temperature rating may be found on the piece of equipment, but this is the exception and not the rule. As a general rule the temperature rating of most devices will not exceed 75°C.

When the termination temperature rating is not listed or known, *NEC® Section 110.14(C)(1)(a)* states that for circuits rated at 100 A or less, or for #14 AWG through #1 AWG conductors, the ampacity of the wire, regardless of the temperature rating, will be selected from the 60°C column. This does not mean that only those types of insulation listed in the 60°C column can be used, but that the *ampacities* listed in the 60°C column must be used to select the conductor size. For example, assume that a copper conductor with type XHHW insulation is to be connected to a 50 A circuit breaker that does not have a listed temperature rating. According to *NEC® Table 310.16,* a #8 AWG copper conductor with XHHW insulation is rated to carry 55 A of current. Type XHHW insulation is located in the 90°C column, but the temperature rating of the circuit breaker is not known. Therefore, the wire size must be selected from the ampacity ratings in the 60°C column. A #6 AWG copper conductor with type XHHW insulation would be used.

Table 310.16 Allowable Ampacities of Insulated Conductors Rated 0 Through 2000 Volts, 60°C Through 90°C (140°F Through 194°F), Not More Than Three Current-Carrying Conductors in Raceway, Cable, or Earth (Directly Buried), Based on Ambient Temperature of 30°C (86°F)

Size AWG or kcmil	Temperature Rating of Conductor (See Table 310.13.)						Size AWG or kcmil
	60°C (140°F)	75°C (167°F)	90°C (194°F)	60°C (140°F)	75°C (167°F)	90°C (194°F)	
	Types TW, UF	Types RHW, THHW, THW, THWN, XHHW, USE, ZW	Types TBS, SA, SIS, FEP, FEPB, MI, RHH, RHW-2, THHN, THHW, THW-2, THWN-2, USE-2, XHH, XHHW, XHHW-2, ZW-2	Types TW, UF	Types RHW, THHW, THW, THWN, XHHW, USE	Types TBS, SA, SIS, THHN, THHW, THW-2, THWN-2, RHH, RHW-2, USE-2, XHH, XHHW, XHHW-2, ZW-2	
	COPPER			ALUMINUM OR COPPER-CLAD ALUMINUM			
18	—	—	14	—	—	—	—
16	—	—	18	—	—	—	—
14*	20	20	25	—	—	—	—
12*	25	25	30	20	20	25	12*
10*	30	35	40	25	30	35	10*
8	40	50	55	30	40	45	8
6	55	65	75	40	50	60	6
4	70	85	95	55	65	75	4
3	85	100	110	65	75	85	3
2	95	115	130	75	90	100	2
1	110	130	150	85	100	115	1
1/0	125	150	170	100	120	135	1/0
2/0	145	175	195	115	135	150	2/0
3/0	165	200	225	130	155	175	3/0
4/0	195	230	260	150	180	205	4/0
250	215	255	290	170	205	230	250
300	240	285	320	190	230	255	300
350	260	310	350	210	250	280	350
400	280	335	380	225	270	305	400
500	320	380	430	260	310	350	500
600	355	420	475	285	340	385	600
700	385	460	520	310	375	420	700
750	400	475	535	320	385	435	750
800	410	490	555	330	395	450	800
900	435	520	585	355	425	480	900
1000	455	545	615	375	445	500	1000
1250	495	590	665	405	485	545	1250
1500	520	625	705	435	520	585	1500
1750	545	650	735	455	545	615	1750
2000	560	665	750	470	560	630	2000

CORRECTION FACTORS

Ambient Temp. (°C)	For ambient temperatures other than 30°C (86°F), multiply the allowable ampacities shown above by the appropriate factor shown below.						Ambient Temp. (°F)
21–25	1.08	1.05	1.04	1.08	1.05	1.04	70–77
26–30	1.00	1.00	1.00	1.00	1.00	1.00	78–86
31–35	0.91	0.94	0.96	0.91	0.94	0.96	87–95
36–40	0.82	0.88	0.91	0.82	0.88	0.91	96–104
41–45	0.71	0.82	0.87	0.71	0.82	0.87	105–113
46–50	0.58	0.75	0.82	0.58	0.75	0.82	114–122
51–55	0.41	0.67	0.76	0.41	0.67	0.76	123–131
56–60	—	0.58	0.71	—	0.58	0.71	132–140
61–70	—	0.33	0.58	—	0.33	0.58	141–158
71–80	—	—	0.41	—	—	0.41	159–176

* See 240.4(D).

Figure 60–8 Table 310.16. (Reprinted with permission from NFPA 70-2005, *National Electrical Code*®, Copyright © 2005, National Fire Protection Association, Quincy, MA 02269.)

NEC® Section 110.14(C)(1)(a)(4) has a special provision for motors with marked NEMA design codes B, C, D, or E. This section states that conductors rated at 75°C or higher may be selected from the 75°C column even if the ampacity is 100 A or less. This code will not apply to motors that do not have a NEMA design code marked on their nameplate. Most motors manufactured before 1996 will not have a NEMA design code. The NEMA design code letter should not be confused with the code letter that indicates the type squirrel cage rotor used in the motor.

EXAMPLE:

A 30 hp three-phase squirrel cage induction motor is connected to a 480 V line. The conductors are run in conduit to the motor. The motor does not have a NEMA design code listed on the nameplate. The termination temperature rating of the devices is not known. Copper conductors with THWN insulation are to be used for this motor connection. What size conductors should be used?

The first step is to determine the full load current of the motor. This is determined from *Table 430.250.* The table indicates a current of 40 A for this motor. The current must be increased by 25% according to *Section 430.22(A).*

$$40 \times 1.25 = 50 \text{ A}$$

Table 310.16 is used to determine the conductor size. Locate the column that contains THWN insulation in the copper section of the table. THWN is located in the 75°C column. Since this circuit is less than 100 A and the termination temperature is not known, and the motor does not contain a NEMA design code letter, the conductor size must be selected from the ampacities listed in the 60°C column. A #6 AWG copper conductor with type THWN insulation will be used.

For circuits rated over 100 A, or for conductor sizes larger than #1 AWG, *Section 110.14(C)(1)(b)* states that the ampacity ratings listed in the 75°C column may be use to select wire sizes unless conductors with a 60°C temperature rating have been selected for use. For example, types TW and UF insulation are listed in the 60°C column. If one of these two insulation types has been specified, the wire size must be chosen from the 60°C column regardless of the ampere rating of the circuit.

Overload Size

When determining the overload size for a motor the *nameplate* current rating of the motor is used instead of the current values listed in the tables *(NEC® Section 430.6(A))*. Other factors such as the service factor (SF) or temperature rise (°C) of the motor are also to be considered when determining the overload size for a motor. The temperature rise of the motor is an indication of the type of insulation used on the motor windings and should not be confused with termination temperature discussed in *Section 110.14(C). NEC® Section 430.32* (Figure 60–9) is used to

430.32 Continuous-Duty Motors.

(A) More Than 1 Horsepower. Each continuous-duty motor rated more than 1 hp shall be protected against overload by one of the means in 430.32(A)(1) through (A)(4).

(1) Separate Overload Device. A separate overload device that is responsive to motor current. This device shall be selected to trip or shall be rated at no more than the following percent of the motor nameplate full-load current rating:

Motors with a marked service factor 1.15 or greater	125%
Motors with a marked temperature rise 40°C or less	125%
All other motors	115%

Figure 60–9 Section 430.32. (Reprinted with permission from NFPA 70-2005, *National Electrical Code®*, Copyright © 2005, National Fire Protection Association, Quincy, MA 02269.)

determine the overload size for motors of 1 hp or more. The overload size is based on a percentage of the full-load current of the motor listed on the motor nameplate.

EXAMPLE:

A 25 hp three-phase induction motor has a nameplate rating of 32 A. The nameplate also shows a temperature rise of 30°C. Determine the ampere rating of the overload for this motor.

NEC® Section 430.32(A)(1) indicates the overload size is 125% of the full-load current rating of the motor.

$$32 \times 1.25 = 40 \text{ A}$$

If for some reason this overload size does not permit the motor to start without tripping out, *Section 430.32(C)* permits the overload size to increase to a maximum of 140% for this motor. If this increase in overload size does not solve the starting problem, the overload may be shunted out of the circuit during the starting period in accordance with *Section 430.35(A) & (B).*

Table 430.7(B) Locked-Rotor Indicating Code Letters

Code Letter	Kilovolt-Amperes per Horsepower with Locked Rotor
A	0–3.14
B	3.15–3.54
C	3.55–3.99
D	4.0–4.49
E	4.5–4.99
F	5.0–5.59
G	5.6–6.29
H	6.3–7.09
J	7.1–7.99
K	8.0–8.99
L	9.0–9.99
M	10.0–11.19
N	11.2–12.49
P	12.5–13.99
R	14.0–15.99
S	16.0–17.99
T	18.0–19.99
U	20.0–22.39
V	22.4 and up

Figure 60–10 Table 430.7(B). (Reprinted with permission from NFPA 70-2005, *National Electrical Code®*, Copyright © 2005, National Fire Protection Association, Quincy, MA 02269.)

Determining Locked-Rotor Current

There are two basic methods for determining the locked-rotor current (starting current) of a squirrel cage induction motor depending on the information available. If the motor nameplate lists code letters that range from A to V, they indicate the type of rotor bars used when the rotor was made. Different types of bars are used to make motors with different operating characteristics. The type of rotor bars largely determines the maximum starting current of the motor. *NEC® Table 430.7(B)* (Figure 60–10) lists the different code letters and gives the locked-rotor kVA per hp. The starting current can be determined by multiplying the kVA rating by the hp rating and then dividing by the applied voltage.

EXAMPLE:

A 15 hp, three-phase squirrel cage motor with a code letter K is connected to a 240 V line. Determine the locker-rotor current.

The table lists 8.0 to 8.99 kVA per hp for a motor with a code letter of K. An average value of 8.5 will be used.

$$8.5 \times 15 = 127.5 \text{ kVA} \quad \text{or} \quad 127{,}500 \text{ VA}$$

$$\frac{127{,}500}{240 \times \sqrt{3}} = 306.7 \text{ A}$$

The second method of determining locked-rotor current is to use *Tables 430.251(A) & (B)* (Figure 60–11) if the motor nameplate lists NEMA design codes. *Table 430.251(A)* lists the locked-rotor currents for single-phase motors and *Table 430.251(B)* lists the locked-rotor currents for polyphase motors.

Table 430.251(A) Conversion Table of Single-Phase Locked-Rotor Currents for Selection of Disconnecting Means and Controllers as Determined from Horsepower and Voltage Rating
For use only with 430.110, 440.12, 440.41 and 455.8(C).

Rated Horsepower	Maximum Locked-Rotor Current in Amperes, Single Phase		
	115 Volts	208 Volts	230 Volts
½	58.8	32.5	29.4
¾	82.8	45.8	41.4
1	96	53	48
1½	120	66	60
2	144	80	72
3	204	113	102
5	336	186	168
7½	480	265	240
10	600	332	300

Table 430.251(B) Conversion Table of Polyphase Design B, C, and D Maximum Locked-Rotor Currents for Selection of Disconnecting Means and Controllers as Determined from Horsepower and Voltage Rating and Design Letter [ROP 11–90]
For use only with 430.110, 440.12, 440.41 and 455.8(C).

Rated Horse-power	Maximum Motor Locked-Rotor Current in Amperes, Two- and Three-Phase, Design B, C, and D					
	115 Volts	200 Volts	208 Volts	230 Volts	460 Volts	575 Volts
	B, C, D	B, C, D	B, C, D	B, C, D	B, C, D	B, C, D
½	40	23	22.1	20	10	8
¾	50	28.8	27.6	25	12.5	10
1	60	34.5	33	30	15	12
1½	80	46	44	40	20	16
2	100	57.5	55	50	25	20
3	—	73.6	71	64	32	25.6
5	—	105.8	102	92	46	36.8
7½	—	146	140	127	63.5	50.8
10	—	186.3	179	162	81	64.8
15	—	267	257	232	116	93
20	—	334	321	290	145	116
25	—	420	404	365	183	146
30	—	500	481	435	218	174
40	—	667	641	580	290	232
50	—	834	802	725	363	290
60	—	1001	962	870	435	348
75	—	1248	1200	1085	543	434
100	—	1668	1603	1450	725	580
125	—	2087	2007	1815	908	726
150	—	2496	2400	2170	1085	868
200	—	3335	3207	2900	1450	1160
250	—	—	—	—	1825	1460
300	—	—	—	—	2200	1760
350	—	—	—	—	2550	2040
400	—	—	—	—	2900	2320
450	—	—	—	—	3250	2600
500	—	—	—	—	3625	2900

Figure 60–11 Tables 430.251(A) and 430.251(B). (Reprinted with permission from NFPA 70-2005, *National Electrical Code*®, Copyright © 2005, National Fire Protection Association, Quincy, MA 02269.)

Short-Circuit Protection

The rating of the short-circuit protective device is determined by *NEC*® *Table 430.52,* (Figure 60–12). The far left-hand column lists the type of motor that is to be protected. To the right of this are four columns that list different types of short-circuit protective devices; nontime delay fuses, dual-element time delay fuses, instantaneous trip circuit breakers, and inverse time circuit breakers. Although it is permissible to use non-time delay fuses and instantaneous trip circuit breakers, most motor circuits are protected by dual-element time delay fuses, or inverse time circuit breakers.

Each of these columns lists the percentage of motor current that is to be used in determining the ampere rating of the short-circuit protective device. The current listed in the appropriate motor table is to be used instead of the nameplate current. *NEC*® *Section 430.52(C)(1)* states that the protective device is to have a rating or setting not exceeding the value calculated in accord with *Table 430.52. Exception No. 1* of this section, however, states that if the calculated value does not correspond to a standard size or rating of a fuse or circuit breaker, it shall be permissible to use the next higher standard size. The standard sizes of fuses and circuit breakers are listed in *NEC*® *Section 240.6* (Figure 60–13).

Starting in 1996, *Table 430.52* lists squirrel cage motor types by NEMA design letters instead of code letters. *Section 430.7(A)(9)* requires that motor nameplates be marked with design letters B, C, or D. Motors manufactured before this requirement, however, do not list design letters on the nameplate. Most common squirrel cage motors used in industry actually fall in the design B classification, and for purposes of selecting the short-circuit protective device are considered to be design B unless otherwise listed.

Table 430.52 Maximum Rating or Setting of Motor Branch-Circuit Short-Circuit and Ground-Fault Protective Devices [ROP 11–36]

	Percentage of Full-Load Current			
Type of Motor	**Nontime Delay Fuse[1]**	**Dual Element (Time-Delay) Fuse[1]**	**Instantaneous Trip Breaker**	**Inverse Time Breaker[2]**
Single-phase motors	300	175	800	250
AC polyphase motors other than wound-rotor				
Squirrel cage — other than Design B energy efficient	300	175	800	250
Design B energy efficient	300	175	1100	250
Synchronous[3]	300	175	800	250
Wound rotor	150	150	800	150
Direct current (constant voltage)	150	150	250	150

Note: For certain exceptions to the values specified, see 430.54.
[1]The values in the Nontime Delay Fuse column apply to Time-Delay Class CC fuses.
[2]The values given in the last column also cover the ratings of nonadjustable inverse time types of circuit breakers that may be modified as in 430.52(C), Exception No. 1 and No. 2.
[3]Synchronous motors of the low-torque, low-speed type (usually 450 rpm or lower), such as are used to drive reciprocating compressors, pumps, and so forth, that start unloaded, do not require a fuse rating or circuit-breaker setting in excess of 200 percent of full-load current.

Figure 60–12 Table 430.52. (Reprinted with permission from NFPA 70-2005, *National Electrical Code*®, Copyright © 2005, National Fire Protection Association, Quincy, MA 02269.)

EXAMPLE:

A 100 hp three-phase squirrel cage induction motor is connected to a 240 V line. The motor does not contain a NEMA design code. A dual-element time delay fuse is to be used as the short-circuit protective device. Determine the size needed.

Table 430.250 lists a full-load current of 248 A for this motor. *Table 430.52* indicates that a dual-element time delay fuse is to be calculated at 175% of the full-load current rating for an ac polyphase (more than one phase) squirrel cage motor. Since the motor does not list a NEMA design code on the nameplate, it will be assumed that the motor is design B.

$$248 \times 1.75 = 434 \text{ A}$$

The nearest standard fuse size above the computed value listed in *Section 240.6* is 450 A. 450 A fuses will be used to protect this motor.

240.6 Standard Ampere Ratings.

(A) Fuses and Fixed-Trip Circuit Breakers. The standard ampere ratings for fuses and inverse time circuit breakers shall be considered 15, 20, 25, 30, 35, 40, 45, 50, 60, 70, 80, 90, 100, 110, 125, 150, 175, 200, 225, 250, 300, 350, 400, 450, 500, 600, 700, 800, 1000, 1200, 1600, 2000, 2500, 3000, 4000, 5000, and 6000 amperes. Additional standard ampere ratings for fuses shall be 1, 3, 6, 10, and 601. The use of fuses and inverse time circuit breakers with nonstandard ampere ratings shall be permitted.

Figure 60–13 Section 240.6. (Reprinted with permission from NFPA 70-2005, *National Electrical Code®*, Copyright © 2005, National Fire Protection Association, Quincy, MA 02269.)

If for some reason this fuse does not permit the motor to start without blowing, *NEC® Section 430.52(C)(1) Exception 2(b)* states that the rating of a dual-element time delay fuse may be increased to a maximum of 225% of the full-load motor current.

Starter Size

Another factor that must be considered when installing a motor is the size of the starter used to connect the motor to the line. Starter sizes are rated by motor type, horsepower, and connected voltage. The two most common ratings are NEMA and IEC. A chart showing common NEMA size starters for alternating current motors is shown in Figure 60–14. A chart showing IEC starters for alternating current motors is shown in Figure 60–15. Each of these charts lists the minimum size starter designed to connect the listed motors to the line. It is not uncommon to employ larger size starters than those listed. This is especially true when using IEC-type starters because of their smaller load contact size.

EXAMPLE:

A 40 hp three-phase squirrel cage motor is connected to a 208 V line. What are the minimum size NEMA and IEC starters that should be used to connect this motor to the line?

NEMA: The 200 V listing is used for motors rated at 208 V. Locate the NEMA size starter that corresponds to 200 V and 40 hp. Since the motor is three-phase, 40 hp will be in the polyphase column. A NEMA size 4 starter is the minimum size for this motor.

IEC: As with the NEMA chart, the IEC chart lists 200 V instead of 208 V. A size N starter lists 200 V and 40 hp in the three-phase column.

Example Problems

Example 1 A 40 hp 240 V DC motor has a nameplate current rating of 132 A. The conductors are to be copper with type TW insulation. The short-circuit protective device is to be an instantaneous trip circuit breaker. The termination temperature rating of the connected devices is not known. Determine the conductor size, overload size, and circuit breaker size for this installation. Refer to Figure 60–16.

The conductor size must be determined from the current listed in *Table 430.247*. This value is to be increased by 25%. (Note: Multiplying by 1.25 has the same effect as multiplying by 0.25 and then adding the product back to the original number ($140 \times 0.25 = 35$) ($35 + 140 = 175$ A.)

$$140 \times 1.25 = 175 \text{ A}$$

Table 310.16 is used to find the conductor size. Although *Section 110.14(C)* states that for currents of

NEMA Size	Load Volts	Maximum Horsepower Rating—Nonplugging and Nonjogging Duty: Single Phase	Maximum Horsepower Rating—Nonplugging and Nonjogging Duty: Poly Phase
00	115	½	. . .
	200	. . .	1½
	230	1	1½
	380	. . .	1½
	460	. . .	2
	575	. . .	2
0	115	1	. . .
	200	. . .	3
	230	2	3
	380	. . .	5
	460	. . .	5
	575	. . .	5
1	115	2	. . .
	200	. . .	7½
	230	3	7½
	380	. . .	10
	460	. . .	10
	575	. . .	10
*1P	115	3	. . .
	230	5	. . .
2	115	3	. . .
	200	. . .	10
	230	7½	15
	380	. . .	25
	460	. . .	25
	575	. . .	25

NEMA Size	Load Volts	Maximum Horsepower Rating—Nonplugging and Nonjogging Duty: Single Phase	Maximum Horsepower Rating—Nonplugging and Nonjogging Duty: Poly Phase
3	115	7½	. . .
	200	. . .	25
	230	15	30
	380	. . .	50
	460	. . .	50
	575	. . .	50
4	200	. . .	40
	230	. . .	50
	380	. . .	75
	460	. . .	100
	575	. . .	100
5	200	. . .	75
	230	. . .	100
	380	. . .	150
	460	. . .	200
	575	. . .	200
6	200	. . .	150
	230	. . .	200
	380	. . .	300
	460	. . .	400
	575	. . .	400
7	230	. . .	300
	460	. . .	600
	575	. . .	600
8	230	. . .	450
	460	. . .	900
	575	. . .	900

Tables are taken from NEMA Standards.

*1¾, 10 hp is available.

Figure 60–14 NEMA-size starters for alternating-current motors.

I.E.C. Motor Starters (60 Hz.)

Size	Max Amps	Motor Voltage	Maximum Horsepower	
			1 Ø	3 Ø
A	7	115	1/4	
		200		1 1/2
		230	1/2	1 1/2
		460		3
		575		5
B	10	115	1/2	
		200		2
		230	1	2
		460		5
		575		7 1/2
C	12	115	1/2	
		200		3
		230	2	3
		460		7 1/2
		575		10
D	18	115	1	
		200		5
		230	3	5
		460		10
		575		15
E	25	115	2	
		200		5
		230	3	7 1/2
		460		15
		575		20
F	32	115	2	
		200		7 1/2
		230	5	10
		460		20
		575		25
G	37	115	3	
		200		7 1/2
		230	5	10
		460		25
		575		30
H	44	115	3	
		200		10
		230	7 1/2	15
		460		30
		575		40
J	60	115	5	
		200		15
		230	10	20
		460		40
		575		40
K	73	115	5	
		200		20
		230	10	25
		460		50
		575		50
L	85	115	7 1/2	
		200		25
		230	10	30
		460		60
		575		75

Size	Max Amps	Motor Voltage	Maximum Horsepower	
			1 Ø	3 Ø
M	105	115	10	
		200		30
		230	10	40
		460		75
		575		100
N	140	115	10	
		200		40
		230	10	50
		460		100
		575		125
P	170	115		
		200		50
		230		60
		460		125
		575		125
R	200	115		
		200		60
		230		75
		460		150
		575		150
S	300	115		
		200		75
		230		100
		460		200
		575		200
T	420	115		
		200		125
		230		125
		460		250
		575		250
U	520	115		
		200		150
		230		150
		460		350
		575		250
V	550	115		
		200		150
		230		200
		460		400
		575		400
W	700	115		
		200		200
		230		250
		460		500
		575		500
X	810	115		
		200		250
		230		300
		460		600
		575		600
Z	1215	115		
		200		450
		230		45 0
		460		900
		575		900

Figure 60–15 I.E.C. motor starters rated by size, horsepower, and voltage for 60 Hz circuits.

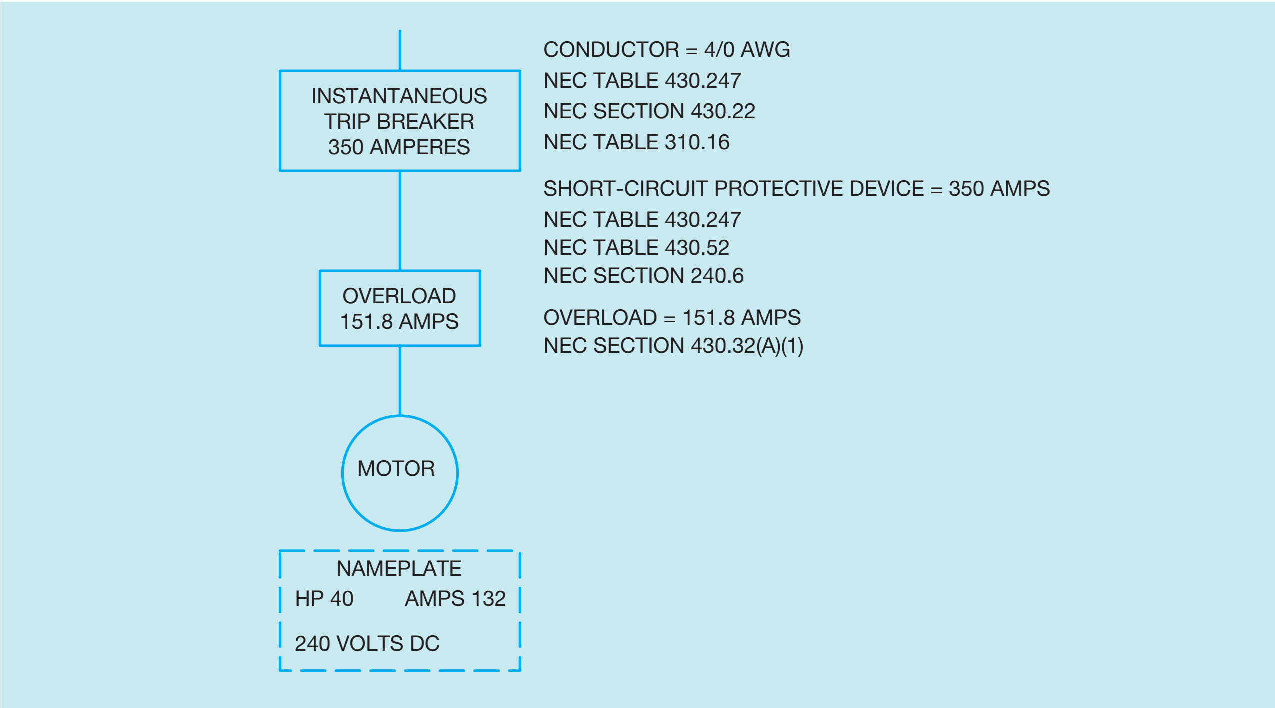


Figure 60–16 Example problem #1.

100 A or greater, the ampacity rating of the conductor is to be determined from the 75°C column, in this instance the insulation type is located in the 60°C column. Therefore, the conductor size must be determined using the 60°C column instead of the 75°C column. A 4/0 AWG copper conductor with type TW insulation will be used.

The overload size is determined from *NEC® Section 430.32(A)(1)*. Since there is no service factor or temperature rise listed on the motor nameplate, the heading *ALL OTHER MOTORS* will be used. The motor nameplate current will be increased by 15%.

$$132 \times 1.15 = 151.8 \text{ A}$$

The circuit breaker size is determined from *Table 430.52*. The current value listed in *Table 430.247* is used instead of the nameplate current. Under dc motors (constant voltage), the instantaneous trip circuit breaker rating is given at 250%.

$$140 \times 2.50 = 350 \text{ A}$$

Since 350 A is one of the standard sizes of circuit breakers listed in *NEC® Section 240.6*, that size breaker will be employed as the short-circuit protective device.

Example 2 A 150 hp three-phase squirrel cage induction motor is connected to a 440 V line. The motor nameplate lists the following information:

Amps 175 SF 1.25 Code D NEMA code B

The conductors are to be copper with type THHN insulation. The short-circuit protective device is to be an inverse time circuit breaker. The termination temperature rating is not known. Determine the conductor size, overload size, circuit breaker size, minimum NEMA starter size, and IEC starter size. Refer to Figure 60–17.

The conductor size is determined from the current listed in *Table 430.250* and increased by 25%.

$$180 \times 1.25 = 225 \text{ A}$$

Table 310.16 is used to determine the conductor size. Type THHN insulation is located in the 90°C column. Since the motor nameplate lists NEMA Code B, and the amperage is over 100 A, the conductor will be selected from the 75°C column. The conductor size will be 4/0 AWG.

The overload size is determined from the nameplate current and *NEC® Section 430.32(A)(1)*. The motor has a marked service factor of 1.25. The motor nameplate current will be increased by 25%.

$$175 \times 1.25 = 218.75 \text{ A}$$

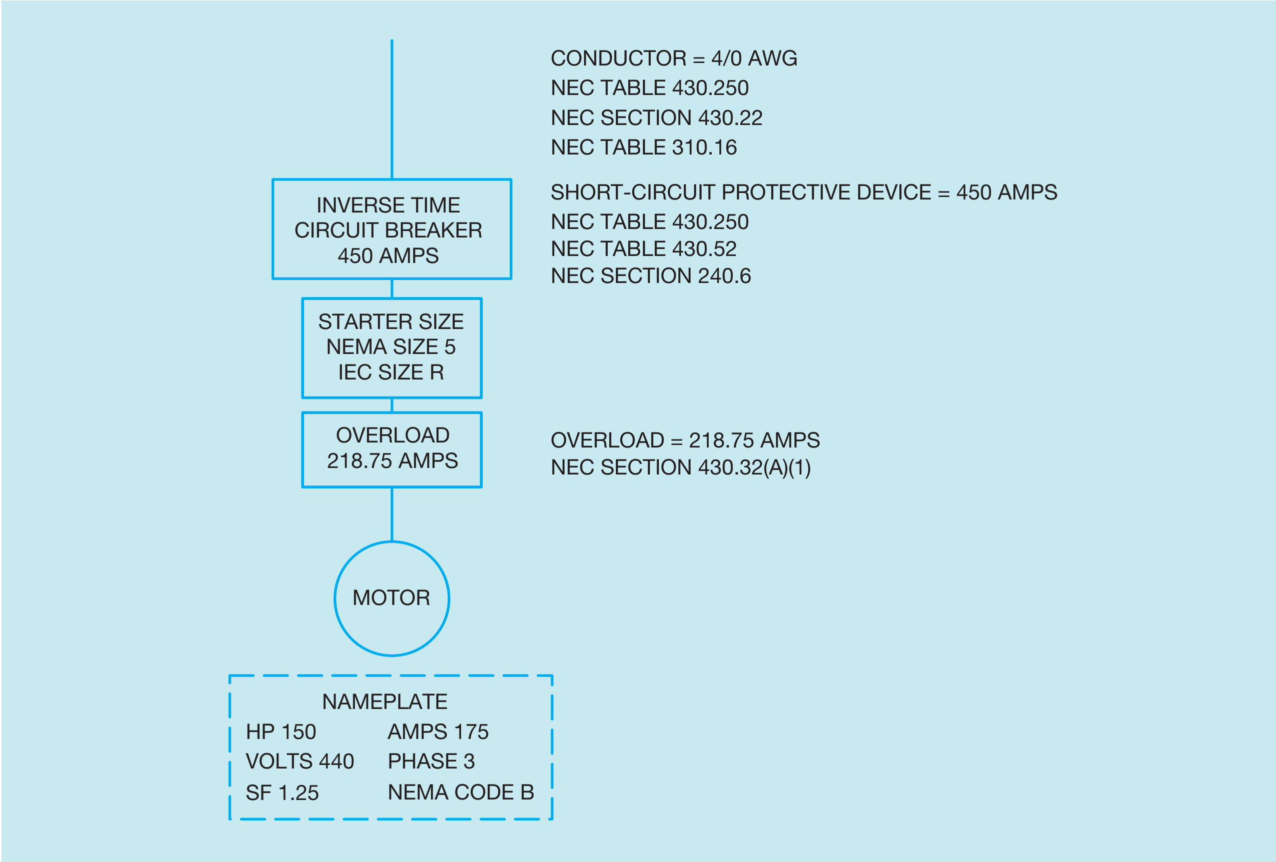


Figure 60–17 Example problem #2.

The circuit breaker size is determined by *Tables 430.250* and *430.52*. *Table 430.52* indicates a factor of 250% for squirrel cage motors with NEMA design code B. The value listed in *Table 430.250* will be increased by 250%.

$$180 \times 2.50 = 450 \text{ A}$$

One of the standard circuit breaker sizes listed in *NEC® Section 240.6* is 450 A. A 450 A inverse time circuit breaker will be used as the short-circuit protective device.

The proper motor starter sizes are selected from the NEMA and IEC charts shown in Figures 60–14 and 60–15. The minimum size NEMA starter is 5 and the minimum size IEC starter is R.

Multiple Motor Calculations

The main feeder short-circuit protective devices and conductor sizes for multiple motor connections are set forth in *NEC® Section 430.62(A)* and *430.24*. In this example, three motors are connected to a common feeder. The feeder is 480 V three-phase and the conductors are to be copper with type THHN insulation. Each motor is to be protected with dual-element time delay fuses and a separate overload device. The main feeder is also protected by dual-element time delay fuses. The termination temperature rating of the connected devices is not known. The motor nameplates state the following:

Motor #1

Phase 3	HP 20
SF 1.25	NEMA code C
Volts 480	Amperes 23
Type Induction	

Motor #2

Phase 3	HP 60
Temp. 40°C	Code J
Volts 480	Amperes 72
Type Induction	

Motor #3

Phase 3	HP 100
Code A	Volts 480
Amperes 96	PF 90%
Type Synchronous	

Motor #1 Calculation

The first step is to calculate the values for motor amperage, conductor size, overload size, short-circuit protection size, and starter size for each motor. Both NEMA and IEC starter sizes will be determined. The values for motor #1 are shown in Figure 60–18.

The ampere rating from *Table 430.250* is used to determine the conductor and the fuse size. The amperage rating must be increased by 25% for the conductor size.

$$27 \times 1.25 = 33.75 \text{ A}$$

The conductor size is chosen from *Table 310.16*. Although type THHN insulation is located in the 90°C column, the conductor size will be chosen from the 75°C column. Although the current is less than 100 A, *NEC® Section 110.14(C)(1)(d)* permits the conductors to be chosen from the 75°C column if the motor has a NEMA design code.

$$33.75 \text{ A} = \#10 \text{ AWG}$$

The overload size is computed from the nameplate current. The demand factors in *Section 430.32(A)(1)* are used for the overload calculation.

$$23 \times 1.25 = 28.75 \text{ A}$$

The fuse size is determined by using the motor current listed in *Table 430.250* and the demand factor from *Table 430.52*. The percentage of full-load current for a dual-element time delay fuse protecting a squirrel cage motor listed as design C is 175%. The current listed in *Table 430.250* will be increased by 175%.

$$27 \times 1.75 = 47.25 \text{ A}$$

The nearest standard fuse size listed in *Section 240.6* is 50 A. 50 A fuses will be used.

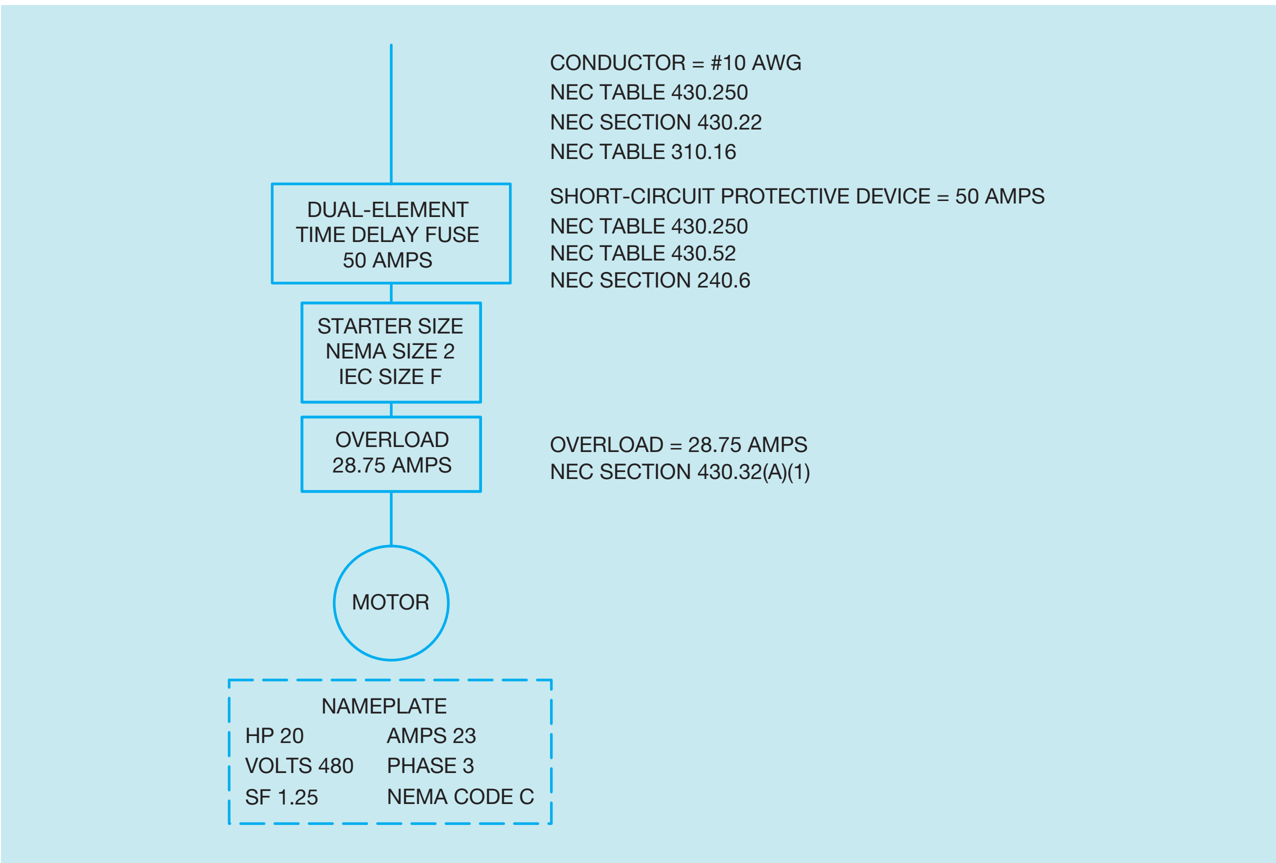


Figure 60–18 Motor #1 calculation.

The starter sizes are determined from the NEMA and IEC charts shown in Figures 60–14 and 60–15. A 20 hp motor connected to 480 V would require a NEMA size 2 starter and an IEC size F starter.

Motor #2 Calculation

Figure 60–19 shows an example of the calculation for motor #2. *Table 430.250* lists a full-load current of 77 A for this motor. This value of current is increased by 25% for the calculation of the conductor current.

$$77 \times 1.25 = 96.25 \text{ A}$$

Table 310.16 indicates a #1 AWG conductor should be used for this motor connection. The conductor size is chosen from the 60°C column because the circuit current is less than 100 A in accord with *Section 110.14(C)*, and the motor nameplate does not indicate a NEMA design code. (The code J indicates the type of bars used in the construction of the rotor.)

The overload size is determined from *Section 430.32(A)(1)*. The motor nameplate lists a temperature rise of 40°C for this motor. The nameplate current will be increased by 25%.

$$72 \times 1.25 = 90 \text{ A}$$

The fuse size is determined from *Table 430.52*. The table current is increased by 175% for squirrel cage motors other than design E.

$$771 \times 1.75 = 134.25 \text{ A}$$

The nearest standard fuse size listed in *Section 240.6* is 150 A. 150 A fuses will be used to protect this circuit.

The starter sizes are chosen from the NEMA and IEC starter charts. This motor would require a NEMA size 4 starter or a size L IEC starter.

Motor #3 Calculation

Motor #3 is a synchronous motor intended to operate with a 90% power factor. Figure 60–20 shows an

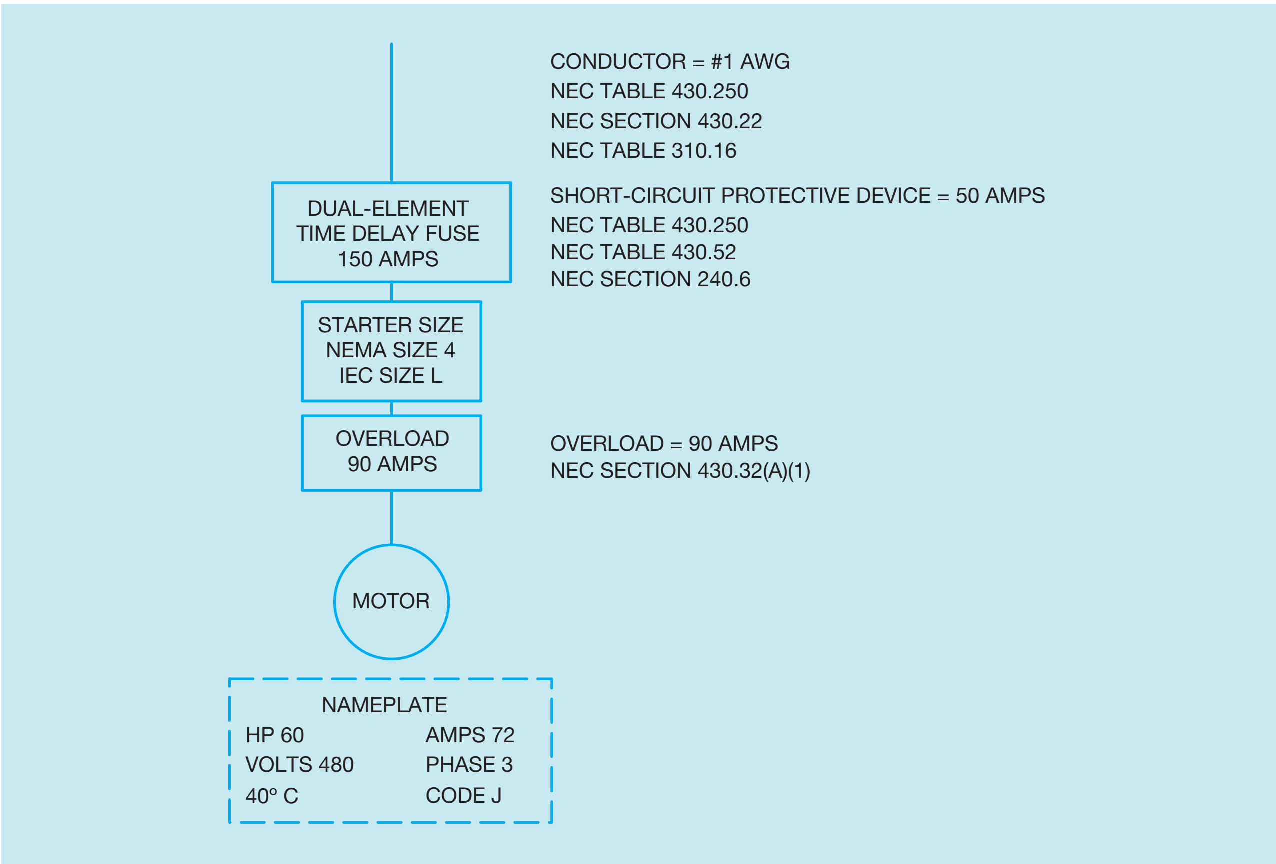


Figure 60–19 Motor #2 calculation.

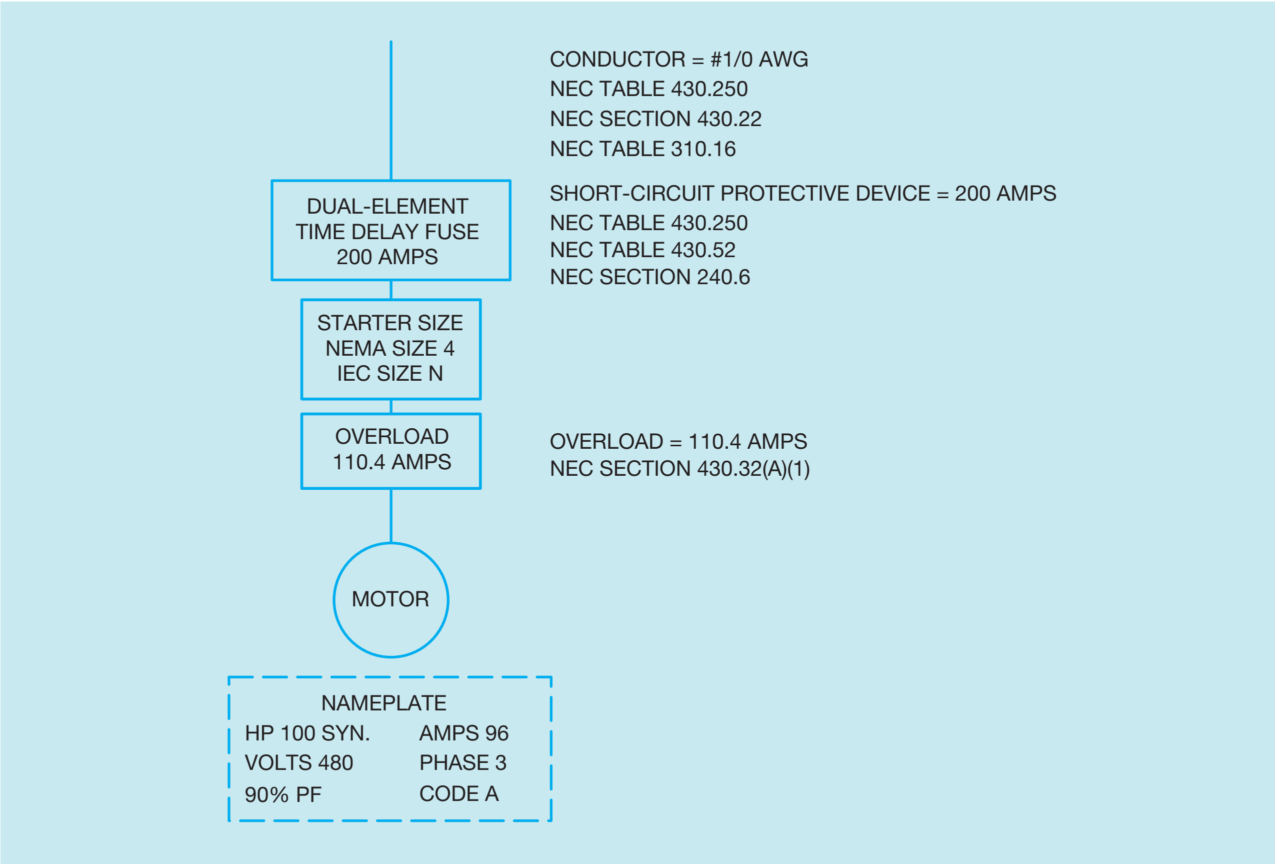


Figure 60–20 Motor #3 calculation.

example of this calculation. The notes at the bottom of *Table 430.250* indicate that the listed current is to be increased by 10% for synchronous motors with a listed power factor of 90%.

$$101 \times 1.10 = 111 \text{ A}$$

The conductor size is computed by using this current rating and increasing it by 25%.

$$111 \times 1.25 = 138.75 \text{ A}$$

Table 310.16 indicates that a #1/0 AWG conductor will be used for this circuit. Since the circuit current is over 100 A, the conductor size is chosen from the 75°C column.

This motor does not have a marked service factor or a marked temperature rise. The overload size will be calculated by increasing the nameplate current by 15% as indicated in *Section 430.32(A)(1)* under the heading ALL OTHER MOTORS.

$$96 \times 1.15 = 110.4 \text{ A}$$

The fuse size is determined from *Table 430.52*. The percent of full-load current for a synchronous motor is 175%.

$$111 \times 1.75 = 194.25 \text{ A}$$

The nearest standard size fuse listed in *Section 240.6* is 200 A. 200 A fuses will be used to protect this circuit.

The NEMA and IEC starter sizes are chosen from the charts shown in Figures 60–14 and 60–15. The motor will require a NEMA size 4 starter and an IEC size N starter.

Main Feeder Calculation

An example of the main feeder connections is shown in Figure 60–21. The conductor size is computed in accord with *NEC® Section 430.24* by increasing the largest amperage rating of the motors connected to the feeder by 25% and then adding the ampere rating of the other motors to this amount. In this example, the 100 hp synchronous motor has the largest running

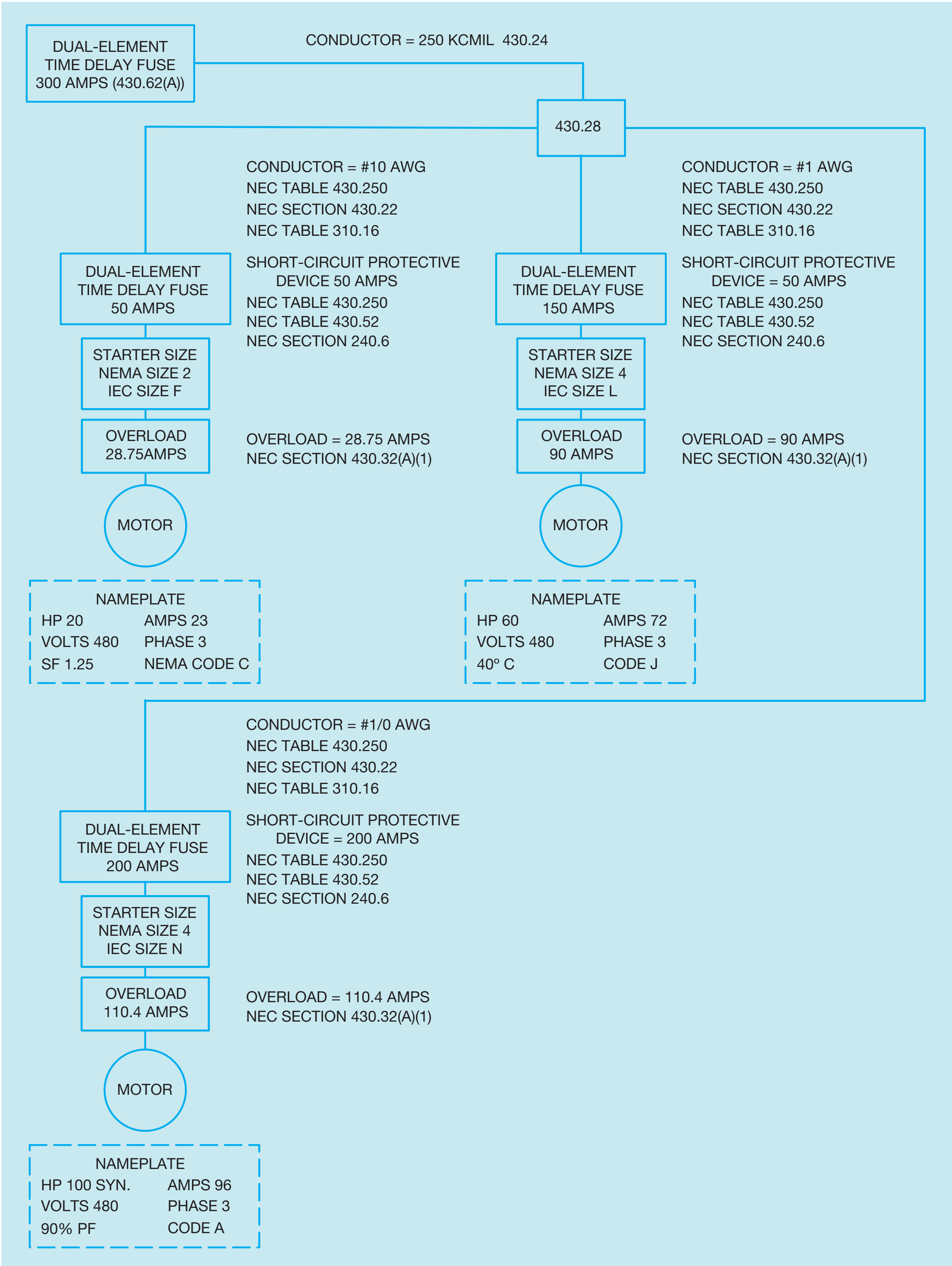

DUAL-ELEMENT TIME DELAY FUSE 300 AMPS (430.62(A))
CONDUCTOR = 250 KCMIL 430.24
430.28
CONDUCTOR = #10 AWG
NEC TABLE 430.250
NEC SECTION 430.22
NEC TABLE 310.16
DUAL-ELEMENT TIME DELAY FUSE 50 AMPS
SHORT-CIRCUIT PROTECTIVE DEVICE 50 AMPS
NEC TABLE 430.250
NEC TABLE 430.52
NEC SECTION 240.6
STARTER SIZE NEMA SIZE 2 IEC SIZE F
OVERLOAD 28.75AMPS
OVERLOAD = 28.75 AMPS
NEC SECTION 430.32(A)(1)
MOTOR
NAMEPLATE
HP 20
AMPS 23
VOLTS 480
PHASE 3
SF 1.25
NEMA CODE C
CONDUCTOR = #1 AWG
NEC TABLE 430.250
NEC SECTION 430.22
NEC TABLE 310.16
DUAL-ELEMENT TIME DELAY FUSE 150 AMPS
SHORT-CIRCUIT PROTECTIVE DEVICE = 50 AMPS
NEC TABLE 430.250
NEC TABLE 430.52
NEC SECTION 240.6
STARTER SIZE NEMA SIZE 4 IEC SIZE L
OVERLOAD 90 AMPS
OVERLOAD = 90 AMPS
NEC SECTION 430.32(A)(1)
MOTOR
NAMEPLATE
HP 60
AMPS 72
VOLTS 480
PHASE 3
40° C
CODE J
CONDUCTOR = #1/0 AWG
NEC TABLE 430.250
NEC SECTION 430.22
NEC TABLE 310.16
DUAL-ELEMENT TIME DELAY FUSE 200 AMPS
SHORT-CIRCUIT PROTECTIVE DEVICE = 200 AMPS
NEC TABLE 430.250
NEC TABLE 430.52
NEC SECTION 240.6
STARTER SIZE NEMA SIZE 4 IEC SIZE N
OVERLOAD 110.4 AMPS
OVERLOAD = 110.4 AMPS
NEC SECTION 430.32(A)(1)
MOTOR
NAMEPLATE
HP 100 SYN.
AMPS 96
VOLTS 480
PHASE 3
90% PF
CODE A

Figure 60–21

current. This current will be increased by 25% and then the running currents of the other motors as determined from *Table 430.250* will be added.

$$111 \times 1.25 = 138.75 \text{ A}$$
$$138.75 + 77 + 27 = 242.75 \text{ A}$$

Table 310.16 lists that 250 kcmil copper conductors are to be used as the main feeder conductors. The conductors were chosen from the 75°C column.

The size of the short-circuit protective device is determined by *Section 430.62(A)*. The code states that the rating or setting of the short-circuit protective device ***shall not be greater than*** the largest rating or setting of the largest branch-circuit short-circuit and ground-fault protective device for any motor supplied by the feeder, plus the sum of the full-load running currents of the other motors connected to the feeder. The largest fuse size in this example is the 100 hp synchronous motor. The fuse calculation for this motor is 200 A. The running currents of the other two motors will be added to this value to determine the fuse size for the main feeder.

$$200 + 77 + 27 = 304 \text{ A}$$

The closest standard fuse size listed in *Section 240.6* without going over 304 A is 300 A. 300 A fuses will be used to protect this circuit.

Review Questions

1. A 20 hp dc motor is connected to a 500 V dc line. What is the full-load running current of this motor?
2. What rating is used to find the full-load running current of a torque motor?
3. A ¾ hp, single-phase squirrel cage motor is connected to 240 V ac line. What is the full-load current rating of this motor and what minimum size NEMA and IEC starters should be used?
4. A 30 hp two-phase motor is connected to a 230 V ac line. What is the rated current of the phase conductors and the rated current of the neutral?
5. A 125 hp synchronous motor is connected to a 230 V three-phase ac line. The motor is intended to operate at 80% power factor. What is the full-load running current of this motor? What minimum size NEMA and IEC starters should be used to connect this motor to the line?
6. What is the full-load running current of a three-phase 50 hp motor connected to a 560 V line? What minimum size NEMA and IEC starters should be used to connect this motor to the line?
7. A 125 hp three-phase squirrel cage induction motor is connected to 560 V. The nameplate current is 115 A. It has a marked temperature rise of 40°C and a code letter J. The conductors are to be type THHN copper and they are run in conduit. The short-circuit protective device is dual-element time delay fuses. Find the conductor size, overload size, fuse size, minimum NEMA and IEC starter sizes, and the upper and lower range of starting current for this motor.
8. A 7.5 hp single-phase squirrel cage induction motor is connected to 120 V ac. The motor has a code letter of H. The nameplate current is 76 A. The conductors are copper with type TW insulation. The short-circuit protection device is a non-time delay fuse. Find the conductor size, overload size, fuse size, minimum NEMA and IEC starter sizes, and upper and lower starting currents.
9. A 75 hp three-phase, synchronous motor is connected to a 230 V line. The motor is to be operated at 80% power factor. The motor nameplate lists a full-load current of 185 A, a temperature rise of 40°C, and a code letter A. The conductors are to be made of copper and have type THHN insulation. The short-circuit protective device is to be an inverse time circuit breaker. Determine the conductor size, overload size, circuit breaker size, minimum NEMA and IEC starter sizes, and the upper and lower starting current.
10. Three motors are connected to a single branch circuit. The motors are connected to a 480 V three-phase line. Motor #1 is a 50 hp induction motor with a NEMA code B. Motor #2 is 40 hp with a

code letter of H, and motor #3 is 50 hp with a NEMA code C. Determine the conductor size needed for the branch circuit supplying these three motors. The conductors are copper with type THWN-2 insulation.

11. The short-circuit protective device supplying the motors in question #10 is an inverse time circuit breaker. What size circuit breaker should be used?
12. Five 5-hp three-phase motors with NEMA code B are connected to a 240 V line. The conductors are copper with type THWN insulation. What size conductor should be used to supply all of these motors?
13. If dual-element time delay fuses are to be used as the short-circuit protective device, what size fuses should be used to protect the circuit in question #12?
14. A 75 hp three-phase squirrel cage induction motor is connected to 480 V. The motor has a NEMA code D. What is the starting current for this motor?
15. A 20 hp three-phase squirrel cage induction motor has a NEMA code B. The motor is connected to 208 V. What is the starting current for this motor?

Section 7

MOTOR DRIVES

UNIT 61

DIRECT DRIVES AND PULLEY DRIVES

OBJECTIVES

After studying this unit, the student will be able to:

- State the advantages of direct and pulley drives.
- Install directly coupled motor drives and pulley motor drives.
- Check the alignment of the motor and machine shafts, both visually and with a dial indicator.
- Install motors and machines in the proper positions for maximum efficiency.
- Calculate pulley sizes using the equation:

$$\frac{\text{Drive revolutions per minute}}{\text{Driven revolutions per minute}} = \frac{\text{Driven Pulley Diameter}}{\text{Drive Pulley Diameter}}$$

Directly Coupled Drive Installation

The most economical speed for an electrical motor is about 1800 revolutions per minute. Most electrically driven constant speed machines, however, operate at speeds below 1800 rpm. These machines must be provided with either a high-speed motor and some form of mechanical speed reducer, or a low-speed, directly coupled motor.

Synchronous motors can be adapted for direct coupling to machines operating at speeds from 3600 rpm to about 80 rpm, with horsepower ratings ranging from 20 to 5000 and above. It has been suggested that synchronous motors are less expensive to install than squirrel cage motors if the rating exceeds one hp. However, this recommendation considers only the first cost. It does not take into account the higher efficiency and better power factor of the synchronous motor. When the motor speed matches the machine input shaft speed, a simple mechanical coupling is used, preferably a flexible coupling.

Trouble-free operation can usually be obtained by following several basic recommendations for the installation of directly coupled drives, and pulley or chain drives. First, the motor and machine must be installed

in a level position. When connecting the motor to its load, the alignment of the devices must be checked more than once from positions at right angles to each other. For example, when viewed from the side, two shafts may appear to be in line. When the same shafts are viewed from the top, as shown in Figure 61–1, it is evident that the motor shaft is at an angle to the other shaft. A dial indicator should be used to check the alignment of the motor and the driven machinery (Figure 61–2). If a dial indicator is not available, a feeler gauge may be used.

During the installation, the shafts of the motor and the driven machine must be checked to insure that they are not bent. Both machine and motor should be rotated together, just as they rotate when the machine is running, and then rechecked for alignment. After the angle of the shafts is aligned, the shafts may appear to share the same axis. However, as shown in Figure 61–3, the

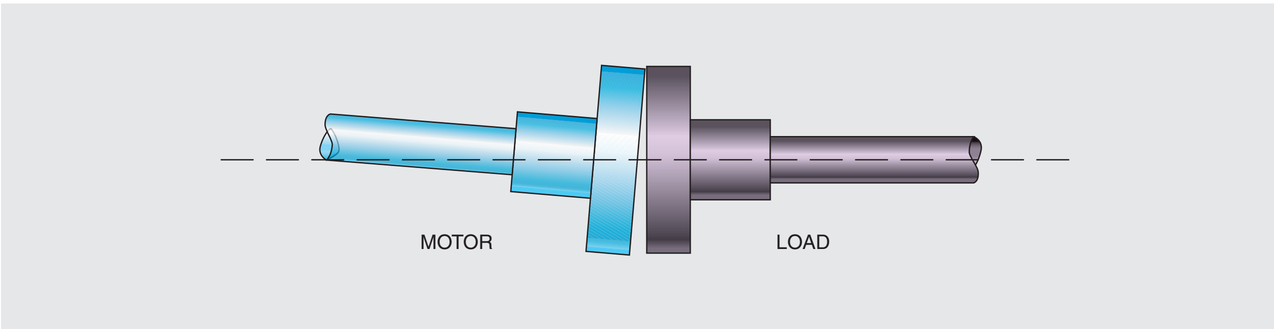


Figure 61–1 Every alignment check must be made from positions 90 degrees apart, or at right angles to each other.

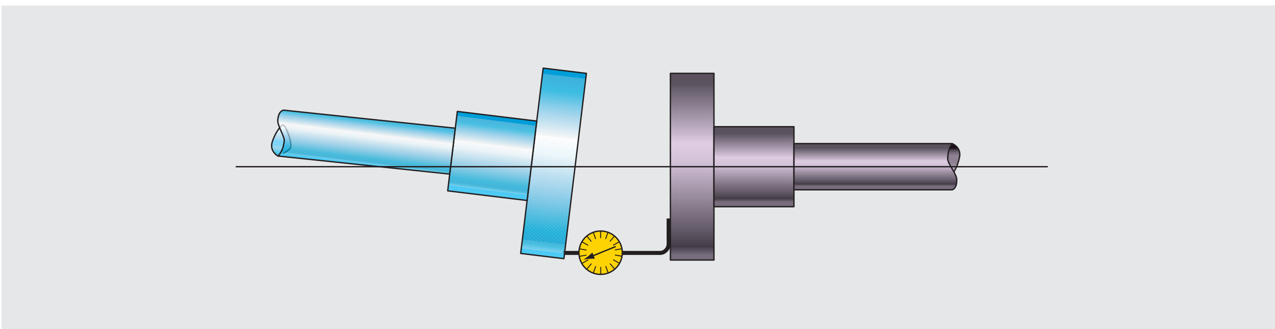


Figure 61–2 Angular check of direct motor couplings.

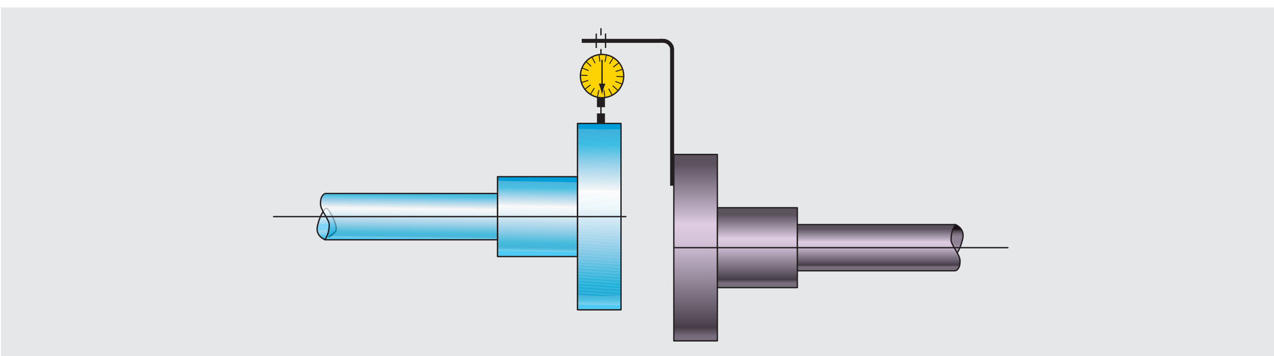


Figure 61–3 Axis alignment of direct motor couplings.

axes of the motor and the driven machine may really be off center. When viewed again from a position 90 degrees away from the original position, it can be seen that the shafts are not on the same axis.

To complete the alignment of the devices, the motor should be moved until rotation of both shafts shows that they share the same axis when viewed from four positions spaced 90 degrees apart around the shafts. The final test is to check the starting and running currents with the connected load to insure that they do not exceed specifications.

There are several disadvantages to the use of low-speed, directly coupled induction motors. They usually have a low power factor and low efficiency. Both of these characteristics increase electric power costs. Because of this, induction motors are rarely used for operation at speeds below 500 rpm.

Constant speed motors are available with a variety of speed ratings. The highest possible speed is generally selected to reduce the size, weight, and cost of the motor. At five horsepower, a 1200 rpm motor is almost 50 percent larger than an 1800 rpm motor. At 600 rpm the motor is well over twice as large as the 1800 rpm motor. In the range from 1200 rpm to 900 rpm, the size and cost disadvantages may not be overwhelming factors. Where this is true, low-speed, directly coupled motors can be used. For example, this type of motor is used on most fans, pumps, and compressors.

Pulley Drives

Installation

Flat belts, V-belts, chains, or gears are used on motors so that smooth speed changes at a constant rpm can be achieved. For speeds below 900 rpm, it is practical to use an 1800 rpm or 1200 rpm motor connected to the driven machine by a V-belt or a flat belt.

Machine shafts and bearings give long service when the power transmission devices are properly installed according to the manufacturer's instructions.

Offset drives, such as V-belts, gears, and chain drives, can be lined up more easily than direct drives. Both the motor and load shafts must be level. A straightedge can be used to insure that the motor is aligned on its axis and that it is at the proper angular position so that the pulley sheaves of the motor and the load are in line (Figure 61–4). When belts are installed, they should be tightened just enough to assure nonslip engagement. The less cross tension there is, the less wear there will be on the bearings involved. Proper and firm positioning and alignment are necessary to control the forces that cause vibration and the forces that cause thrust.

The designer of a driven machine usually determines the motor mount and the type of drive to be used. This means the installer has little choice in the motor location. In many flat belt or V-belt applications,

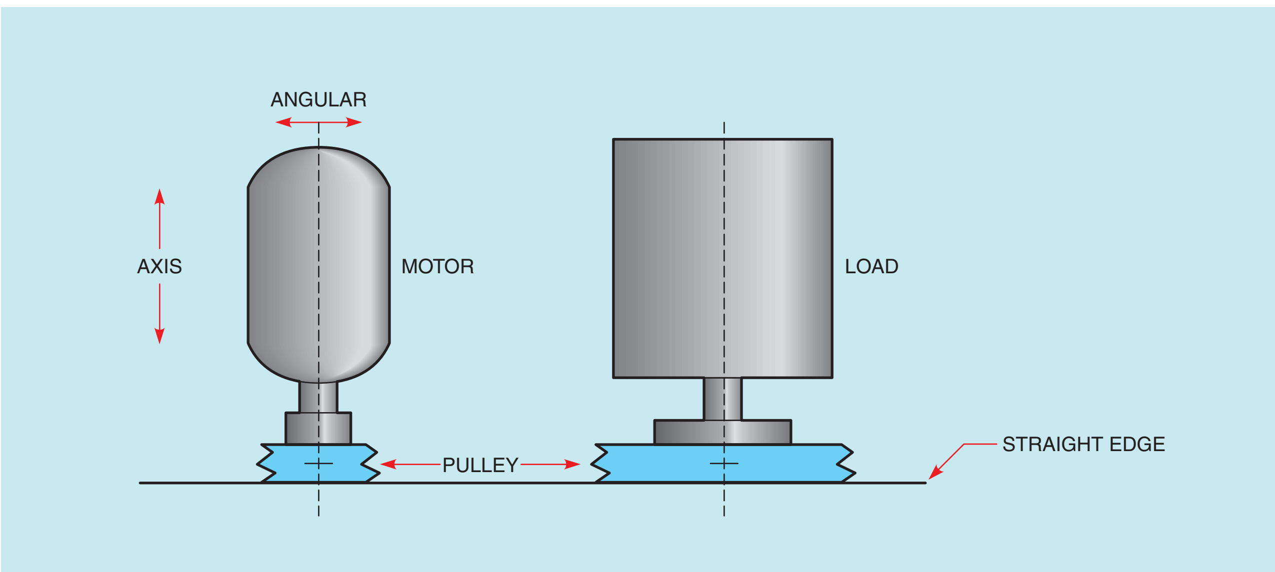


Figure 61–4 Using straightedge for angular and axis alignment.

however, the construction or maintenance electrician may be called upon to make several choices. If a choice can be made, the motor should be placed where the force of gravity helps to increase the grip of the belts. A vertical drive can cause problems because gravity tends to pull the belts away from the lower sheave (Figure 61–5). To counteract this action, the belts require far more tension than the bearings should have to withstand. The electrician should avoid this type of installation, if possible.

There are correct and incorrect placements for horizontal drives. The location where the motor is to be installed can be determined from the direction of rotation of the motor shaft. It is recommended that the motor be placed with the direction of rotation so that the belt slack is on top. In this position, the belt tends to wrap around the sheaves. This problem is less acute with V-belts than it is with flat belts or chains. Therefore, if rotation is to take place in both directions, V-belts should be used. In addition, the motor should be placed on the side of the most frequent direction of rotation (Figure 61–6).

Pulley Speeds

Motors and machines are frequently shipped without pulleys or with pulleys of incorrect sizes. The drive and driven speeds are given on the motor and machine nameplates, or in the descriptive literature accompanying the machines.

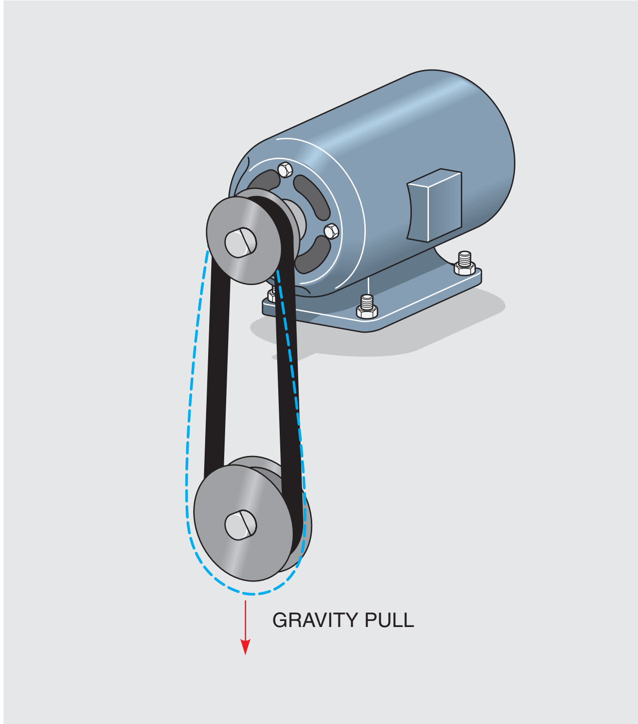


Figure 61–5 Greater belt tension is required in vertical drives where gravity opposes good belt traction. This greater tension generally exceeds that which the bearings should withstand.

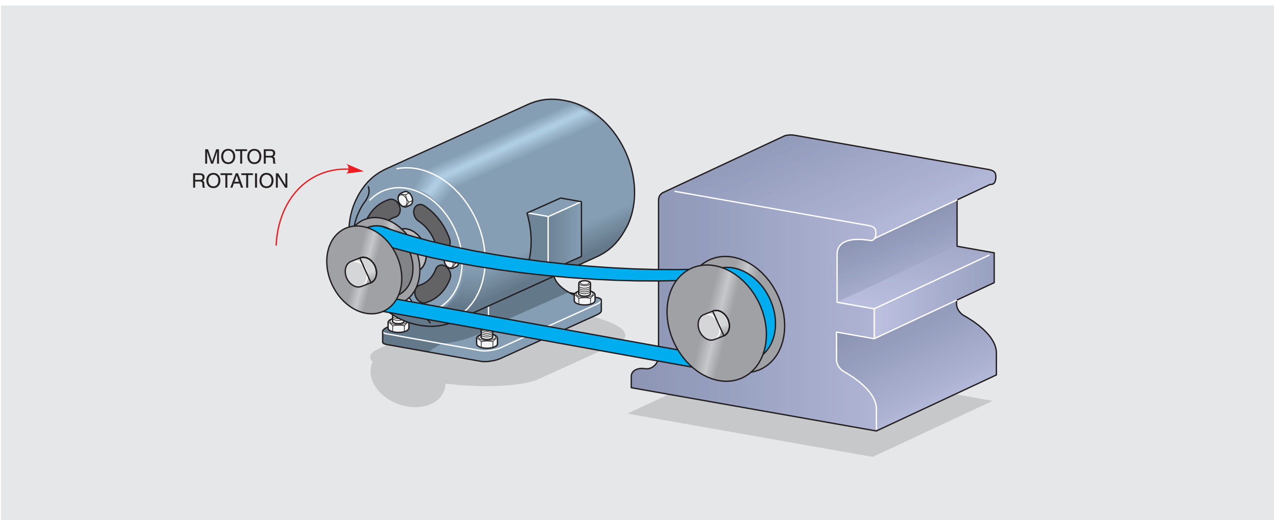


Figure 61–6 Direction of motor rotation can be used to advantage for good belt traction (with clack at top) if motor is placed in proper position.

Four quantities must be known if the machinery is to be set up with the correct pulley sizes: the drive revolutions per minute, the driven revolutions per minute, the diameter of the drive pulley, and the diameter of the driven pulley. If three of these quantities are known, the fourth quantity can be determined. For example, if a motor runs at 3600 rpm, the driven speed is 400 rpm, and there is a four-inch pulley for the motor, the size of the pulley for the driven load can be determined from the following equation.

$$\frac{\text{Drive rpm}}{\text{Driven rpm}} = \frac{\text{Driven Pulley Diameter}}{\text{Drive Pulley Diameter}}$$

$$\frac{3600}{400} = \frac{X}{4} \quad \text{or} \quad \frac{3600}{400} = \frac{X}{4}$$

By cross multiplying and then dividing, we arrive at the pulley size required:

$$4x = 144$$

$$x = \frac{144}{4} = \text{36-inch diameter pulley}$$

If both the drive and driven pulleys are missing, the problem can be solved by estimating a reasonable pulley diameter for either pulley and then using the equation with this value to find the fourth quantity.

Review Questions

1. What are the disadvantages of low-speed, directly coupled induction motors?
2. What type of ac motor can be directly coupled at low rpm with larger horsepower ratings?
3. What three alignment checks should be made to insure satisfactory and long service for directly coupled and belt-coupled power transmissions?
4. What special tools, not ordinarily carried by an electrician, are required to align a directly coupled, motor-generator set?
5. Induction motors should not be used below a certain speed (rpm). What is this speed?
6. What is the primary reason for using a pulley drive?
7. How tightly should V-belts be adjusted?
8. Refer to Figure 61–6 and assume the motor is to rotate in the opposite direction. How can the belt slack be maintained on top?
9. A machine delivered for installation has a two-inch pulley on the motor and a six-inch pulley on the load. The motor nameplate reads 180 rpm. At what speed in rpm will the driven machine rotate?

UNIT 62

DEVELOPING CONTROL CIRCUITS

OBJECTIVES

After studying this unit, the student will be able to:

- Discuss steps for developing a motor control circuit from a list of requirements.
- Draw a control circuit using a list of requirements.

There are times when it becomes necessary to develop a motor control circuit to fulfill a particular need. The idea of designing a motor control circuit may seem almost impossible, but with practice and by following a logical procedure it is generally not as difficult as it would first appear. The best method of designing a motor control circuit is to solve one requirement at a time. When one part is operating, move to the next requirement. A man was once asked, "How do you eat an elephant?" His reply was, "One bite at a time." The same is true for designing a circuit. Don't try to fulfill all the requirements at once.

The following circuits will illustrate a step-by-step procedure for designing a control circuit. Each illustration begins with a statement of the problem and the requirements for the circuit.

Developing Control Circuits

Circuit #1: Two Pump Motors

The water for a housing development is supplied by a central tank. The tank is pressurized by the water as it is filled. Two separate wells supply water to the tank, and each well has a separate pump. It is desirable that water be taken from each well equally, but it is undesirable that both pumps operate at the same time. A circuit is to be constructed that will let the pumps work alternately. Also, a separate switch must be installed that will override the automatic control and let either pump operate independently of the other in the event one pump fails. The requirements of the circuit are as follows:

1. The pump motors are operated by a 480-volt three-phase system, but the control circuit must operate on a 120-volt supply.
2. Each pump motor contains a separate overload protector. If one pump overloads, it will not prevent operation of the second pump.
3. A manual ON-OFF switch can be used to control power to the circuit.
4. A pressure switch mounted on the tank controls the operation of the pump motors. When the pressure of the tank drops to a certain level, one of the pumps will be started. When the tank has been filled with water, the pressure switch will turn the pump off. When the pressure of the tank drops low enough again, the other pump will be started and run until the pressure switch is satisfied. Each time the pressure drops to a low enough level, the alternate pump motor will be used.
5. An override switch can be used to select the operation of a particular pump, or to permit the circuit to operate automatically.

When developing a control circuit, the logic of the circuit is developed one stage at a time until the circuit operates as desired. The first stage of the circuit is shown in Figure 62–1. In this stage, a control transformer has been used to step the 480-volt supply line voltage down to 120 volts for use by the control circuit. A fuse is used as short-circuit protection for the control wiring. A manually operated ON-OFF switch permits the control circuit to be disconnected from the power source. The pressure switch must close when the pressure drops. For this reason, it will be connected as normally closed. This is a normally closed held-open switch. A set of normally closed overload contacts are connected in series with coil 1M, which will operate the motor starter of pump motor #1.

To understand the operation of this part of the circuit, assume that the manual power switch has been set to the ON position. When the tank pressure drops sufficiently, pressure switch PS will close and energize coil 1M, starting pump #1. As water fills the tank, the pressure increases. When the pressure has increased sufficiently, the pressure switch opens and disconnects coil 1M, stopping the operation of pump #1.

If pump #1 is to operate alternately with pump #2, some method must be devised to remember which pump operated last. This function will be performed by control relay CR. Since relay CR is to be used as a memory device, it must be permitted to remain energized when either or both of the motor starters are not energized. For this reason, this section of the circuit is connected to the input side of pressure switch PS. This addition to the circuit is shown in Figure 62–2.

The next stage of circuit development can be seen in Figure 62–3. In this stage of the circuit, motor starter 2M has been added. When pressure switch PS closes and energizes motor starter coil 1M, all 1M contacts change position. Contacts $1M_1$ and $1M_2$ close at the same time. When $1M_1$ contact closes, coil CR is energized, changing the position of all CR contacts. Contact CR_1 opens, but the current path to coil 1M is maintained by contact $1M_1$. Contact CR_2 is used as a holding contact around contact $1M_2$. Notice that each motor starter coil is protected by a separate overload contact. This fulfills the requirement that an overload on either motor will not prevent the operations of the other

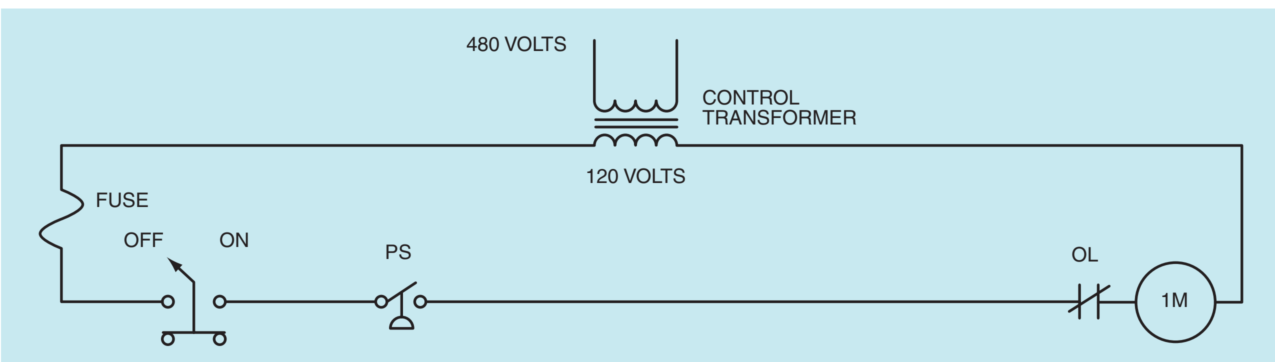


Figure 62–1 The pressure switch starts pump #1.

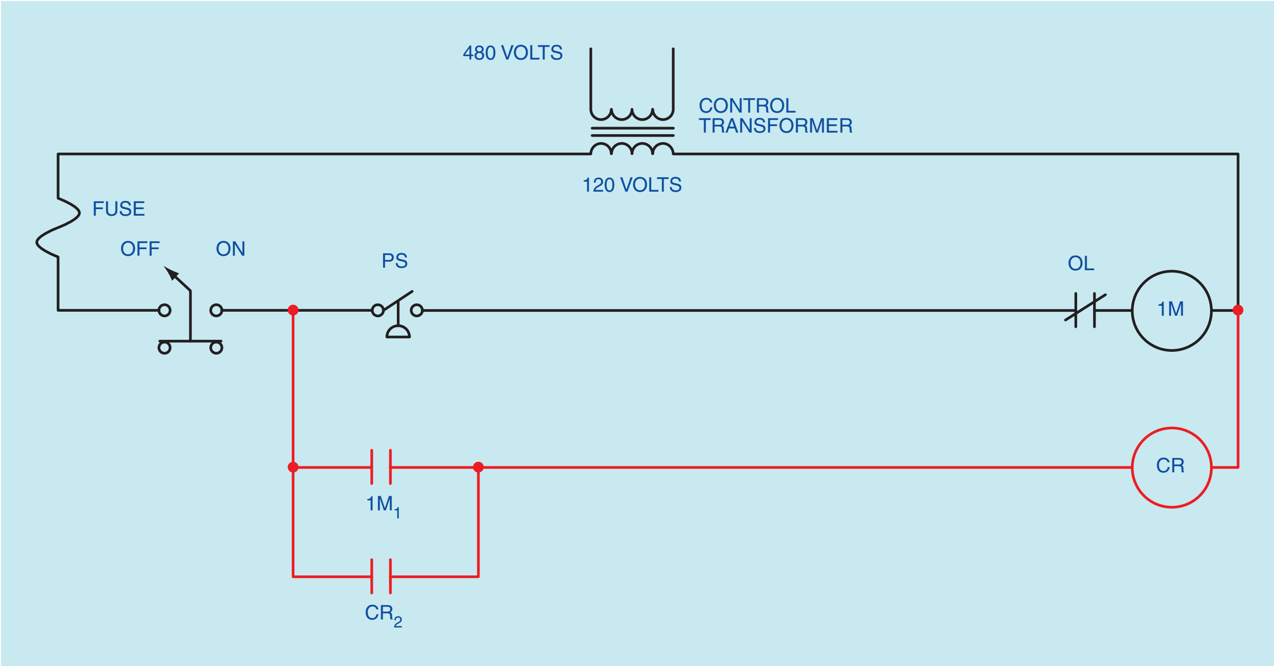


Figure 62–2 The control relay is used as a memory device.

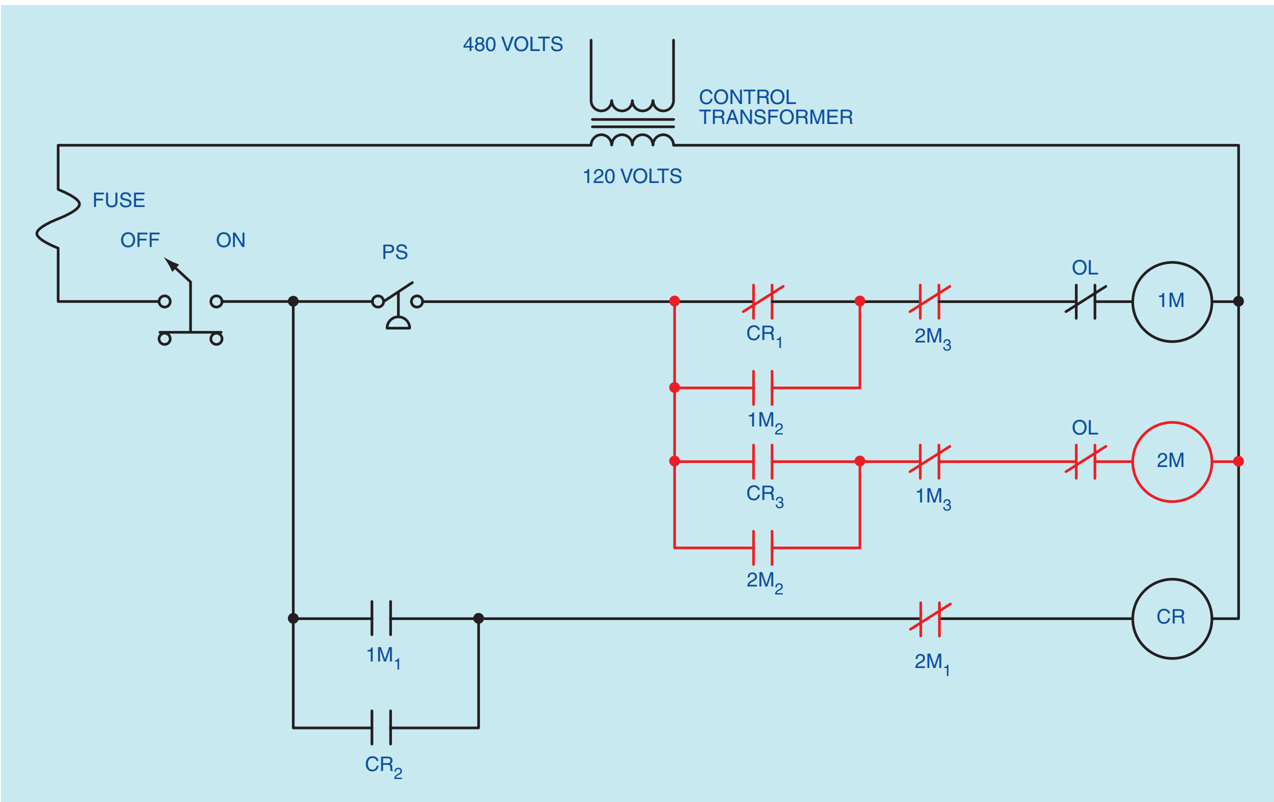


Figure 62–3 The addition of the second motor starter.

motor. Also notice that this section of the circuit has been connected to the output side of pressure switch PS. This permits the pressure switch to control the operation of both pumps.

To understand the operation of the circuit, assume pressure switch PS closes. This provides a current path to motor starter coil 1M. When coil 1M energizes, all 1M contacts change position and pump #1 starts. Contact $1M_1$ closes and energizes coil CR. Contact $1M_2$ closes to maintain a current path to coil 1M. Contact $1M_3$ opens to provide interlock with coil 2M, which prevents it from energizing whenever coil 1M is energized.

When coil CR energizes, all CR contacts change position. Contact CR_1 opens to break the circuit to coil 1M. Contact CR_2 closes to maintain a current path around contact $1M_1$, and contact CR_3 closes to provide a current path to motor starter coil 2M. Coil 2M cannot be energized, however, because of the now open $1M_3$ contact.

When the pressure switch opens, coil 1M will deenergize, permitting all 1M contacts to return to their normal positions, and the circuit will be left as shown in Figure 62–4. Note that this diagram is intended to show the condition of the circuit when the pressure switch is opened it is not intended to show the contacts in their normal deenergized position. At this point in time, a current path is maintained to control relay CR.

When pressure switch PS closes again, contact CR_1 prevents a current path from being established to coil 1M, but contact CR_3 permits a current path to be established to coil 2M. When coil 2M energizes, pump #2 starts and all 2M contacts change position.

Contact $2M_1$ opens and causes coil CR to deenergize. Contact $2M_2$ closes to maintain a circuit to coil 2M when contact CR_3 returns to its normally open position, and contact $2M_3$ opens to prevent coil 1M from being energized when contact CR_1 returns to its normally closed position. The circuit will continue to operate in this manner until pressure switch PS opens and disconnects coil 2M from the line. When this happens, all 2M contacts will return to their normal positions as shown in Figure 62–3.

The only requirement not fulfilled is a switch that permits either pump to operate independently if one pump fails. This addition to the circuit is shown in

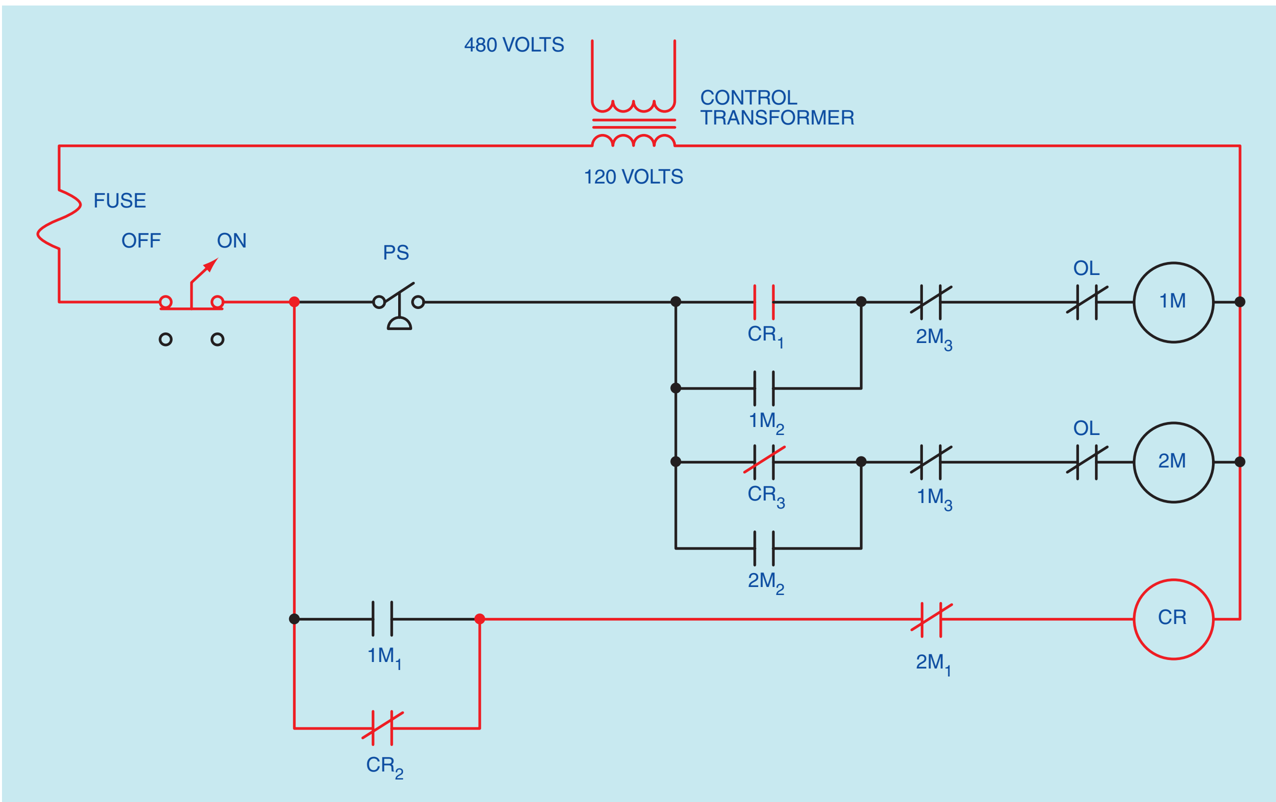


Figure 62–4 Coil CR remembers which pump operated last.

Figure 62–5. A three-position selector switch is connected to the output of the pressure switch. The selector switch will permit the circuit to alternate operation of the two pumps, or permit the operation of one pump only.

Although the logic of the circuit is now correct, there is a potential problem. After pump #1 has completed a cycle and the circuit is set as shown in Figure 62–4, there is a possibility that contact CR_3 will reopen before contact $2M_2$ closes to seal the circuit. If this happens, coil 2M will deenergize and coil 1M will be energized. This is often referred to as a contact race. To prevent this problem, an OFF DELAY timer will be added as shown in Figure 62–6. In this circuit, coil CR has been replaced by coil TR of the timer. When coil TR energizes, contact TR will close immediately, energizing coil CR. When coil TR deenergizes, contact TR will remain closed for one second before reopening and permitting coil CR to deenergize. This short delay time will ensure proper operation of the circuit.

Circuit #2: Speed Control of a Wound Rotor Induction Motor

The second circuit to be developed will control the speed of a wound rotor induction motor. The motor will have three steps of speed. Separate push buttons are used to select the speed of operation. The motor will accelerate automatically to the speed selected. For example, if second speed is selected, the motor must start in the first or lowest speed and then accelerate to second speed. If third speed is selected, the motor must start in first speed, accelerate to second speed, and then accelerate to third speed. The requirements of the circuit are as follows:

1. The motor is to operate on a 480-volt three-phase power system, but the control system is to operate on 120 volts.
2. One stop button can stop the motor regardless of which speed has been selected.

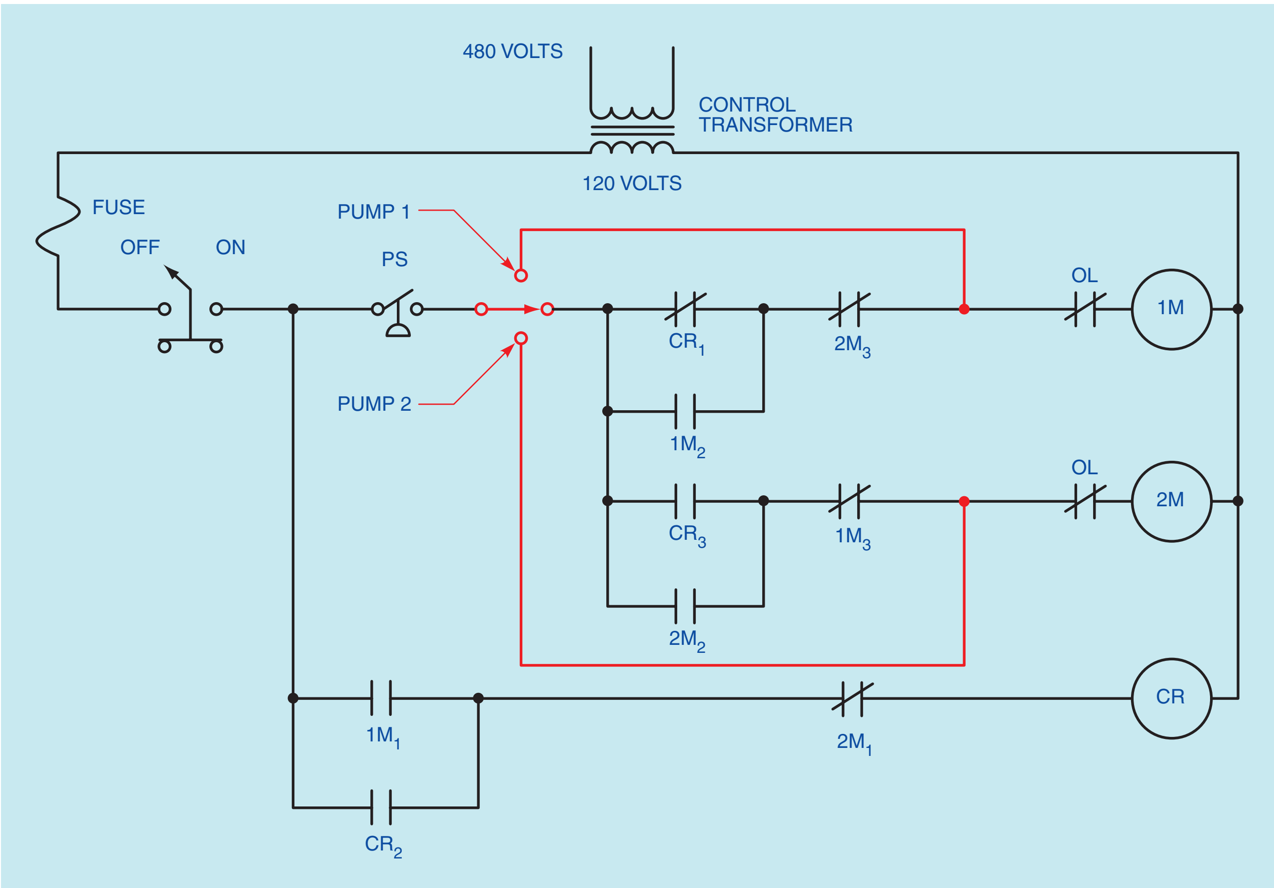


Figure 62–5 The basic logic of the circuit is complete.

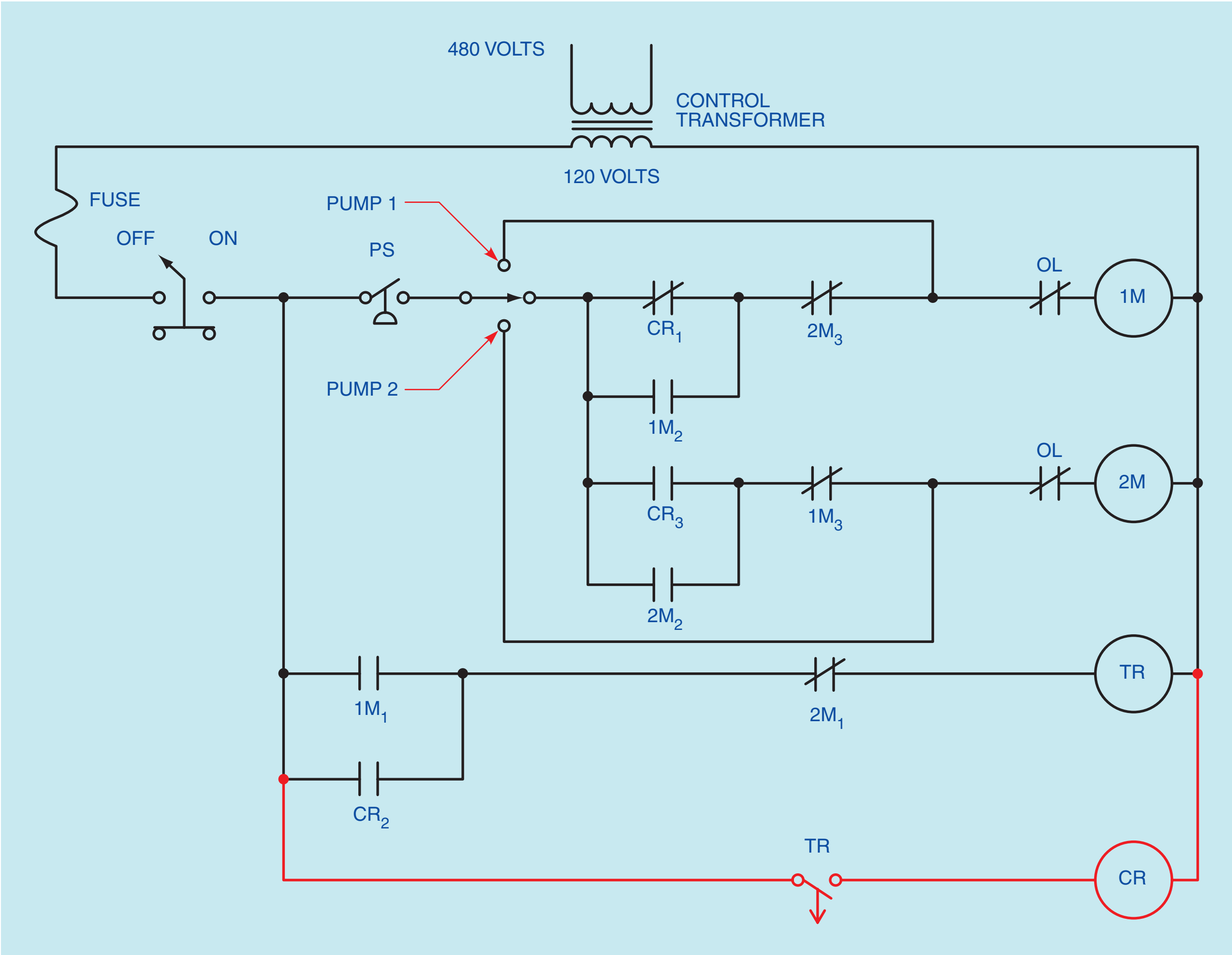


Figure 62–6 A timer is added to ensure proper operation.

3. The motor will have overload protection.

4. Three separate push buttons will select first, second, or third speed.

5. There will be a three-second time delay between accelerating from one speed to another.

6. If the motor is in operation and a higher speed is desired, it can be obtained by pushing the proper button. If the motor is operating and a lower speed is desired, the stop button must be pressed first.

Recall that speed control for a wound rotor motor is obtained by placing resistance in the secondary or rotor circuit as shown in Figure 62–7. In this circuit, load contacts 1M are used to connect the stator or primary of the motor to the power line. Two banks of three-phase resistors have been connected to the rotor. When power is applied to the stator, all resistance is connected in the rotor circuit and the motor will operate in its lowest or first speed. Second speed is obtained by closing contacts 1S and shorting out the first three-phase resistor bank. Third speed is obtained by closing contacts 2S. This shorts the rotor winding and the motor operates as a squirrel cage motor. A control transformer is connected to two of the three-phase lines to provide power for the control system.

The first speed can be obtained by connecting the circuit shown in Figure 62–8. When the FIRST SPEED button is pressed, motor starter coil 1M will close and connect the stator of the motor to the power line. Because all the resistance is in the rotor circuit, the motor

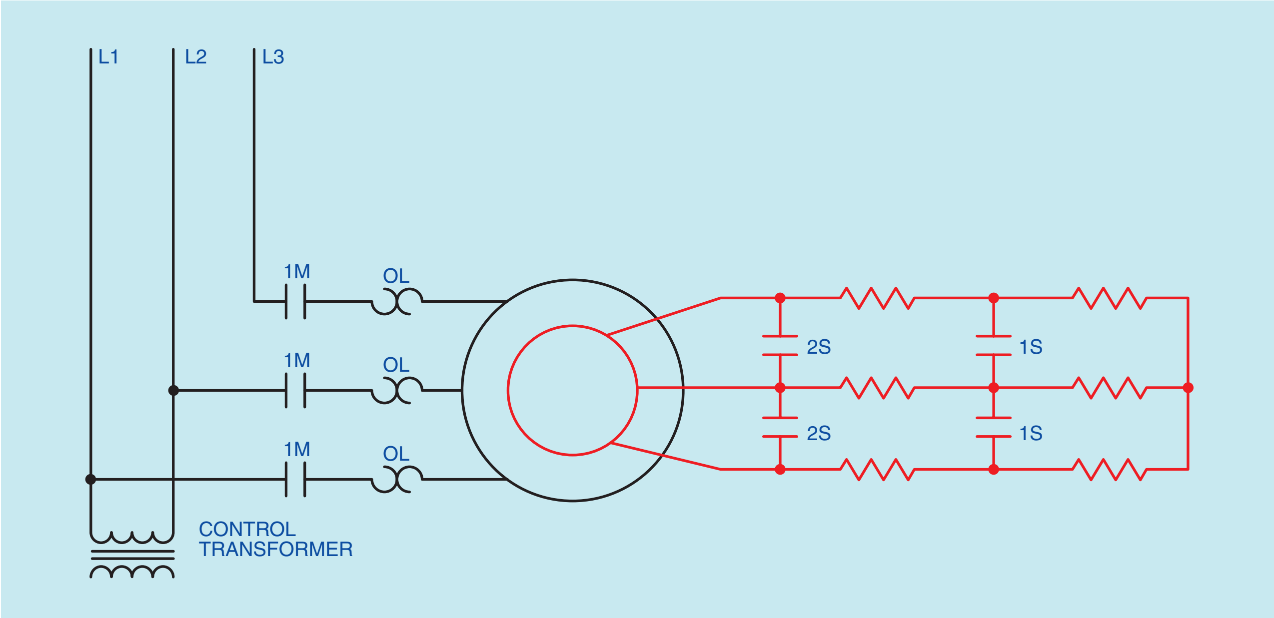


Figure 62–7 Speed is controlled by connecting resistance in the rotor circuit.

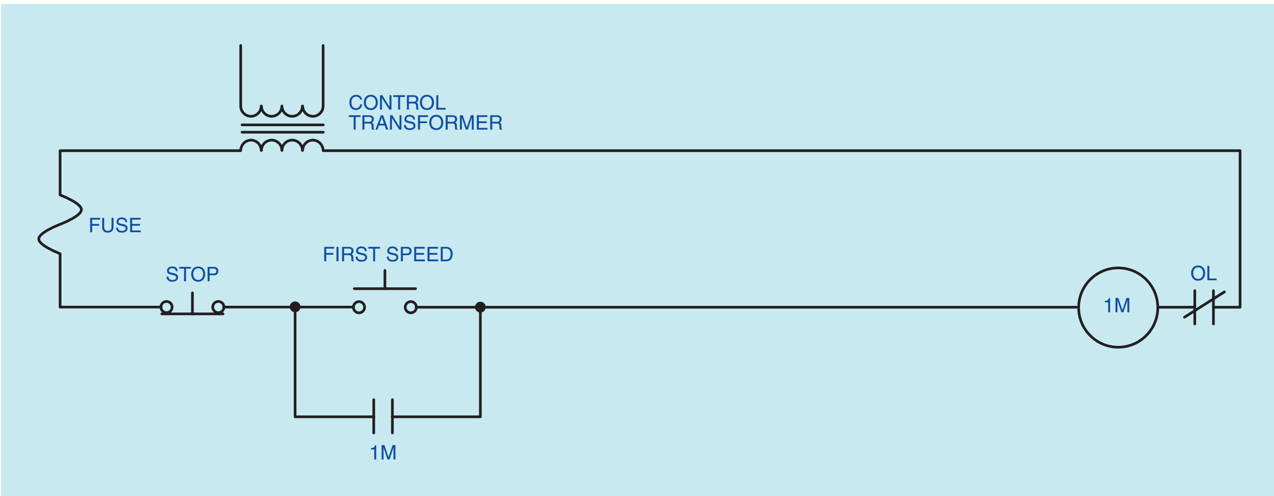


Figure 62–8 First speed.

will operate in its lowest speed. Auxiliary contact $1M_1$ is used as a holding contact. A normally closed overload contact is connected in series with coil 1M to provide overload protection. Notice that only one overload contact is shown, indicating the use of a three-phase overload relay.

The second stage of the circuit can be seen in Figure 62–9. When the SECOND SPEED button is pressed, the coil of ON delay timer 1TR is energized. Since the motor must be started in the first speed position, instantaneous timer contact $1TR_1$ closes to energize coil 1M and connect the stator of the motor to the line. Contact $1TR_2$ is used as a holding contact to keep coil 1TR energized when the SECOND SPEED button is released. Contact $1TR_3$ is a timed contact. At the end of three seconds, it will close and energize contactor coil 1S, causing all 1S contacts to close and shunt the first set of resistors. The motor now operates in second speed.

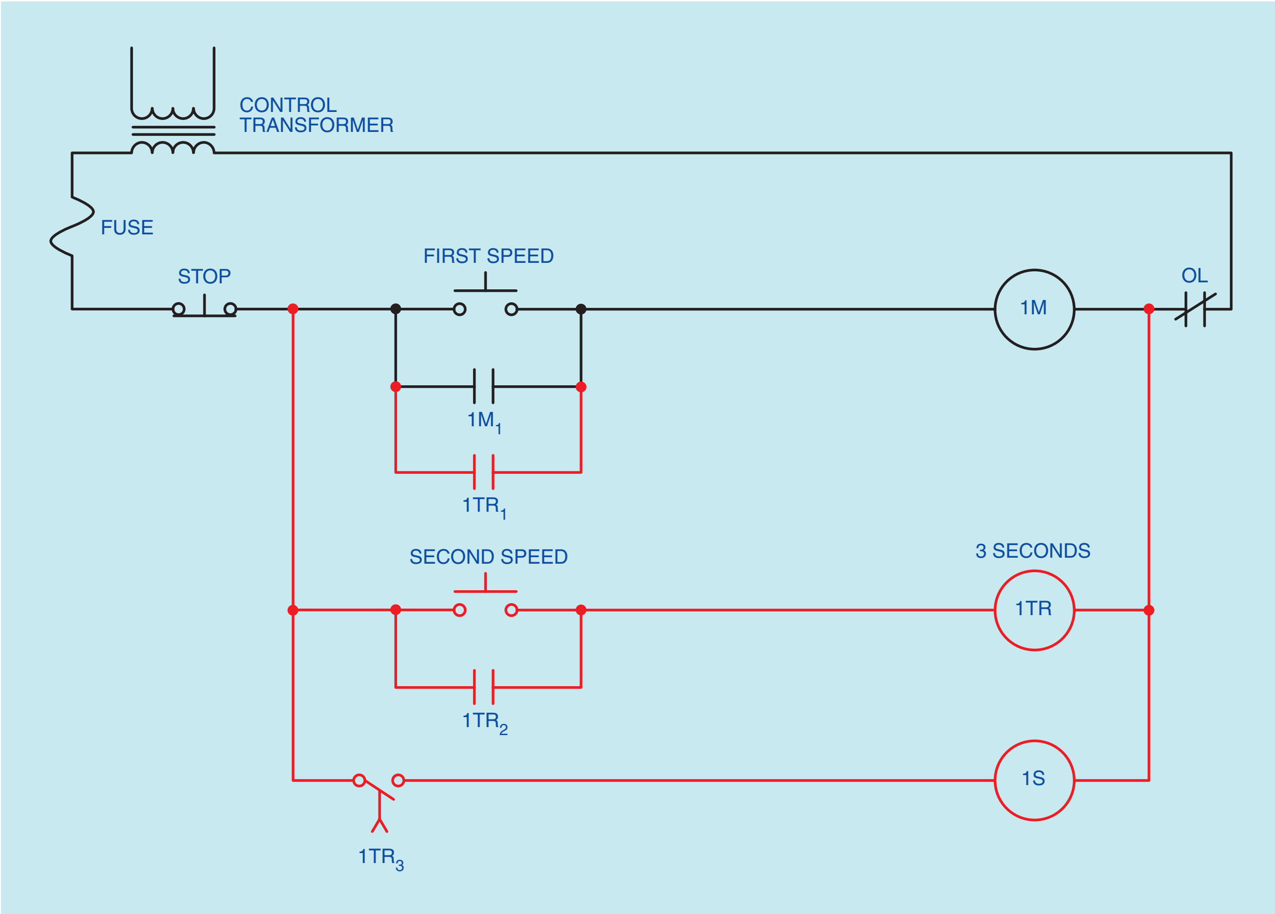


Figure 62–9 Second speed.

The final stage of the circuit is shown in Figure 62–10. The THIRD SPEED button is used to energize the coil of control relay 1CR. When coil 1CR is energized, all 1CR contacts change position. Contact $1CR_1$ closes to provide a current path to motor starter coil 1M, causing the motor to start in its lowest speed. Contact $1CR_2$ closes to provide a current path to timer 1TR. This permits timer 1TR to begin its timer operation. Contact $1CR_3$ maintains a current path to coil 1CR after the THIRD SPEED button is opened, and contact $1CR_4$ permits a current path to be established to timer 2TR. This contact is also used to prevent a current path to coil 2TR when the motor is to be operated in the second speed.

After timer 1TR has been energized for a period of three seconds, contact $1TR_3$ closes and energizes coil 1S. This permits the motor to accelerate to the second speed. Coil 1S also closes auxiliary contact $1S_1$ and completes a circuit to timer 2TR.

After a delay of three seconds, contact 2TR closes and energizes coil 2S. This causes contacts 2S to close and the motor operates in its highest speed.

Circuit #3: An Oil Heating Unit

In the circuit shown in Figure 62–11, motor starter 1M controls a motor that operates a high-pressure

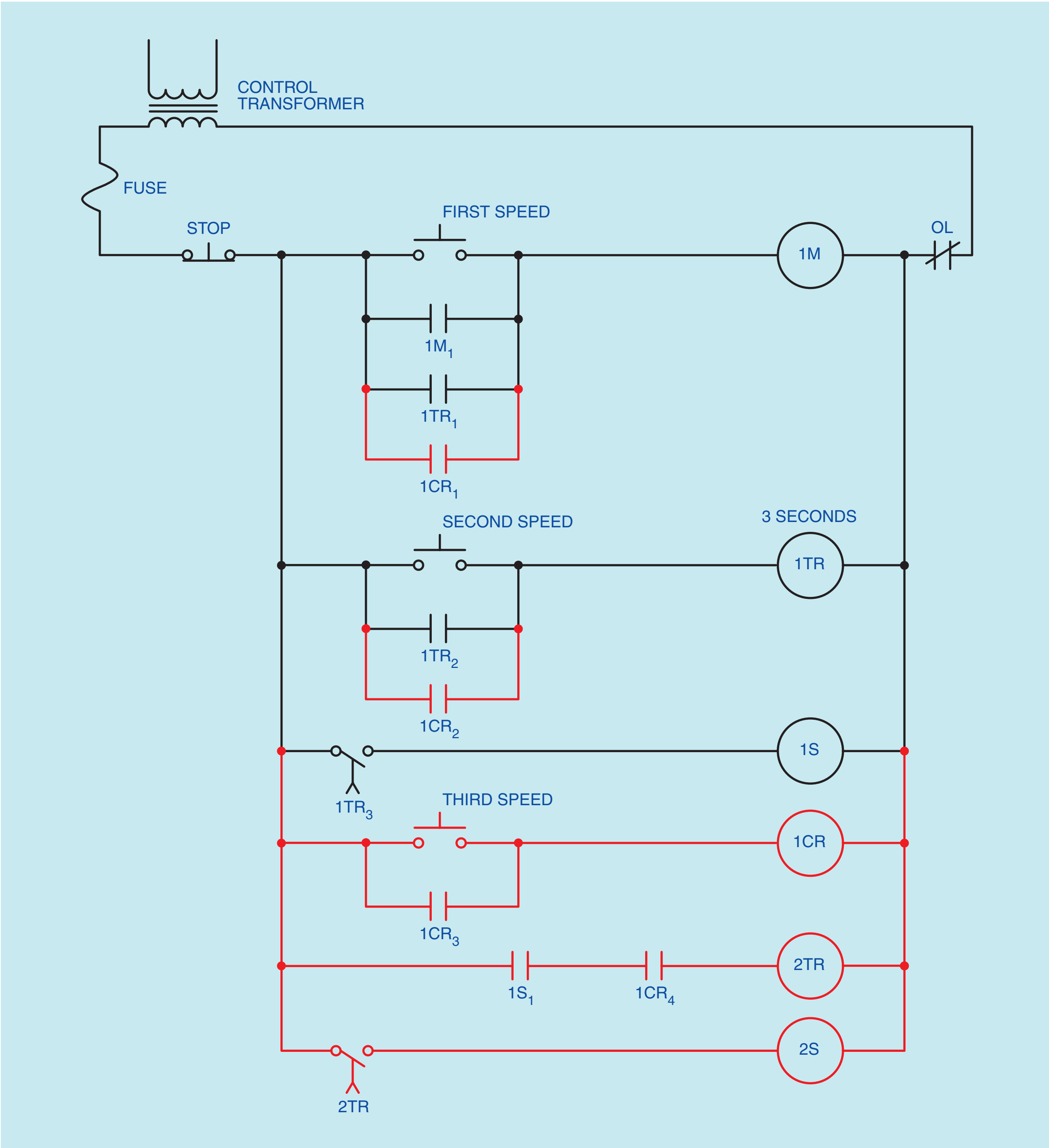


Figure 62–10 Third speed.

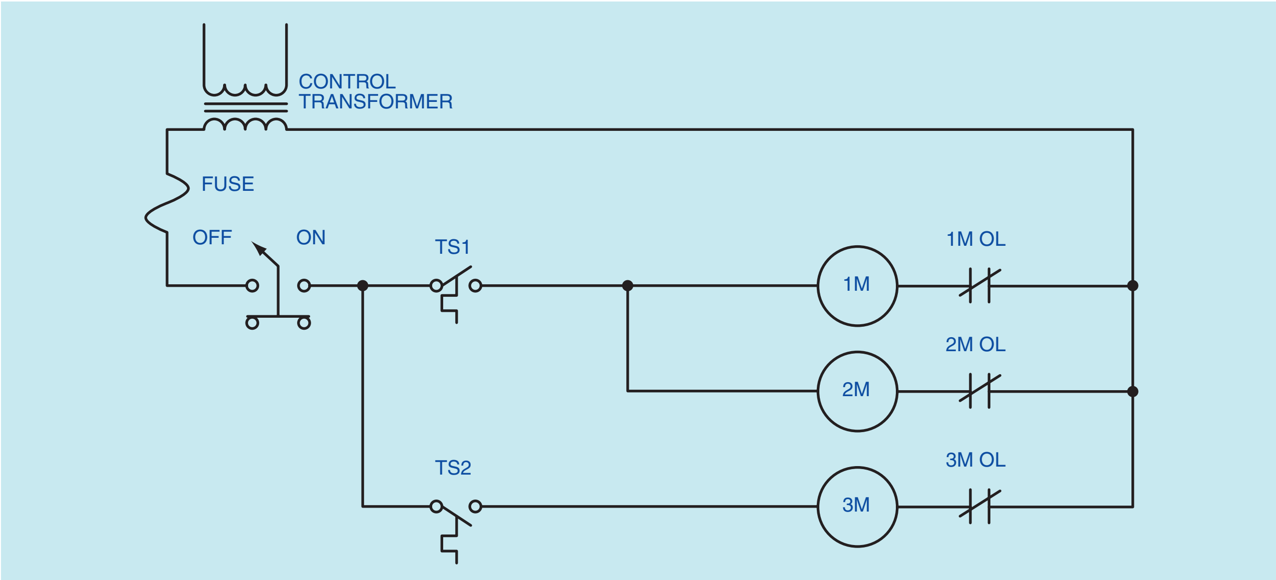


Figure 62–11 Heating system control.

pump. The pump is used to inject fuel oil into a combustion chamber where it is burned. Motor starter 2M operates an air induction blower that forces air into the combustion chamber when the oil is being burned. Motor starter 3M controls a squirrel cage blower which circulates air across a heat exchanger to heat a building. A control transformer is used to change the incoming voltage from 240 volts to 120 volts, and a separate OFF-ON switch can be used to disconnect power from the circuit. Thermostat TS1 senses temperature inside the building and thermostat TS2 is used to sense the temperature of the heat exchanger.

To understand the operation of the circuit, assume the manual OFF-ON switch is set in the ON position. When the temperature inside the building drops to a low enough level, thermostat TS1 closes and provides power to starters 1M and 2M. This permits the pump motor and air induction blower to start. When the temperature of the heat exchanger rises to a high enough level, thermostat TS2 closes and energizes starter 3M. The blower circulates the air inside the building across the heat exchanger and raises the temperature inside the building. When the building temperature rises to a high enough level, thermostat TS1 opens and disconnects the pump motor and air induction motor. The blower will continue to operate until the heat exchanger has been cooled to a low enough temperature to permit thermostat TS2 to open its contact.

After some period of operation, it is discovered that the design of this circuit can lead to some serious safety hazards. If the overload contact connected to starter 2M should open, the high-pressure pump motor will continue to operate without sufficient air being injected into the combustion chamber. Also, there is no safety switch to turn the pump motor off if the blower motor fails to provide cooling air across the heat exchanger. It is recommended that the following changes be made to the circuit:

1. If an overload occurs to the air induction motor, it will stop operation of both the high-pressure pump motor and the air induction motor.
2. An overload of the high pressure pump motor will stop only that motor and permit the air induction motor to continue operation.
3. The air induction motor will continue operating for one minute after the high-pressure pump motor has been turned off. This will clear the combustion chamber of excessive smoke and fumes.
4. A high-limit thermostat is added to the heat exchanger to turn the pump motor off if the temperature of the heat exchanger should become excessive.

These circuit changes can be seen in Figure 62–12. Thermostat TS3 is the high limit thermostat. Since it is to be used to perform the function of stop, it is normally closed and connected in series with motor starter 1M.

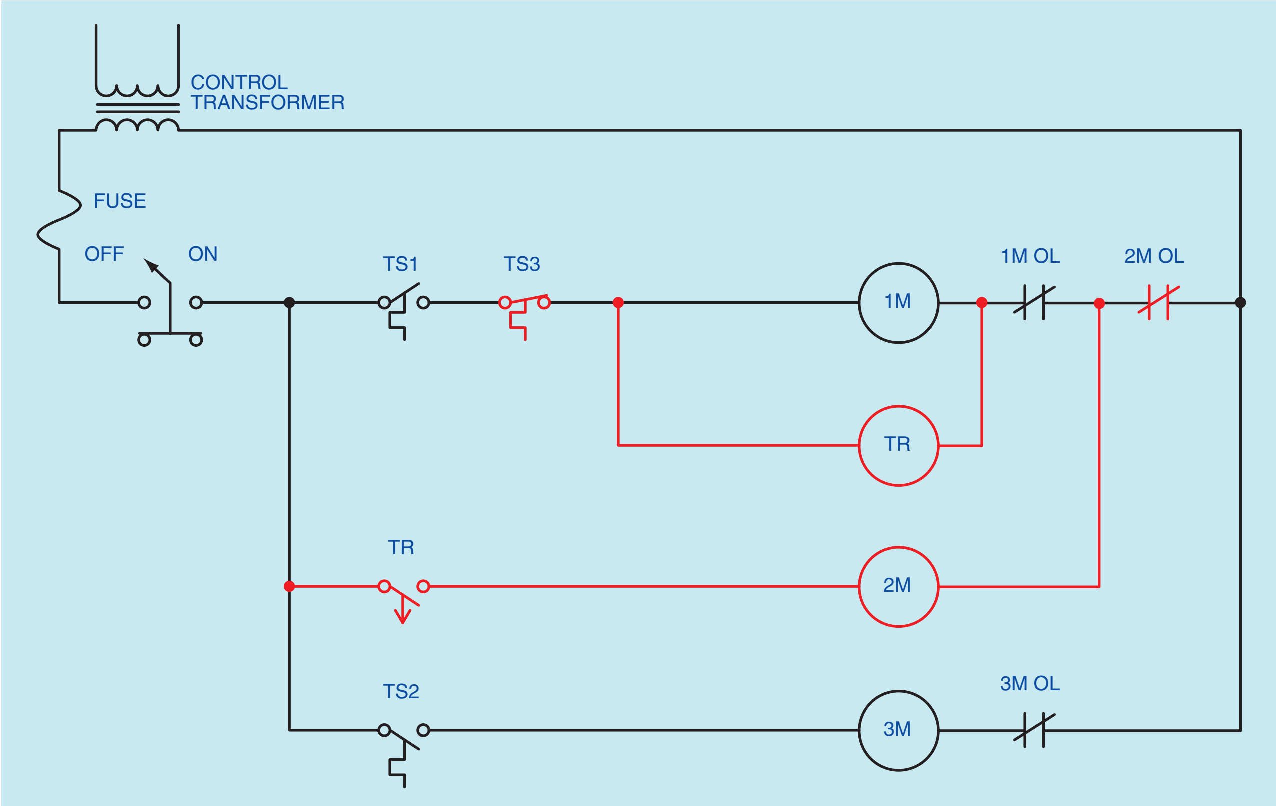


Figure 62–12 A timer is added to operate the air induction blower.

An off delay timer is used to control starter 2M, and the overload contact of starter 2M has been connected in such a manner that it can stop the operation of both the air induction blower and the high-pressure pump. Notice, however, that if 1M overload contact opens, it will not stop the operation of the air induction blower motor. The air induction blower motor would continue to operate for a period of one minute before stopping.

The logic of the circuit is as follows: When thermostat TS1 closes its contact, coils 1M and TR are energized. Because timer TR is an off delay timer, contact TR closes immediately, permitting motor starter 2M to energize. When thermostat TS1 is satisfied and reopens its contact, or if thermostat TS3 opens its contact, coils 1M and TR will deenergize. Contact TR will remain closed for a period of one minute before opening and disconnecting starter 2M from the power line.

Although the circuit in Figure 62–12 satisfies the basic circuit requirement, there is still a potential problem. If the air induction blower fails for some reason other than the overload contact opening, the high-pressure pump motor will continue to inject oil into the combustion chamber. To prevent this situation, an air-flow switch, FL1, is added to the circuit as shown in Figure 62–13. This flow switch is mounted in such a position that it can sense the movement of air produced by the air induction blower.

When thermostat contact TS1 closes, coil TR energizes and closes contact TR. This provides a circuit to motor starter 2M. When the air injection blower starts, flow switch FL1 closes its contact and permits the high-pressure pump motor to start. If the air injection blower motor stops for any reason, flow switch FL1 will disconnect motor starter 1M from the power line and stop operation of the high-pressure pump.

Although the circuit now operates as desired, the owner of the building later decides the blower should circulate air inside the building when the heating system is not in use. To satisfy this request, an AUTO-MANUAL switch is added as shown in Figure 62–14. When the switch is set in the AUTO position, it permits the blower motor to be controlled by the thermostat TS2. When the switch is set in the MANUAL position, it connects the coil of starter 3M directly to the power line and permits the blower motor to operate independently of the heating system.

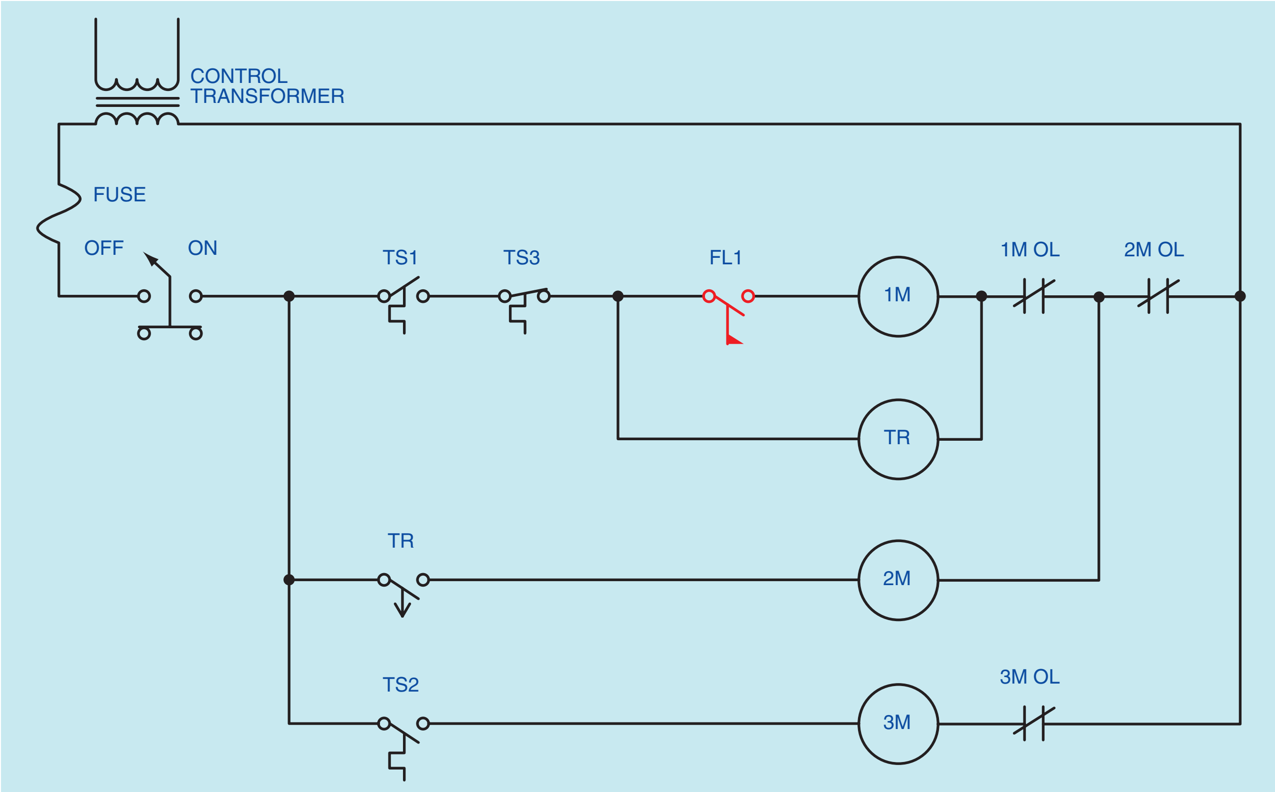


Figure 62–13 An air flow switch controls operation of the high-pressure burner motor.

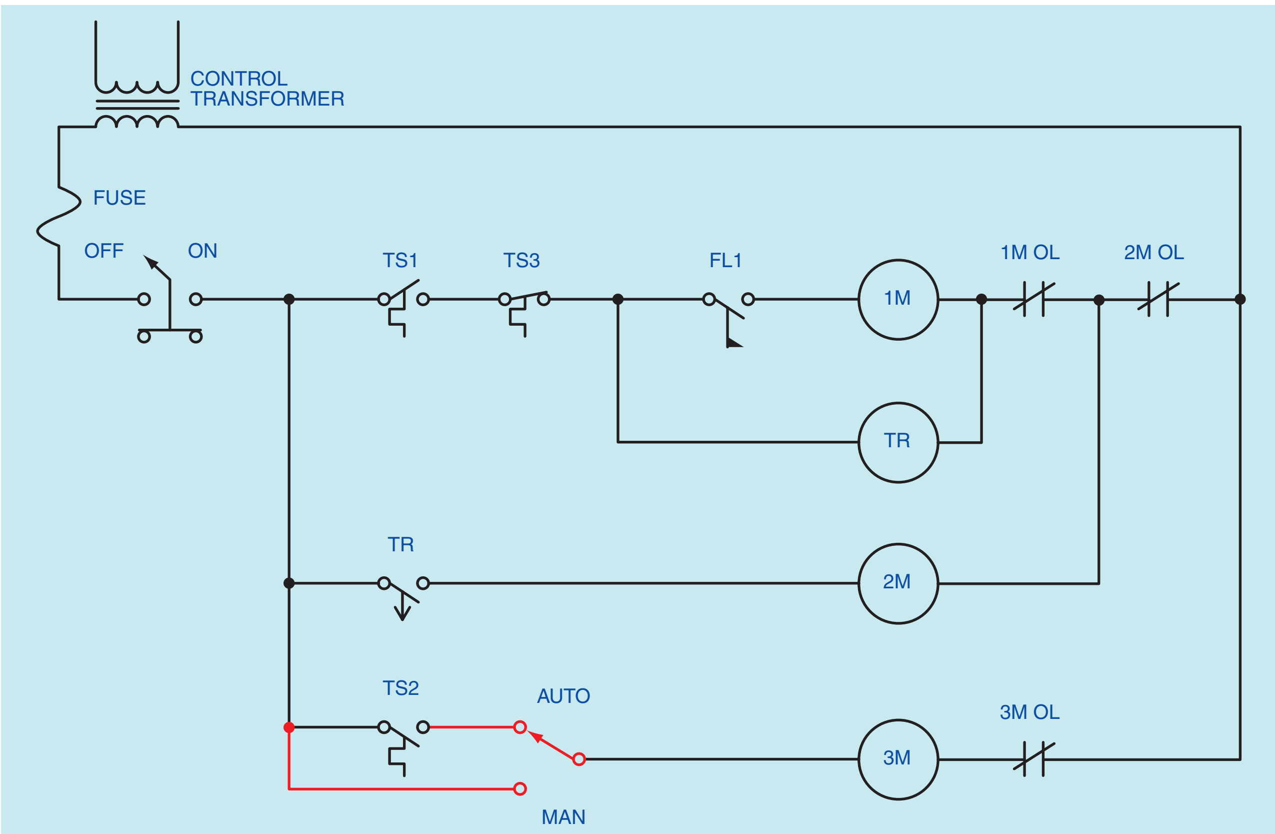


Figure 62–14 An AUTO-MANUAL switch is added to the blower motor.

Review Questions

To answer the following questions refer to the circuit in Figure 62–6

1. The pressure switch is shown as:
   a. Normally open
   b. Normally closed
   c. Normally open held closed
   d. Normally closed held open
2. When the pressure switch closes, which starter will energize first, 1M or 2M? Explain your answer.
3. Is timer TR an on-delay timer or an off-delay timer? Explain how you can determine which it is by looking at the schematic diagram.
4. What is the purpose of timer TR in this circuit?
5. What is the purpose of the rotary switch connected after the pressure switch?

To answer the following questions refer to the circuit shown in Figure 62–10

6. Is timer 1TR an on-delay or off-delay timer?
7. Assume that the THIRD SPEED push button is pressed. Explain the sequence of operation for the circuit.
8. Assume that the third speed push button is pressed and the motor starts in its first or lowest speed. After a delay of three seconds the motor accelerates to its second speed, but never accelerates to its highest or third speed. Which of the following could cause this problem?
   a. CR coil is open
   b. Coil 2TR is open
   c. Coil 1TR is open
   d. Coil 1S is open
9. Assume that both timers are set for a delay of three seconds. Now assume that coil 1S is open. If the THIRD SPEED push button is pressed, will the motor accelerate to third speed after a delay of 6 seconds? Explain your answer.
10. Assume that timer 2TR is replaced with an off-delay timer, and that both timers are set for a delay of three seconds. Explain the operation of the circuit when the THIRD SPEED push button is pressed. Also explain the operation of the circuit when the STOP button is pressed.

To answer the following questions refer to the circuit shown in Figure 62–14

11. Temperature switch TS1 is shown as:
    a. Normally open
    b. Normally closed
    c. Normally open held closed
    d. Normally closed held open
12. Temperature switch TS2 is shown as:
    a. Normally open
    b. Normally closed
    c. Normally open held closed
    d. Normally closed held open
13. Is timer TR an on-delay or off-delay timer?
14. Temperature switch TS3 is shown as:
    a. Normally open
    b. Normally closed
    c. Normally open held closed
    d. Normally closed held open
15. Assume that contact TS1 closes and the air injection blower motor starts operating, but the high pressure pump motor does not start. What could cause this problem?
    a. Temperature switch TS3 is open
    b. Coil 2M is open
    c. Flow switch FL1 is defective and did not close
    d. Coil TR is open

Section 8

SOLID-STATE MOTOR CONTROL

UNIT 63
DIGITAL LOGIC

OBJECTIVES

After studying this unit, the student will be able to:

- Discuss similarities between digital logic circuits and relay logic circuits.
- Discuss different types of digital logic circuits.
- Recognize gate symbols used for computer logic circuits.
- Recognize gate symbols used for NEMA logic circuits.
- Complete a truth table for the basic gates.

The electrician in today's industry must be familiar with solid-state digital logic circuits. Digital, of course, means a device that has only two states, ON or OFF. Most electricians have been using digital logic for many years without realizing it. Magnetic relays, for instance, are digital devices. Relays are generally considered to be single-input, multi-output devices. The coil is the input and the contacts are the output. A relay has only one coil, but it may have a large number of contacts (Figure 63–1).

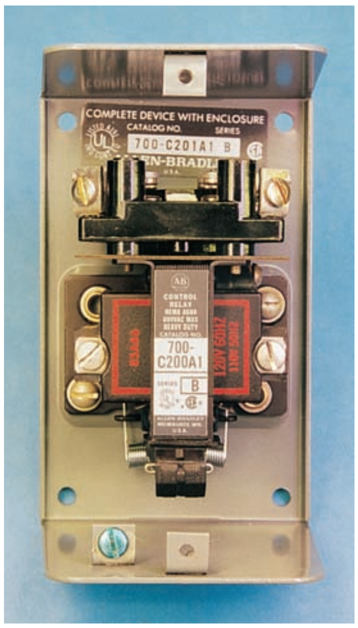


Figure 63–1 Magnetic relay.

Although relays are digital devices, the term "digital logic" has come to mean circuits that use solid state control devices known as gates. There are five basic types of gates: the AND, OR, NOR, NAND, and INVERTER. Each of these gates will be covered later in this text.

There are also different types of logic. For instance, one of the earliest types of logic to appear was *RTL,* which stands for resistor-transistor logic. This was followed by *DTL,* which stands for diode-transistor logic,

and *TTL,* which stands for transistor-transistor logic. *RTL* and *DTL* are not used much anymore, but *TTL* is still used to a fairly large extent. *TTL* can be identified because it operates on five volts.

Another type of logic frequently used in industry is *HTL,* which stands for high-transit logic. *HTL* is used because it does a better job of ignoring the voltage spikes and drops caused by the voltage spikes and drops caused by the starting and stopping of inductive devices such as motors. *HTL* generally operates on 15 volts.

Another type of logic that has become very popular is CMOS, which has very high input impedance. *CMOS comes from COSMOS which means complementary-symmetry metal-oxide-semiconductor.* The advantage of CMOS logic is that it requires very little power to operate, but there are also some disadvantages. One disadvantage is that CMOS logic is so sensitive to voltage that the static charge of a person's body can sometimes destroy an IC just by touching it. People that work with CMOS logic often use a ground strap which straps around the wrist like a bracelet. This strap is used to prevent a static charge from building up on the body.

Another characteristic of CMOS logic is that unused inputs cannot be left in an indeterminate state. Unused inputs must be connected to either a high state or a low state.

The AND Gate

While magnetic relays are single-input, multi-output devices, gate circuits are multi-input, single-output devices. For instance, an AND gate may have several inputs, but only one output. Figure 63–2 shows the USASI symbol for an AND gate with three inputs, labeled A, B, and C, and one output, labeled Y.

USASI symbols are more commonly referred to as computer logic symbols. Unfortunately for industrial electricians, there is another system known as NEMA logic which uses a completely different set of symbols. The NEMA symbol for a three-input AND gate is shown in Figure 63–3.

Although both symbols mean the same thing, they are drawn differently. Electricians working in industry must learn both sets of symbols because both types of symbols are used. Regardless of which type of symbol is used, the AND gate operates the same way. An AND gate must have all of its inputs high in order to get an output. If it is assumed that TTL logic is being used, a high level is considered to be +5 volts and a low level is considered to be 0 volts. Figure 63–4 shows the truth table for a two-input AND gate.

The truth table is used to illustrate the state of a gate's output with different conditions of input. The number one represents a high state and zero represents a low state. Notice in Figure 63–4 that the output of the AND gate is high only when both of its inputs are high. The operation of the AND gate is very similar to that of the simple relay circuit shown in Figure 63–5.

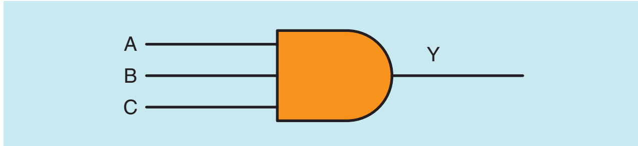


Figure 63–2 USASI symbol for a three-input AND gate.

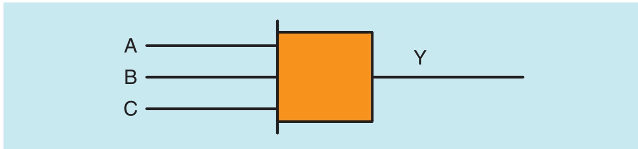


Figure 63–3 NEMA logic symbol for a three-input AND gate.

A	B	Y
0	0	0
0	1	0
1	0	0
1	1	1

Figure 63–4 Truth table for a two-input AND gate.

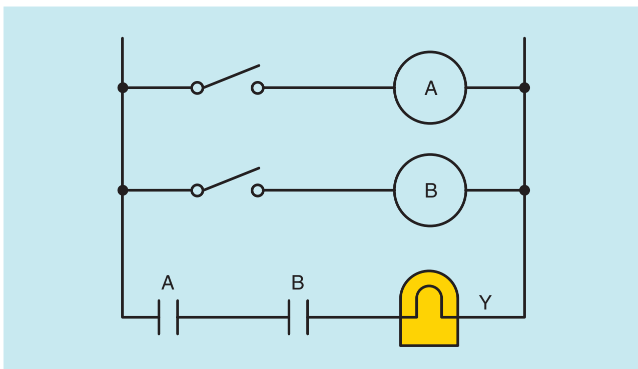


Figure 63–5 Relay equivalent circuit for a three-input AND gate.

A	B	C	Y
0	0	0	0
0	0	1	0
0	1	0	0
0	1	1	0
1	0	0	0
1	0	1	0
1	1	0	0
1	1	1	1

Figure 63–6 Truth table for a three-input AND gate.

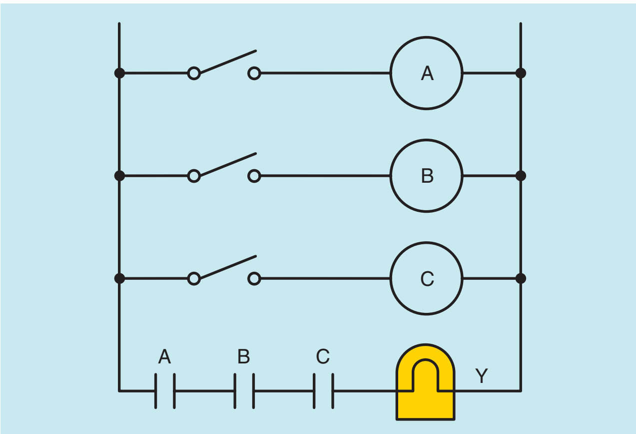


Figure 63–7 Relay equivalent circuit for a three-input AND gate.

If a lamp is used to indicate the output of the AND gate, both relay coils A and B must be energized before there can be an output. Figure 63–6 shows the truth table for a three-input AND gate. Notice that there is still only one condition that permits a high output for the gate, and that condition is when all inputs are high or at logic level one. *When using an AND gate, any zero input = a zero output.* An equivalent relay circuit for a three-input AND gate is shown in Figure 63–7.

The OR Gate

The computer logic symbol and the NEMA logic symbol for the OR gate are shown in Figure 63–8. The OR gate has a high output when either or both of its inputs are high. Refer to the truth table shown in Figure 63–9. *An easy way to remember how an OR gate functions is to say that any one input = a one output.* An equivalent relay circuit for the OR gate is shown in Figure 63–10. Notice in this circuit that if either or both of the relays are energized, there will be an output at Y.

Another gate which is very similar to the OR gate is known as an EXCLUSIVE OR gate. The symbol for an EXCLUSIVE OR gate is shown in Figure 63–11. The EXCLUSIVE OR gate has a high output when either, but not both, of its inputs are high. Refer to the truth table shown in Figure 63–12. An equivalent relay circuit for the EXCLUSIVE OR gate is shown in Figure 63–13. Notice that if both relays are energized or de-energized at the same time, there is no output.

The INVERTER

The simplest of all the gates is the INVERTER. The INVERTER has one input and one output. As its name implies, *the output is inverted, or the opposite of the input.* For example, if the input is high, the output is low, or if the input is low, the output is high. Figure 63–14 shows the computer logic and NEMA symbols for an INVERTER.

In computer logic, a circle drawn on a gate means to invert. Since the "O" appears on the output end of the gate, it means the output is inverted. In NEMA logic an

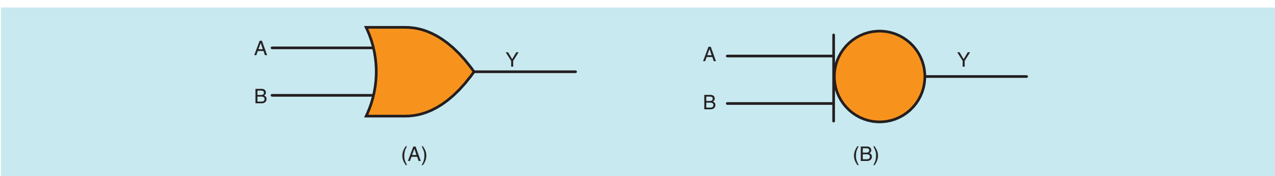


Figure 63–8 (A) Computer logic symbol for an OR gate; (B) NEMA logic symbol for an OR gate.

A	B	Y
0	0	0
0	1	1
1	0	1
1	1	1

Figure 63–9 Truth table for a two-input OR gate.

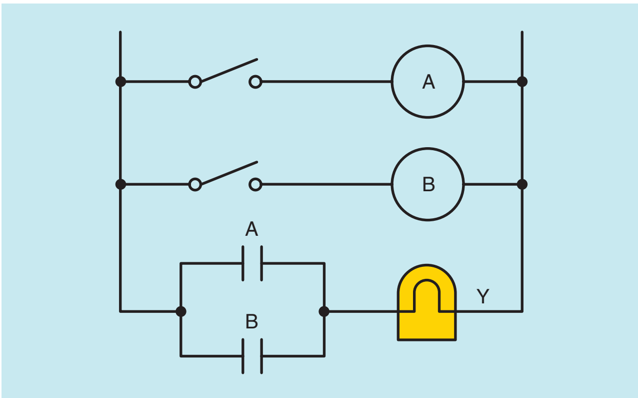


Figure 63–10

X is used to show that a gate is inverted. The truth table for an INVERTER is shown in Figure 63–15. The truth table clearly shows that the output of the INVERTER is the opposite of the input. Figure 63–16 shows an equivalent relay circuit for the INVERTER.

The NOR Gate

The NOR gate is the "NOT OR" gate. Referring to the computer logic and NEMA logic symbols for a NOR gate in Figure 63–17, notice that the symbol for the

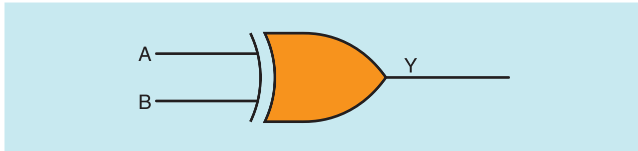


Figure 63–11

A	B	Y
0	0	0
0	1	1
1	0	1
1	1	0

Figure 63–12 Truth table for an EXCLUSIVE OR gate.

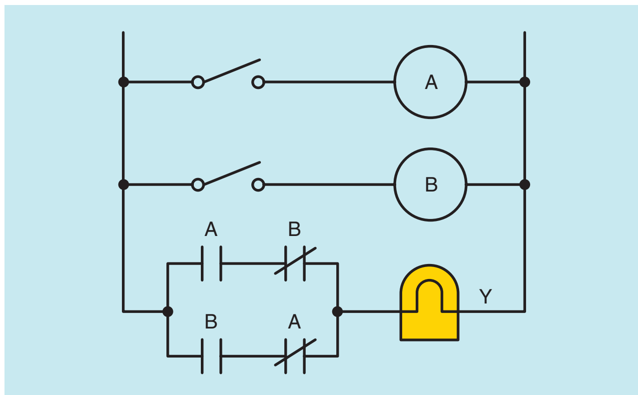


Figure 63–13 Equivalent relay circuit for an EXCLUSIVE OR gate.

NOR gate is the same as the symbol for the OR gate with an inverted output. A NOR gate can be made by connecting an INVERTER to the output of an OR gate as shown in Figure 63–18.

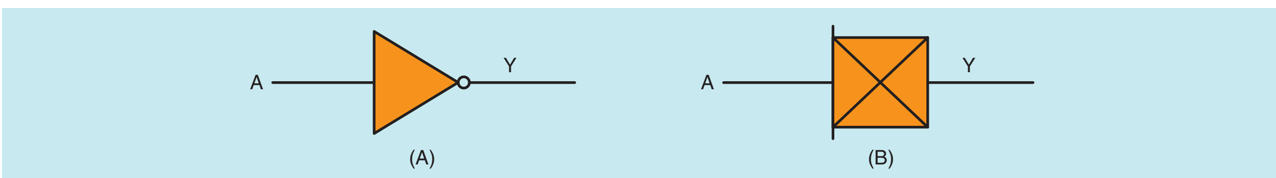


Figure 63–14 (A) Computer logic symbol for an INVERTER; (B) NEMA logic symbol for an INVERTER.

A	Y
0	1
1	0

Figure 63–15 Truth table for an INVERTER.

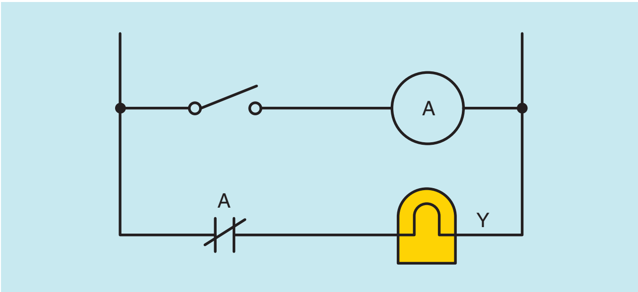


Figure 63–16 Equivalent relay circuit for an INVERTER.

The truth table shown in Figure 63–19 shows that the output of a NOR gate is zero, or low. when any input is high. Therefore, it could be said that *any one input = a zero output for the NOR gate.* An equivalent relay circuit for the NOR gate is shown in Figure 63–20. Notice in Figure 63–20 that if either relay A or B is energized, there is no output at Y.

The NAND Gate

The NAND gate is the "NOT AND" gate. Figure 63–21 shows the computer logic symbol and the NEMA logic symbol for the NAND gate. Notice that these symbols are the same as the symbols for the AND gate with inverted outputs. If any input of a NAND gate is low, the output is high. Refer to the truth table in Figure 63–22. Notice that the truth table clearly indicates that *any zero input = a one output.* Figure 63–23 shows an equivalent relay circuit for the NAND gate. If either relay A or relay B is de-energized, there is an output at Y.

The NAND gate is often referred to as the basic gate because it can be used to make any of the other gates. For instance, Figure 63–24 shows the NAND gate connected to make an INVERTER. If a NAND gate is used as an INVERTER and is connected to the output of another NAND gate, it will become an AND gate as shown in Figure 63–25. When two NAND gates are connected as INVERTERS, and these INVERTERS are connected to the inputs of another NAND gate, an OR gate is formed (Figure 63–26). If an INVERTER is added to the output of the OR gate shown in Figure 63–26, a NOR gate is formed (Figure 63–27).

Integrated Circuits

Digital logic gates are generally housed in 14-pin, IC packages. One of the old reliable types of TTL logic which is frequently used is the 7400 family of devices. For instance, a 7400 IC is a quad, two-input, positive NAND gate. The word quad means that there are four NAND gates contained in the package. Each NAND gate has two inputs, and positive means that a level one is considered to be a positive voltage.

There can, however, be a difference in the way ICs are connected. A 7400 (J or N) IC has a different pin connection than a 7400 (W) package. In Figure 63–28, both ICs contain four two-input NAND gates, but the pin connections are different. For this reason, it is necessary to use a connection diagram when connecting or testing integrated circuits. A 14-pin IC is shown in Figure 63–29.

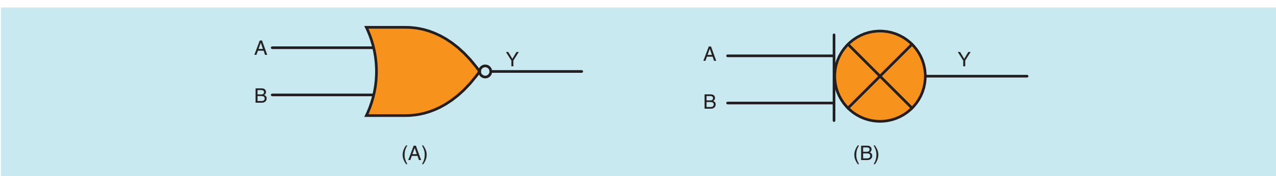


Figure 63–17 (A) Computer symbol for a two-input NOR gate; (B) NEMA logic symbol for a two-input NOR gate.

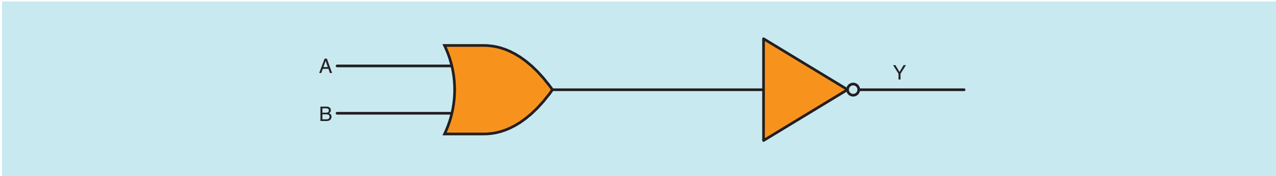


Figure 63–18 Equivalent NOR gate.

A	B	Y
0	0	1
0	1	0
1	0	0
1	1	0

Figure 63–19 Truth table for a two-input NOR gate.

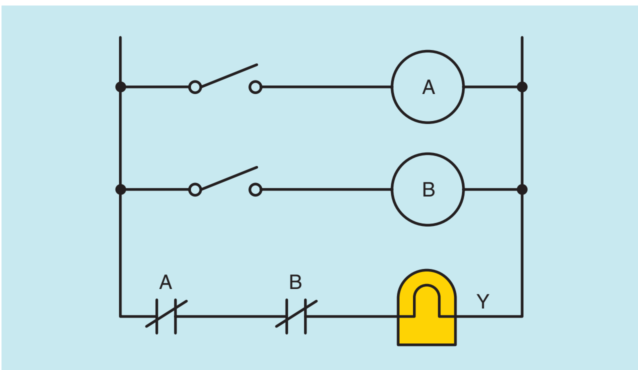


Figure 63–20 Equivalent relay circuit for a two-input NOR gate.

A	B	Y
0	0	1
0	1	1
1	0	1
1	1	0

Figure 63–22 Truth table for a two-input NAND gate.

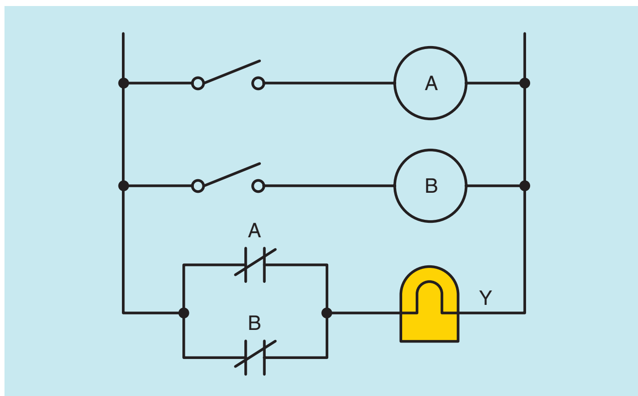


Figure 63–23 Equivalent relay circuit for a two-input NAND gate.

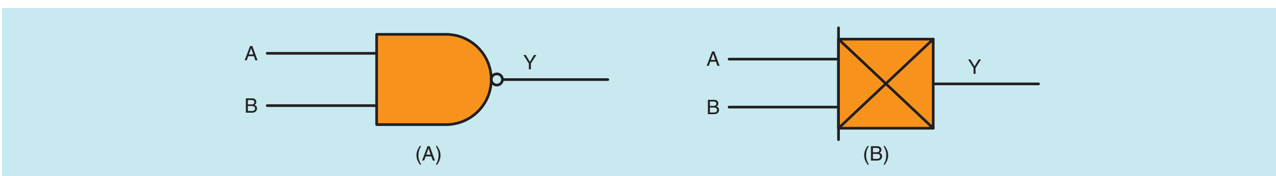


Figure 63–21 (A) Computer logic symbol for a two-input NAND gate (B) NEMA logic symbol for a two-input NAND gate.

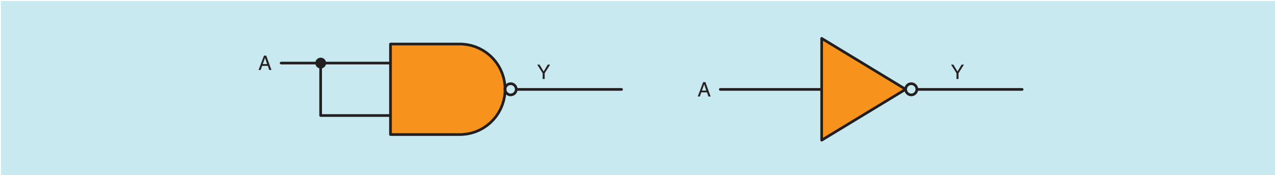


Figure 63–24 NAND gate connected as an INVERTER.

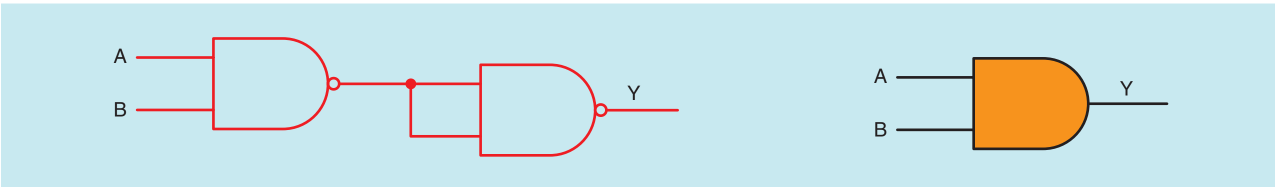


Figure 63–25 NAND gates connected as an AND gate.

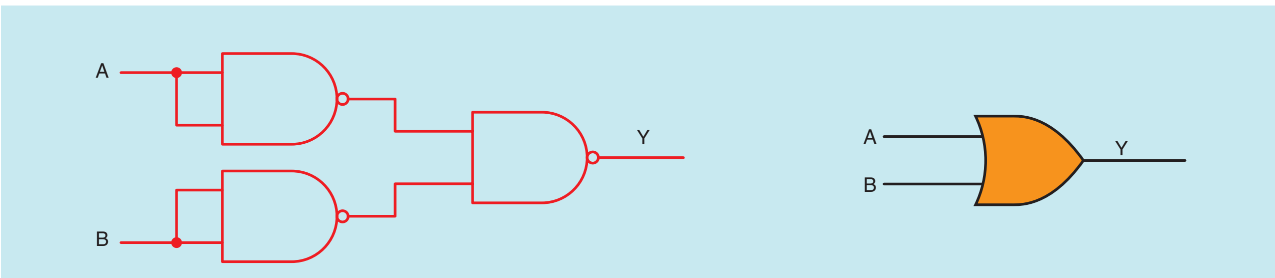


Figure 63–26 NAND gates connected as an OR gate.

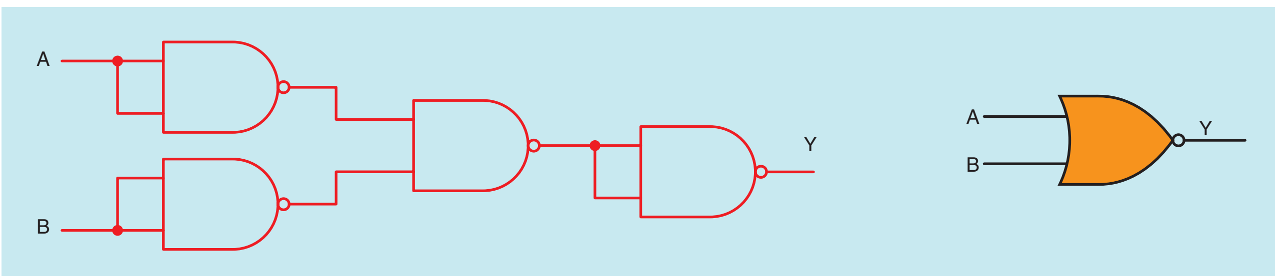


Figure 63–27 NAND gates connected as a NOR gate.

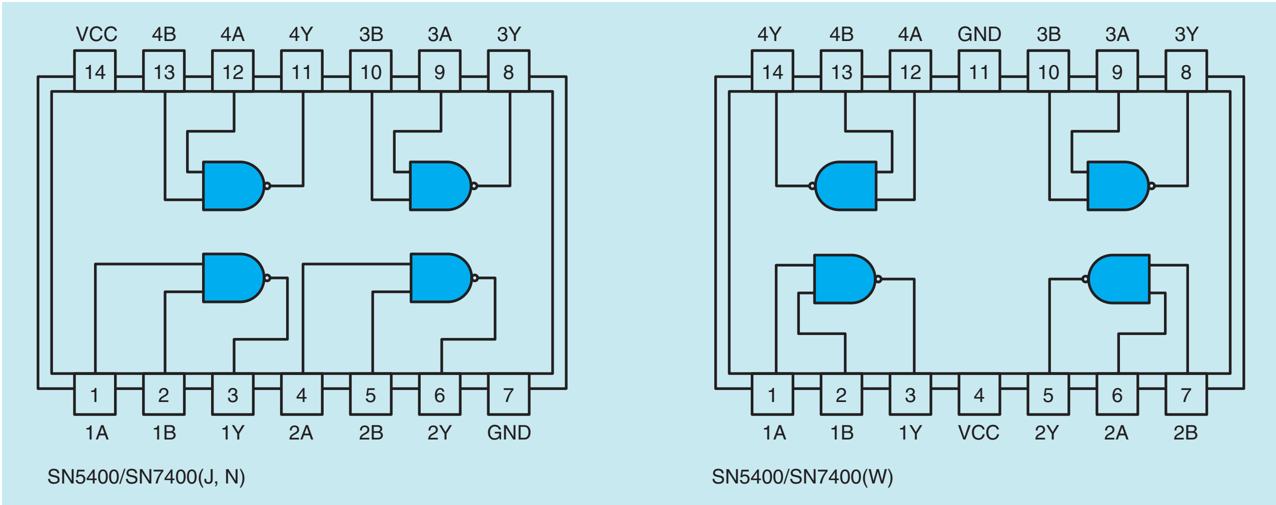


Figure 63–28 Integrated circuit connection of a quad, two-input NAND gate. (Courtesy Tektronix, Inc.)

Testing Integrated Circuits

Integrated circuits cannot be tested with a volt-ohm-milliammeter. Most ICs must be tested by connecting power to them and then testing the inputs and outputs with special test equipment. Most industrial equipment is designed with different sections of the control system built in modular form. The electrician determines which section of the circuit is not operating and replaces that module. The defective module is then sent to the electronics department or to a company outside of the plant for repair.

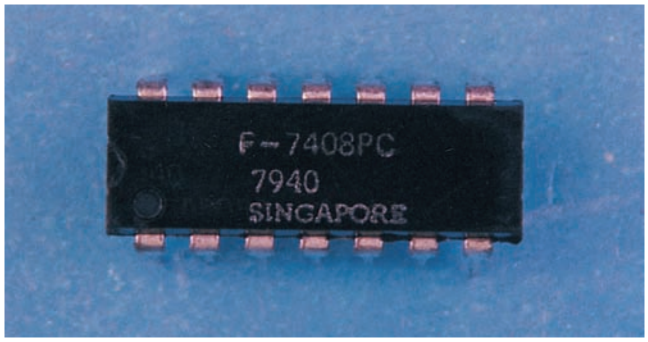


Figure 63–29 Fourteen-pin inline integrated circuit used to house digital logic gates.

Review Questions

1. What type of digital logic operates on 5 volts?
2. What precautions must be taken when connecting CMOS logic?
3. What do the letters COSMOS stand for?
4. When using a two-input AND gate, what conditions of input must be met to have an output?
5. When using a two-input OR gate, what conditions of input must be met to have an output?
6. Explain the difference between an OR gate and an EXCLUSIVE OR gate.
7. When using a two-input NOR gate, what condition of input must be met to have an output?
8. When using a two-input NAND gate, what condition of input must be met to have an output?
9. If an INVERTER is connected to the output of a NAND gate, what logic gate is formed?
10. If an INVERTER is connected to the output of an OR gate, what gate is formed?
11. What symbol is used to represent “invert” when computer logic symbols are used?
12. What symbol is used to represent “invert” when NEMA logic symbols are used?

UNIT 64

THE BOUNCELESS SWITCH

OBJECTIVES

After studying this unit, the student will be able to:

- Discuss why mechanical contacts should be spring loaded.
- Discuss problems associated with contact bounce.
- Describe methods of eliminating contact bounce.
- Connect a bounceless switch circuit using digital logic gates.

When a control circuit is constructed, it must have sensing devices to tell it what to do. The number and type of sensing devices used are determined by the circuit. Sensing devices can range from a simple push button to float switches, limit switches, and pressure switches. Most of these sensing devices use some type of mechanical switch to indicate their condition. A float switch, for example, indicates its condition by opening or closing a set of contacts (Figure 64–1). The float switch can "tell" the control circuit that a liquid is either at a certain level or not. Most of the other types of sensing devices use this same method to indicate some condition. A pressure switch indicates that a pressure is either at a certain level or not, and a limit switch indicates if some device has moved a certain distance or if a device is present or absent from some location.

Almost all of these devices employ a snap-action switch. When a mechanical switch is used, the snap action is generally obtained by spring loading the contacts. This snap action is necessary to ensure good contact when the switch operates. Assume that a float switch is used to sense when water reaches a certain level in a tank. If the water rises at a slow rate, the contacts will come together at a slow rate, resulting in a poor connection. However, if the contacts are spring loaded, when the water reaches a certain level, the contacts will snap from one position to another.

Although most contacts have a snap action, they do not generally close with a single action. When the movable contacts meet the stationary contact, there is often a fast bouncing action. This means that the contacts may actually make and break contact three or four times in succession before the switch remains closed. When

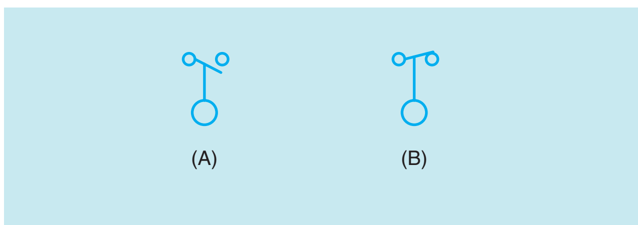


Figure 64–1 (A) Normally open float switch; (B) Normally closed float switch.

this type of switch is used to control a relay, contact bounce does not cause a problem because relays are relatively slow-acting devices (Figure 64–2).

When this type of switch is used with an electronic control system, however, contact bounce can cause a great deal of trouble. Most digital logic circuits are very fast-acting and can count each pulse when a contact bounces. Depending on the specific circuit, each of these pulses may be interpreted as a command. Contact bounce can cause the control circuit to "lose its mind."

Since contact bounce can cause trouble in an electronic control circuit, contacts are debounced before they are permitted to "talk" to the control system. When contacts must be debounced, a circuit called *a bounceless switch* is used. Several circuits can be used to construct a bounceless switch, but the most common construction method uses digital logic gates. Although any of the inverting gates can be used to construct a bounceless switch, in this example only two will be used.

Before construction of the circuit begins, the operation of a bounceless switch circuit should first be discussed. The idea is to construct a circuit that will lock its output either high or low when it detects the first pulse from the mechanical switch. If its output is locked in a position, it will ignore any other pulses it receives from the switch. The output of the bounceless switch is connected to the input of the digital control circuit. The control circuit will now receive only one pulse instead of a series of pulses.

The first gate used to construct a bounceless switch is the INVERTER. The computer symbol and the truth table for the INVERTER are shown in Figure 64–3. The bounceless switch circuit using INVERTERS is shown in Figure 64–4. The output of the circuit should be high with the switch in the position shown. The

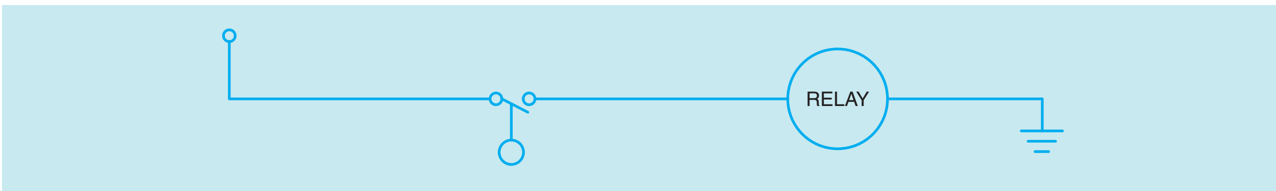


Figure 64–2 Contact bounce does not greatly affect relay circuits.

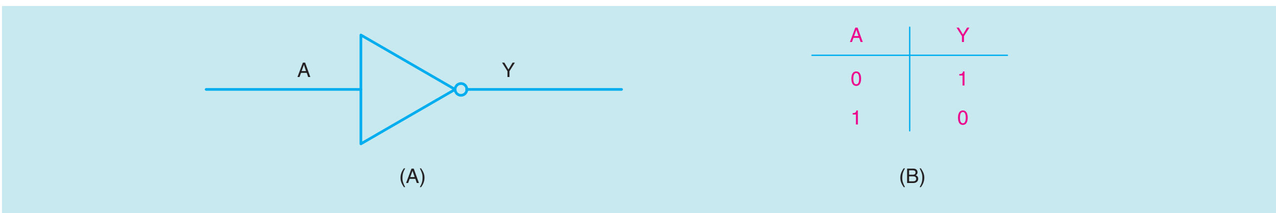


Figure 64–3 (A) Symbol for an INVERTER; L(B) Truth table for an INVERTER.

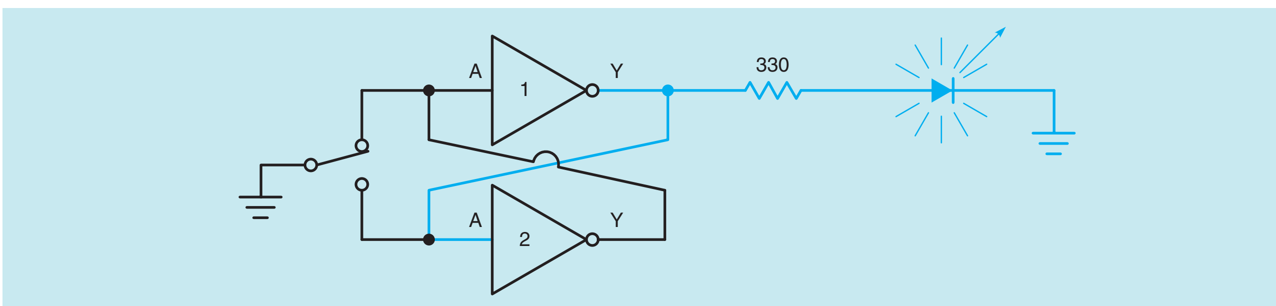


Figure 64–4 High output condition.

switch connects the input of INVERTER #1 directly to ground, or low. This causes the output of INVERTER #1 to be at a high state. The output of INVERTER #1 is connected to the input of INVERTER #2. Since the input of INVERTER #2 is high, its output is low. The output of INVERTER #2 is connected to the input of INVERTER #1. This causes a low condition to be maintained at the input of INVERTER #1.

If the position of the switch is changed as shown in Figure 64–5, the output will change to low. The switch now connects the input of INVERTER #2 to ground, or low. The output of INVERTER #2 is, therefore, high. The high output of INVERTER #2 is connected to the input of INVERTER #1. Since the input connected to INVERTER #1 is now high, its output becomes low. The output of INVERTER #1 is connected to the input of INVERTER #2. This forces a low input to be maintained at INVERTER #2. Notice that the output of one INVERTER is used to lock the input of the other INVERTER.

The second logic gate used to construct a bounceless switch is the NAND gate. The computer symbol and the truth table for the NAND gate are shown in Figure 64–6. The circuit in Figure 64–7 shows the construction of a bounceless switch using NAND gates. In this circuit, the switch has input A of gate #1 connected to low, or ground. Since input A is low, the output is high. The output of gate #1 is connected to input A of gate #2. Input B of gate #2 is connected to a high through the 4.7 kilohm resistor. Since both inputs of gate #2 are high, its output is low. This low output is connected to input B of gate #1. Since gate #1 now has a low connected to input B, its output is forced to remain high even if contact bounce causes a momentary high at input A.

When the switch changes position as shown in Figure 64–8, input B of gate #2 is connected to a low. This forces the output of gate #2 to become high. The high output of gate #2 is connected to input B of gate #1. Input A of gate #1 is connected to a high through a 4.7 kilohm resistor. Since both inputs of gate #1 are

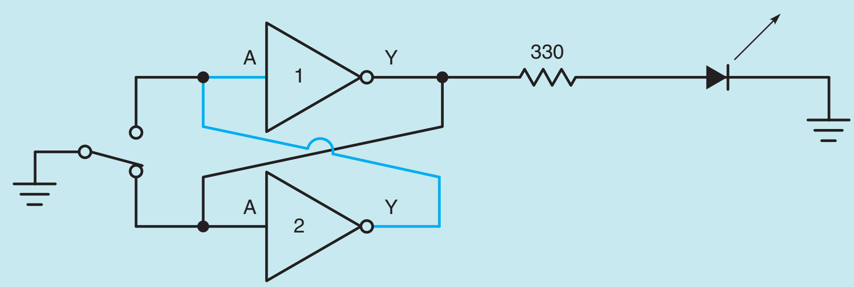
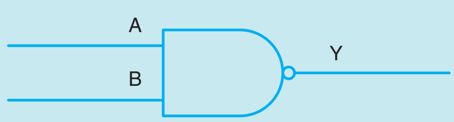


Figure 64–5 Low output condition.



(A)

A	B	Y
0	0	1
0	1	1
1	0	1
1	1	0

(B)

Figure 64–6 (A) Symbol for a NAND gate; (B) Truth table for a NAND gate.

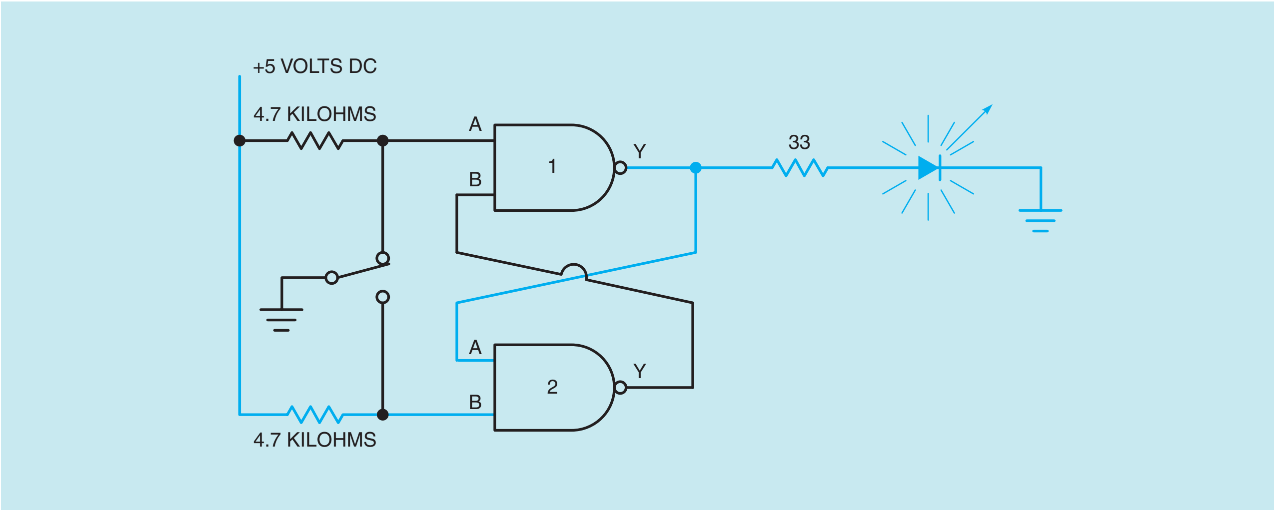


Figure 64–7 High output condition.

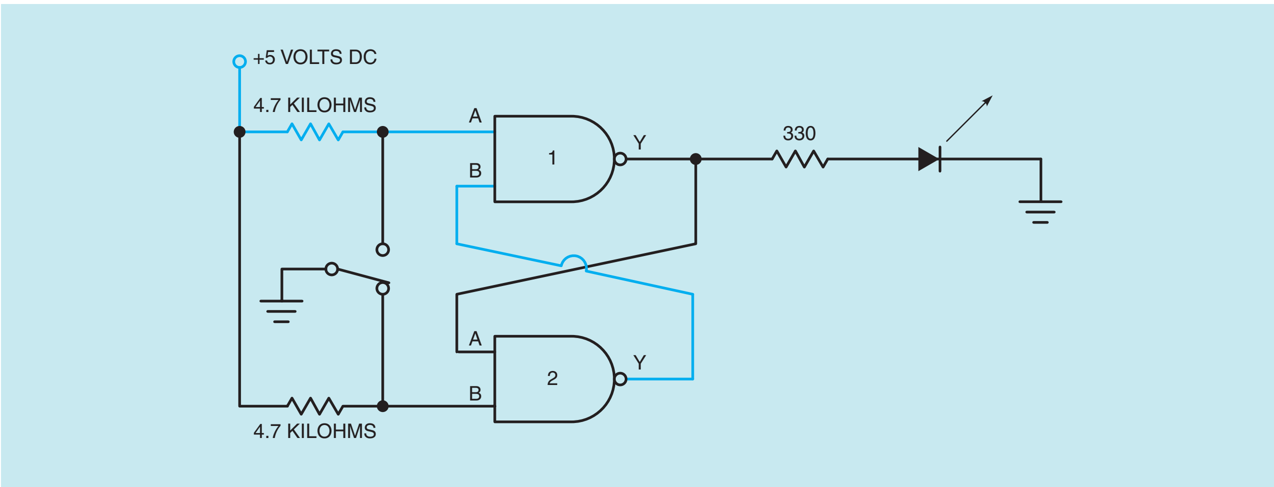


Figure 64–8 Low output condition.

high, its output is low. This low is connected to input A of gate #2, which forces its output to remain high even if contact bounce causes a high to be momentarily connected to input B.

The output of this circuit will remain constant even if the switch contacts bounce. The switch has now been debounced and is ready to be connected to the input of an electronic control circuit.

Review Questions

1. Why should mechanical contacts be spring loaded?
2. Name three examples of sensing devices.
3. Why must contacts be debounced before they are connected to electronic control circuits?
4. What function does a bounceless switch circuit perform?
5. Name two types of logic gates that can be used to construct a bounceless switch circuit.

UNIT 65

START-STOP PUSH-BUTTON CONTROL

OBJECTIVES

After studying this unit, the student will be able to:

- Describe the operation of a start-stop relay control circuit
- Describe the operation of the basic gates used in this unit
- Describe the operation of the solid-state control circuit
- Discuss practical wiring techniques for connecting digital logic circuits
- Connect a start-stop, push-button control using logic gates

In this unit a digital circuit will be designed to perform the same function as a common relay circuit. The relay circuit is a basic stop-start, push-button circuit with overload protection (Figure 65–1).

Before beginning the design of an electronic circuit that will perform the same function as this relay circuit, the operation of the relay circuit should first be discussed. In the circuit shown in Figure 65–1, no current can flow to relay coil M because the normally open START button and the normally open contact are controlled by relay coil M.

When the START button is pushed, current flows through the relay coil and normally closed overload contact to the power source (Figure 65–2). When current flows through relay coil M, the contacts connected parallel to the START button close. These contacts maintain the circuit to coil M when the START button releases and returns to its open position (Figure 65–3).

The circuit will continue to operate until the STOP button is pushed and breaks the circuit to the coil (Figure 65–4). When the current flow to the coil stops, the relay de-energizes and contact M reopens. Since the START button is now open and contact M is open, there is no complete circuit to the relay coil when the STOP button is returned to its normally closed position. If the relay is to be restarted, the START button must be pushed again to provide a complete circuit to the relay coil.

The only other logic condition that can occur in this circuit is caused by the motor connected to the load contacts of relay M. The motor is connected in series

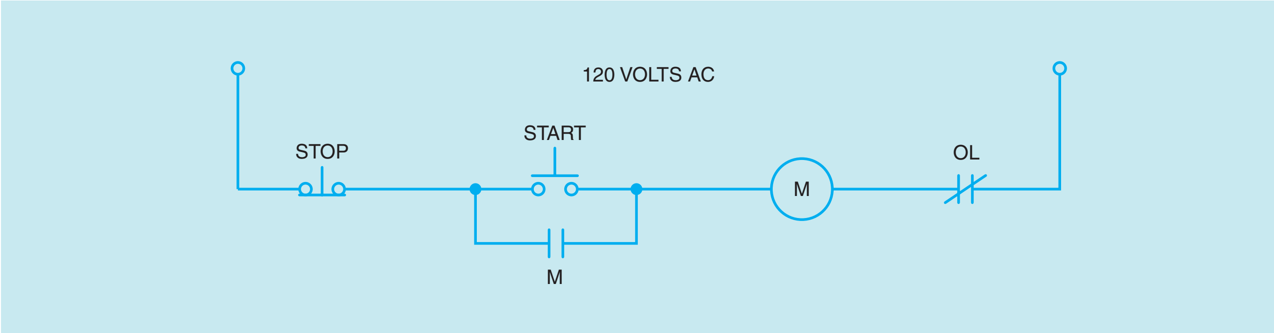


Figure 65–1 Start-stop, push-button circuit.

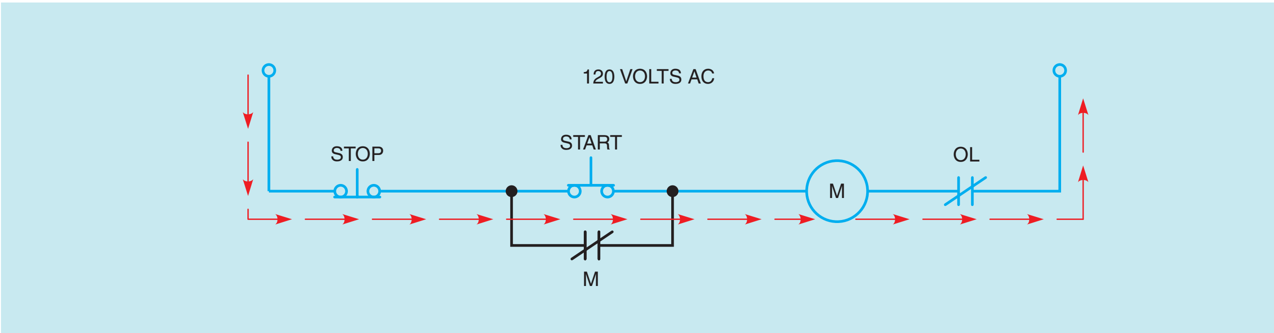


Figure 65–2 START button energizes "M" relay coil.

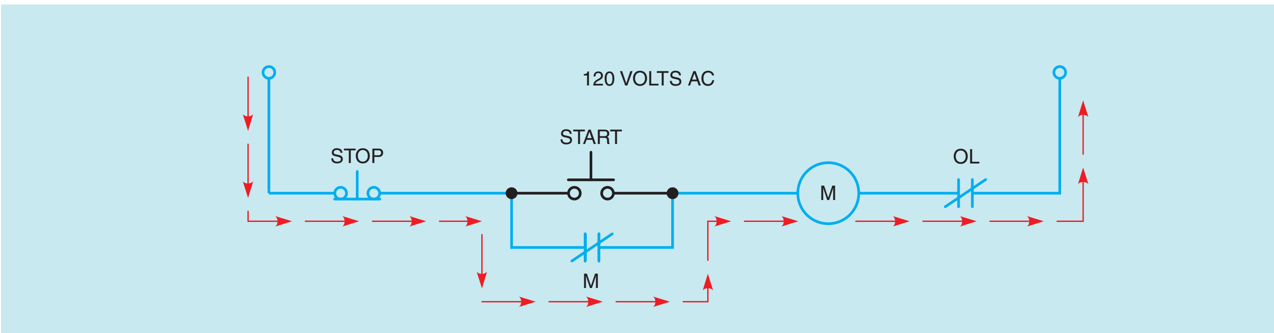


Figure 65–3 "M" contacts maintain the circuit.

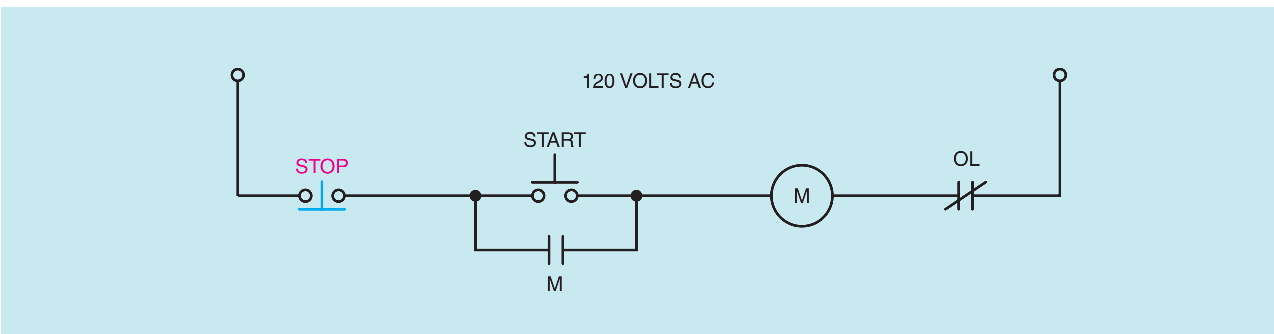


Figure 65–4 STOP button breaks the circuit.

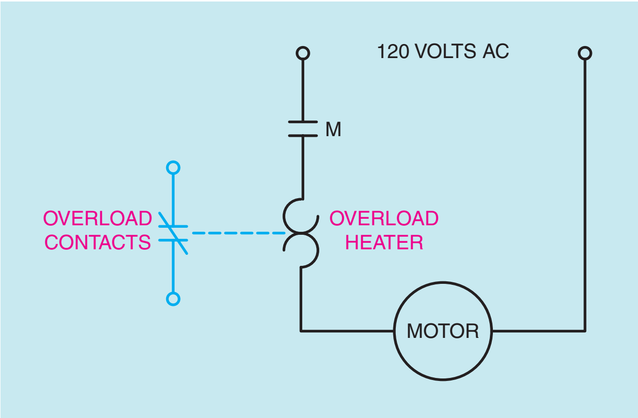


Figure 65–5

with the heater of an overload relay (Figure 65–5). When coil M energizes, it closes the load contact M as shown in Figure 65–6. When the load contact closes, it connects the motor to the 120-volt, ac power line.

If the motor is overloaded, it will cause too much current to flow through the circuit. When a current greater than normal flows through the overload heater, the heater produces more heat than it does under normal conditions. If the current becomes high enough, it will cause the normally closed overload contact to open. Notice that the overload contact is electrically isolated from the heater. The contact, therefore, can be connected to a different voltage source than the motor.

If the overload contact opens, the control circuit is broken and the relay de-energizes as if the STOP button had been pushed. After the overload contact has been reset to its normally closed position, the coil will remain de-energized until the START button is again pressed.

Now that the logic of the circuit is understood, a digital logic circuit that will operate in this manner can be designed. The first problem is to find a circuit that can be turned on with one push button and turned off with another. The circuit shown in Figure 65–7 can perform this function. This circuit consists of an OR gate

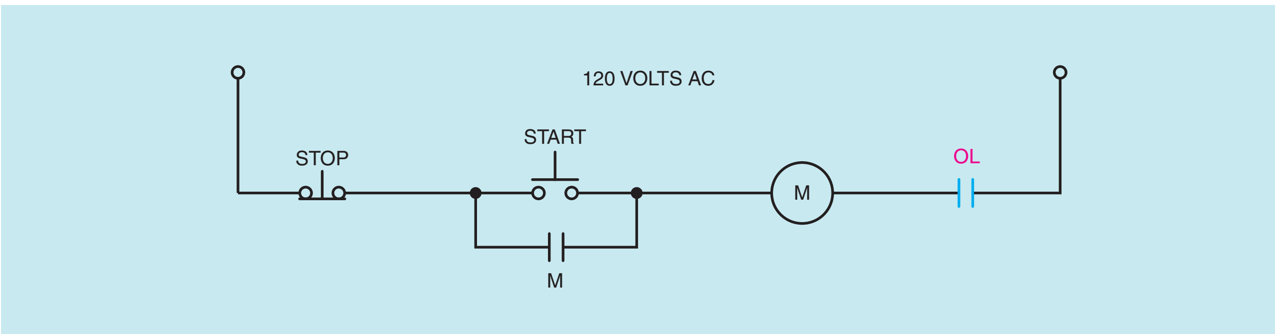


Figure 65–6 Overload contacts break the circuit.

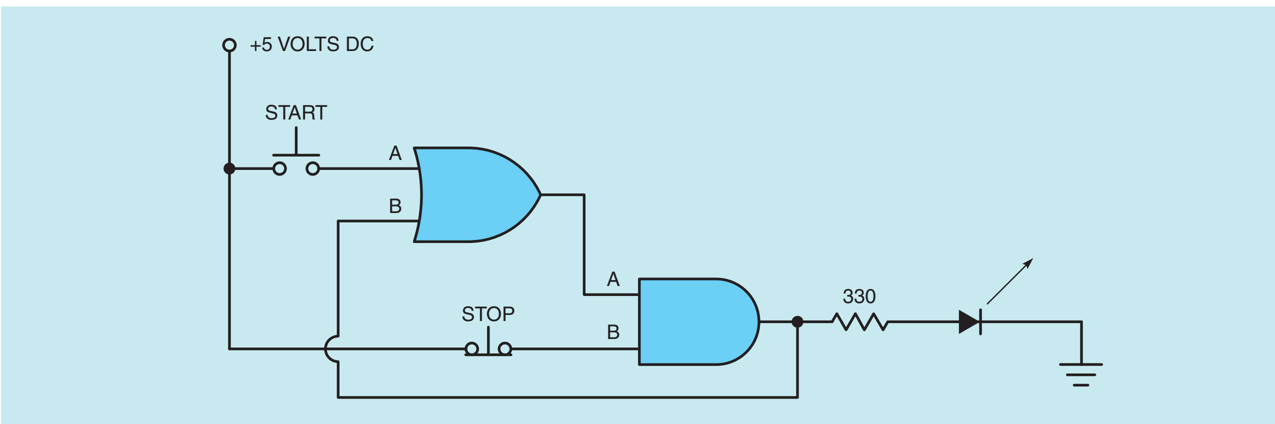


Figure 65–7

and an AND gate. Input A of the OR gate is connected to a normally open push button which is connected to 5 volts dc. Input B of the OR gate is connected to the output of the AND gate. The output of the OR gate is connected to input A of the AND gate. Input B of the AND gate is connected through a normally closed push button to +5 volts dc. This normally closed push button is used as the STOP button. The output of the AND gate is the output of the circuit.

To understand the logic of this circuit, assume that the output of the AND gate is low. This produces a low at input B of the OR gate. Since the push button connected to input A is open, a low is produced at this input also. When all inputs of an OR gate are low, its output is also low. The low output of the OR gate is connected to input A of the AND gate. Input B of the AND gate is connected to a high through the normally closed push-button switch. Since input A of the AND gate is low, the output of the AND gate is forced to remain in a low state.

When the START button is pushed, a high is connected to input A of the OR gate. This causes the output of the OR gate to change to high. This high output is connected to input A of the AND gate. The AND gate now has both of its inputs high, so its output changes from a low to a high state. When the output of the AND gate changes to a high state, input B of the OR gate becomes high also. Since the OR gate now has a high connected to its B input, its output will remain high when the push button is returned to its open condition and input A becomes low. Notice that this circuit operates the same as the relay circuit when the START button is pushed. The output changes from a low state to a high state and the circuit locks in this condition so the START button can be reopened.

When the normally closed STOP button is pushed, input B of the AND gate changes from high to low. When input B changes to a low state, the output of the AND gate changes to a low state also. This causes a low to appear at input B of the OR gate. The OR gate now has both of its inputs low, so its output changes from a high state to a low state. Since input A of the AND gate is now low, the output is forced to remain low when the STOP button returns to its closed position and input B becomes high. The circuit designed here can be turned on with the START button and turned off with the STOP button.

The next design task is to connect the overload contact to the circuit. The overload contact must be connected in such a manner that it will cause the output of the circuit to turn off if it opens. One's first impulse might be to connect the overload contact to the circuit as shown in (Figure 65–8). In this circuit, the output of AND gate #1 has been connected to input A of AND gate #2. Input B of AND gate #2 has been connected to a high through the normally closed overload contact. If the overload contact remains closed, input B will remain

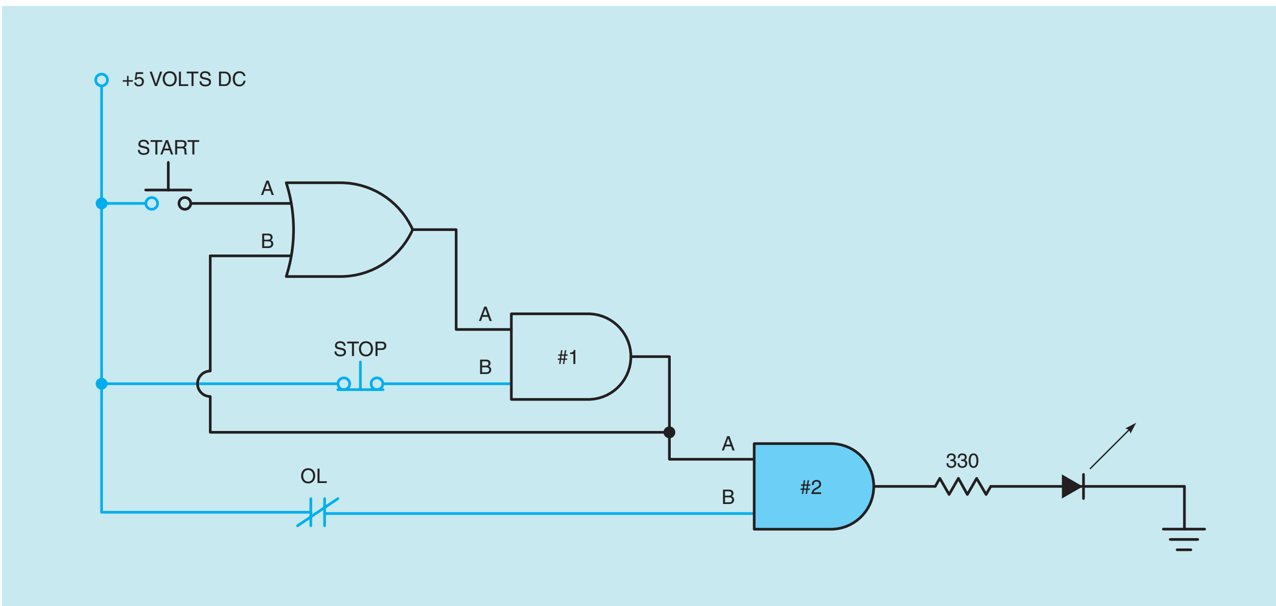


Figure 65–8

high. The output of AND gate #2 is, therefore, controlled by input A. If the output of AND gate #1 changes to a high state, the output of AND gate #2 will also change to a high state. If the output of AND gate #1 becomes low, the output of AND gate #2 will become low also.

If the output of AND gate #2 is high and the overload contact opens, input B will become low and the output will change from a high to a low state. This circuit appears to operate with the same logic as the relay circuit until the logic is examined closely. Assume that the overload contacts are closed and the output of AND gate #1 is high. Since both inputs of AND gate #2 are high, the output is also high. Now assume that the overload contact opens and causes input B to change to a low condition. This forces the output of AND gate #2 to change to low state also. Input A of AND gate #2 is still high, however. If the overload contact is reset, the output will immediately change back to a high state. If the overload contact opens and is then reset in the relay circuit, the relay will not restart itself. The START button must be pushed to restart the circuit. Although this is a small difference in circuit logic, it could become a safety hazard in some cases.

This fault can be corrected with a slight design change. Refer to Figure 65–9. In this circuit, the normally closed STOP button has been connected to input A of AND gate #2, and the normally closed overload switch has been connected to input B. As long as both of these inputs are high, the output of AND gate #2 will provide a high to input B of AND gate #1. If either the STOP button or the overload contact opens, the output of AND gate #2 will change to a low state. When input B of AND gate #2 changes to a low state, it will cause the output of AND gate #1 to change to a low state and unlock the circuit, just as pushing the STOP button did in the circuit shown in Figure 65–8. The logic of this digital circuit is now the same as the relay circuit.

Although the logic of this circuit is now correct, there are still some problems that must be corrected. When gates are used, their inputs must be connected to a definite high or low. When the START button is in its normal position, input A of the OR gate is not connected to anything. When an input is left in this condition, the gate may not be able to determine if the input should be high or low. The gate could, therefore, assume either condition. To prevent this, inputs must always be connected to a definite high or low.

When using TTL logic, inputs are always pulled high with a resistor as opposed to being pulled low. If a resistor is used to pull an input low as shown in Figure 65–10, it will cause the gate to have a voltage drop at its output. This means that in the high state, the output of the gate may be only 3 or 4 volts instead of 5 volts. If this output is used as the input of another gate, and the other gate has been pulled low with a resistor, the output of the second gate may be only 2 or 3 volts. Notice that each time a gate is pulled through a resistor, its outcome voltage becomes low. It this were done through

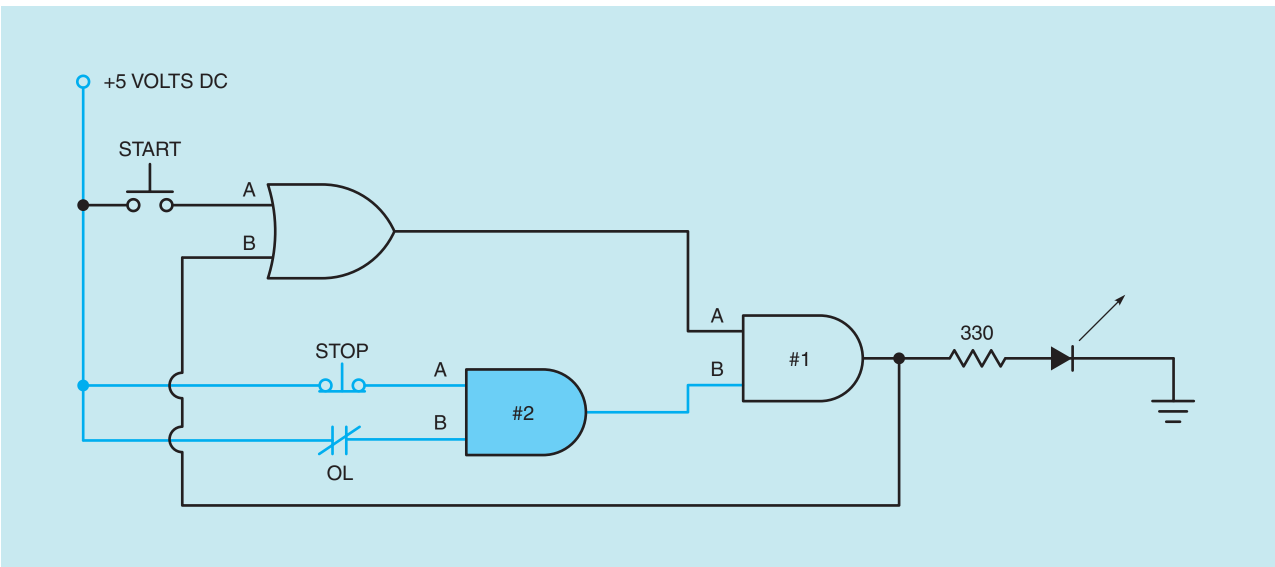


Figure 65–9

several steps, the output voltage would soon become so low it could not be used to drive the input of another gate.

Figure 65–11 shows a resistor used to pull the input of a gate high. In this circuit, the push button is used to connect the input of the gate to ground, or low.

The push button can be adapted to produce a high at the input instead of a low by adding an INVERTER as shown in Figure 65–12. In this circuit, a pull-up resistor is connected to the input of an INVERTER. Since the input of the INVERTER is high, its output

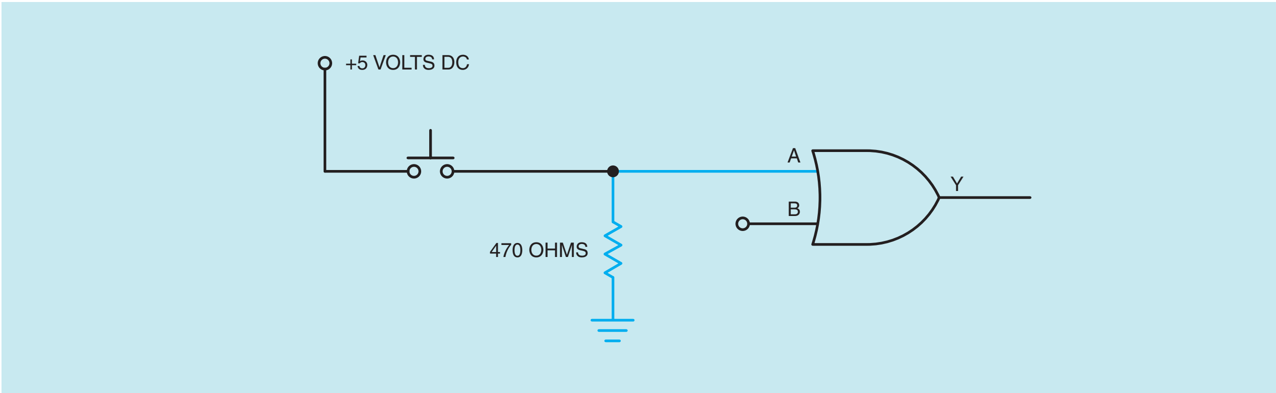


Figure 65–10 Resistor used to lower the input of a gate.

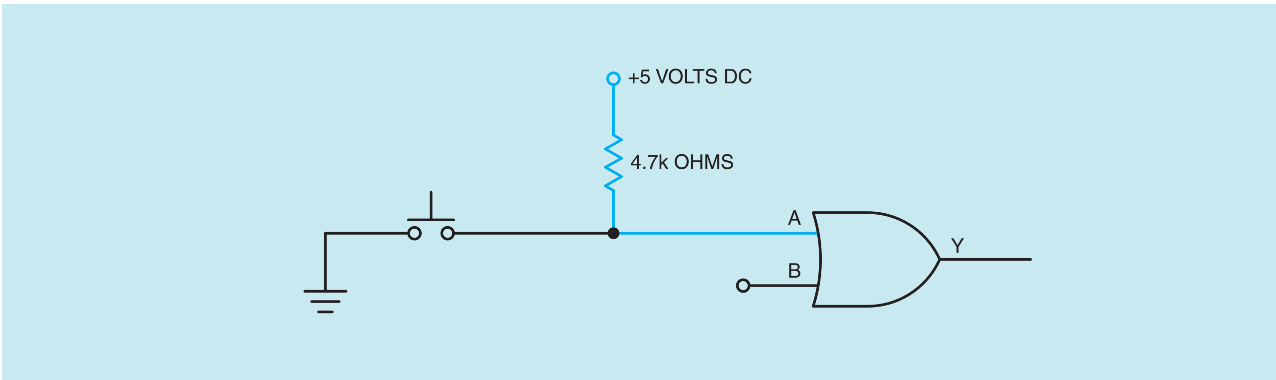


Figure 65–11 Resistor used to raise the input of a gate.

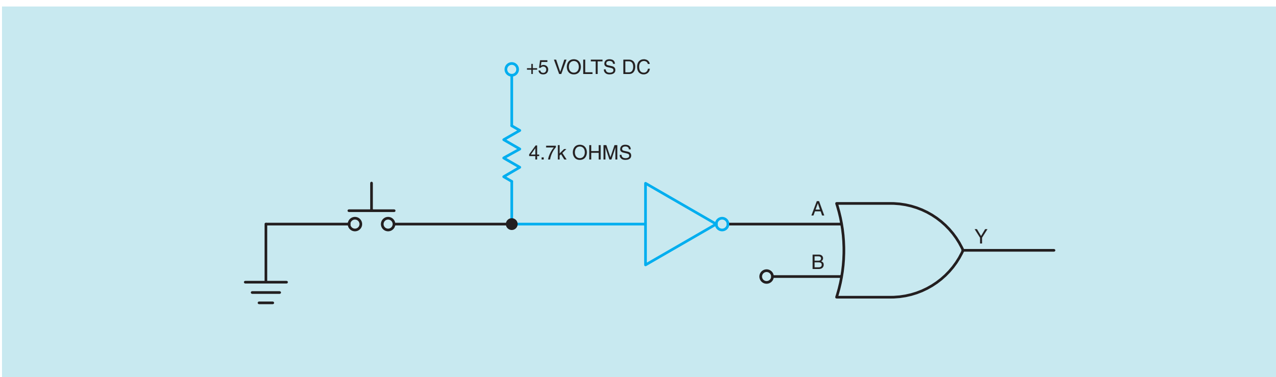


Figure 65–12 Push button produces a high at the input.

will produce a low at input A of the OR gate. When the normally open push button is pressed, a low will be produced at the input of the INVERTER. When the input of the INVERTER becomes low, its output becomes high. Notice that the push button will now produce a high input A of the OR gate when it is pushed.

Since both of the push buttons and the normally closed overload contact are used to provide high inputs, the circuit is changed as shown in Figure 65–13. Notice that the normally closed push button and the normally closed overload switch connected to the inputs of AND gate #2 are connected to ground instead of Vcc. When the switches are connected to ground, a low is provided to the input of the INVERTERS to which they are connected. The INVERTERS, therefore, produce a high at the input of the AND gate. If one of these normally closed switches opens, a high will be provided to the input of the INVERTER. This will cause the output of the INVERTER to become low. If the logic of the circuit shown in Figure 65–13 is checked, it can be seen that it is the same as the logic of Circuit 649.

The final design problem for this circuit concerns the output. So far, a light-emitting diode has been used as the load. The LED is used to indicate when the output is high and when it is low. The original circuit, however, was used to control a 120-volt ac motor. This control can be accomplished by connecting a solid-state relay to the output in place of the LED (Figure 65–14). In this circuit, the output of AND gate #1 is connected to the input of an opto-isolated, solid-state relay. When the output of the AND gate changes to a high condition, the solid-state relay turns on and connects the 120-volt ac load to the line.

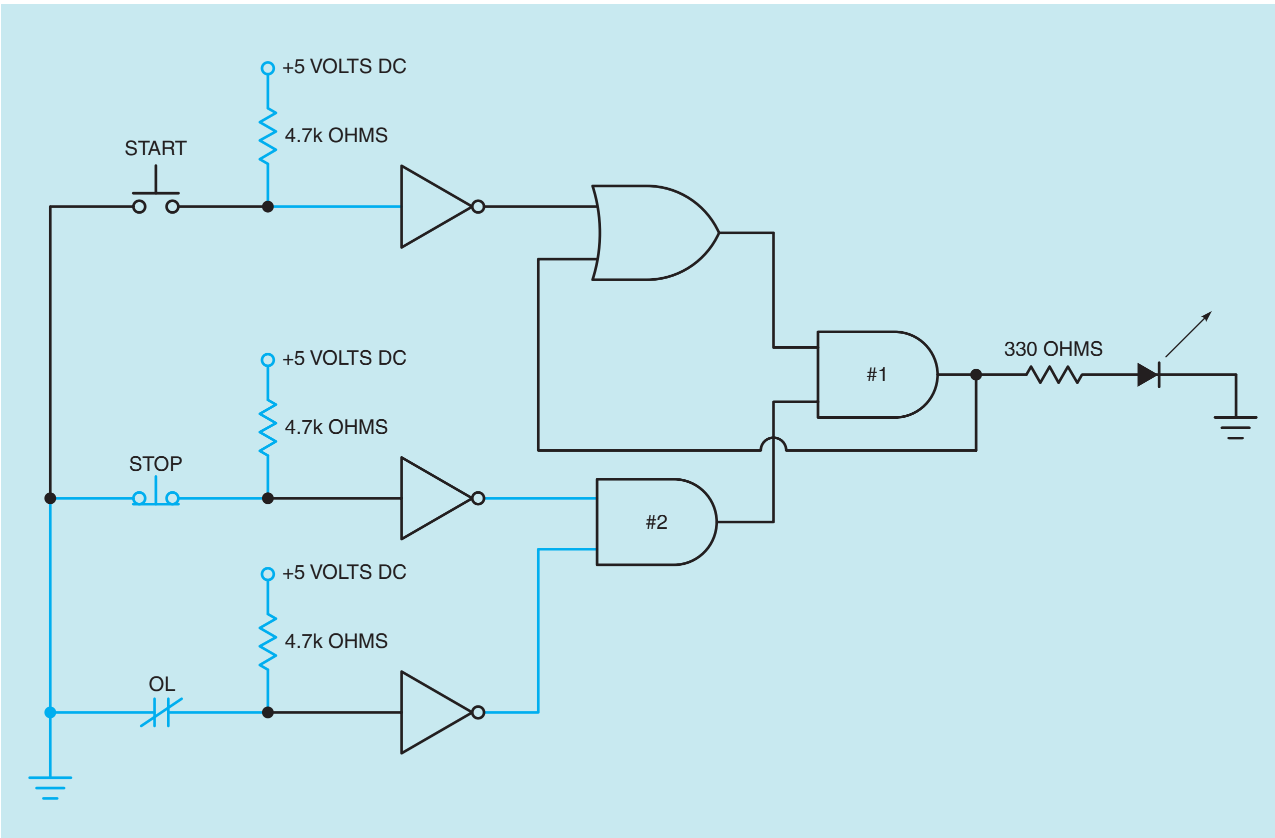


Figure 65–13

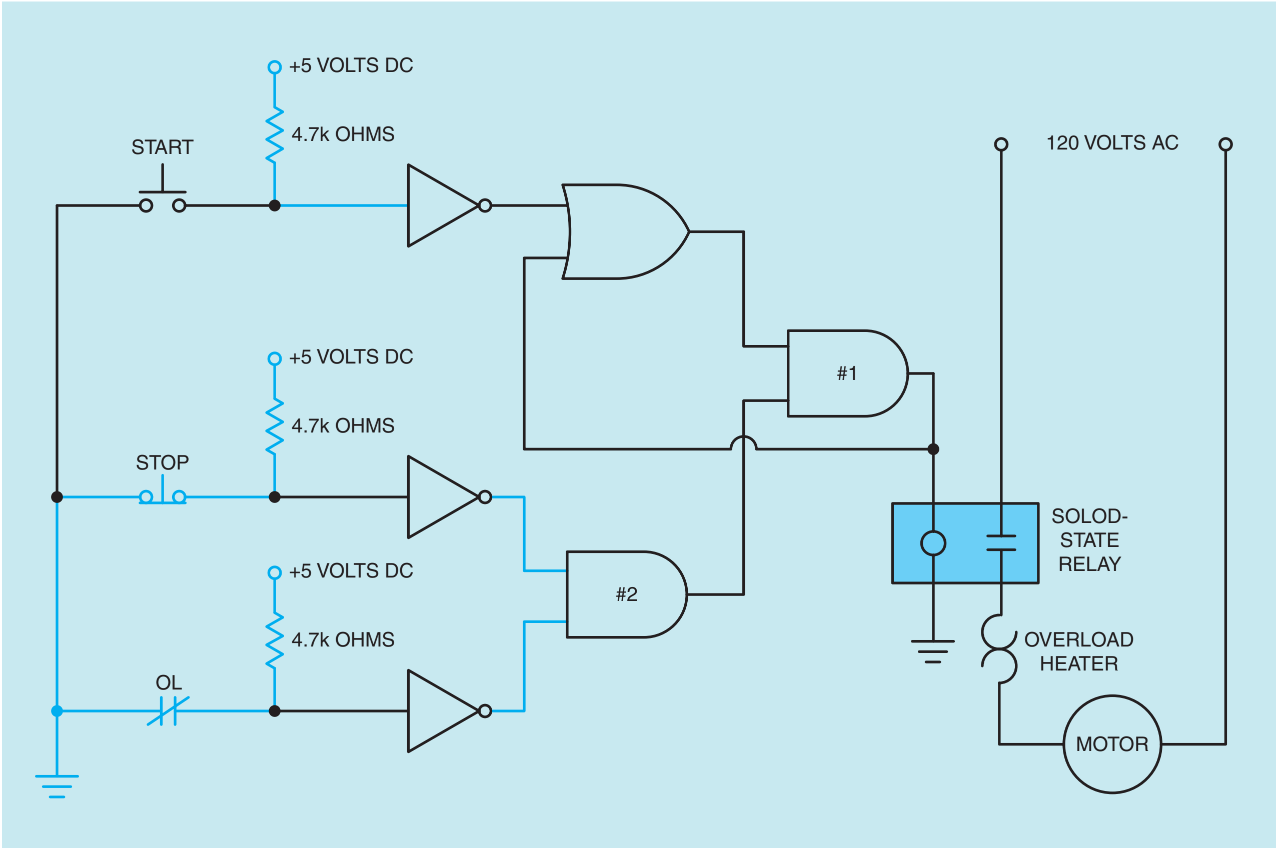


Figure 65–14 Solid-state, start-stop, push-button control.

Review Questions

1. In a relay circuit, what function is served by the holding contacts?
2. What is the function of the overload relay in a motor control circuit?
3. What conditions of input must exist if an OR gate is to produce a high output?
4. What conditions of input must exist if an AND gate is to produce a high output?
5. When connecting TTL logic, why are inputs pulled high instead of low?
6. Referring to Figure 65–9, how would this circuit operate if input B of the OR gate was reconnected to input A of AND gate #1 instead of its output?
7. Referring to Figure 65–12, what function does the INVERTER serve in this circuit?

UNIT 66

PROGRAMMABLE LOGIC CONTROLLERS

OBJECTIVES

After studying this unit, the student will be able to:

- List the principal parts of a programmable logic controller.
- Describe the differences between programmable logic controllers and other types of computers.
- Discuss the operation of the programming terminal, the central processor, and the I/O track.
- Draw basic diagrams of how the input and output modules function.

Programmable controllers were first used by the automobile industry in the late 1960s. Each time a change was made in design, it was necessary to change the control systems operating the machinery. This consisted of physically rewiring the control system to make it perform the new operation. Rewiring the system, of course, was extremely time consuming and costly. What the industry needed was some type of control system that could be changed without the extensive rewiring required to change relay control systems.

One of the first questions that is generally asked is, "Is a programmable logic controller a computer?" The answer to that question is "yes." The programmable logic controller, or PLC, is a special computer designed to perform a special function.

Differences Between the PLC and the Common Computer

Some differences between a PLC and a home and business computer are:

1. The PLC is designed to be operated in an industrial environment. Any computer used in industry must be able to operate in extremes of temperature,

ignore voltage spikes and drops on the incoming power line, survive in an atmosphere that often contains corrosive vapors, oil, and dirt, and withstand shock and vibration.

2. Most programmable logic controllers are designed to be programmed with relay schematic or ladder diagrams instead of the common computer languages such as Basic or Fortran. An electrician who is familiar with relay logic diagrams can generally be trained to program a PLC in a few hours, whereas it generally takes several months to train someone to program a standard computer.

Basic Components

Programmable logic controllers can be divided into four basic parts:

A. The power supply
B. The central processing unit
C. The program loader or terminal
D. The I/O (pronounced eye-oh) track

The Power Supply

The power supply is used to lower the incoming ac voltage to the desired level, rectify it to direct current, and then filter and regulate it. The internal logic circuits of programmable logic controllers operate on 5 to 15 volts dc depending on the type of controller. This voltage must be free of voltage spikes and other electrical noise. It must also be regulated to within 5% of the required voltage value. Some manufacturers of PLCs use a separate power supply, and others build the power supply into the central processor.

The CPU

The central processing unit, or CPU, is the brain of the programmable controller. It contains the microprocessor chip and related integrated circuits to perform all the logic functions. The microprocessor chip used in most PLCs is the same as the common computer chip used in many home and business machines (Figure 66–1).

Figure 66–1 A central processor. (Courtesy Allen-Bradley, a Rockwell International company.)

The central processing unit generally has a key switch located on the front panel. This switch must be turned on before the CPU can be programmed. This is done to prevent the circuit from being changed accidentally. Plug connections mounted on the central processor are used to provide connections for the programming terminal and the I/O tracks (Figure 66–2). Most CPUs are designed so that once the program has been tested, it can be stored on tape or disc. In this way if a central processing unit fails and has to be replaced, the new unit can be reprogrammed from the tape or disc. This eliminates the time consuming process of having to reprogram by hand.

The Programming Terminal

The programming terminal or loading terminal is used to program the CPU. Most terminals are one of two types. One type is a small hand-held device that

Figure 66–2 The central processor unit. (Courtesy Siemens Energy and Automation, Inc.)

uses a liquid crystal display to show the program (Figure 66–3). This terminal, however, will display only one line of the program at a time.

The other type of terminal uses a monitor to show the program. This terminal looks similar to a portable television set with a keyboard attached (Figure 66–4). It may display several lines of the program at a time, depending on the manufacturer. A central processor unit with different I/O modules is shown in Figure 66–5. Some manufacturers can provide a program that can be loaded into a laptop or notebook computer that permits it to be used as a loading terminal. This has become extremely popular because it eliminates the necessity for a special piece of equipment that can perform only one function.

The terminal is not only used to program the controller, but it is also used to troubleshoot the circuit. When the terminal is connected to the CPU, the circuit can be examined while it is in operation. Figure 66–6 illustrates a circuit typical of those which are seen on the display. Notice that this schematic diagram is a little

Figure 66–3 Small programmable controller and hand held programming unit.

different from the typical ladder diagram. All of the line components are shown as normally open or normally closed contacts. There are no NEMA symbols for push-buttons, float switches, limit switches, etc. The programmable logic controller recognizes only open or closed contacts. It does not know if a contact is controlled by a push button, a limit switch, or a float switch. Each contact, however, does have a number. The number is used to distinguish one contact from another.

The coil symbols look like a set of parentheses instead of a circle as shown on most ladder diagrams. Each

Figure 66–4 Programming terminal. (Courtesy Allen-Bradley, a Rockwell International company.)

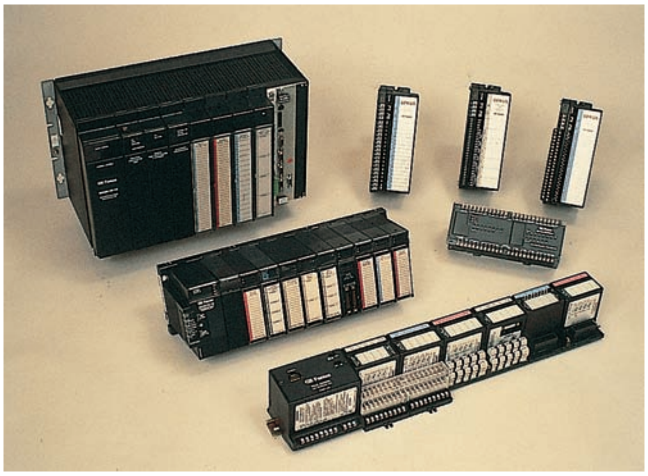


Figure 66–5 A central processing unit with I/O tracks. (Courtesy General Electric.)

line ends with a coil, and each coil has a number. When a contact symbol has the same number as a coil, it means the contact is controlled by that coil. Figure 66–6 shows a coil numbered 257, and two contacts numbered 257. When relay coil 257 is energized, the controller interprets both of these contacts to be closed.

Notice that the 257 contacts, contacts 16 and 18, and coil 257 are drawn with different color lines. When a contact has a complete circuit through it, or a coil is energized, the terminal will illuminate that contact or coil. Contact 16 is illuminated, which means that it is closed and providing a current path. Contact 18 is closed, providing a current path to coil 257. Since coil 257 is energized, both 257 contacts are closed and providing current paths.

Contacts 19, 258, and 301 are not illuminated. This means that contacts 19 and 258 are de-energized and open. Contact 301, however, has been energized. This contact is shown as normally closed. Since it is not illuminated, it is open and no current path exists through it. Notice that the illumination of a contact does not mean that the contact has energized or changed position; it means that there is a complete path for current flow.

When the terminal is used to load a program into the central processing unit, contact and coil symbols on the keyboard are used. These symbol keys are used to load a ladder diagram similar to the one shown in Figure 66–6 into the CPU. Programming will be discussed in Unit 67.

The I/O Track

The I/O track is used to connect the central processing unit to the outside world. It contains input modules which carry information to the CPU, and output modules which carry information from the CPU. An I/O

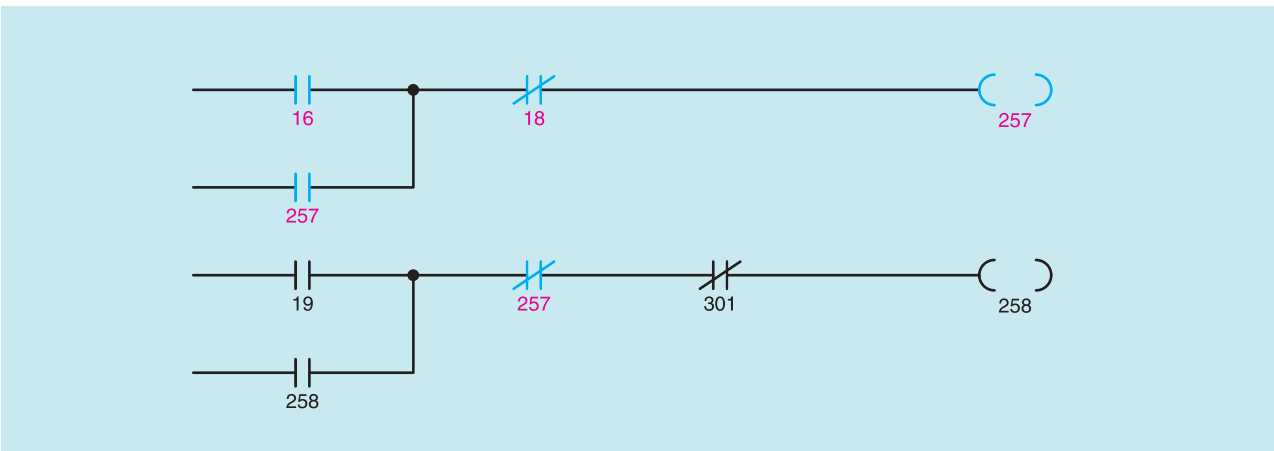


Figure 66–6 Analyzing circuit operation with the terminal.

Figure 66–7A I/O track with input and output modules. (Courtesy Schneider Automation.)

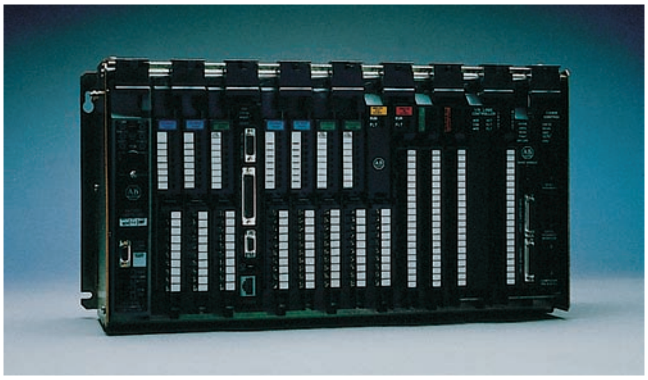


Figure 66–7B I/O track with input and output modules. (Courtesy Allen-Bradley Co., Systems Division.)

track with input and output modules is shown in Figures 66–7A and B. Most modules contain more than one input or output. Any number from four to sixteen is common depending on the manufacturer. The modules shown in Figure 66–7A can each handle sixteen connections. This means that each input module can handle sixteen different inputs from pilot devices such as push buttons, float switches, or limit switches. Each output module can control sixteen external devices such as pilot lights, solenoids, or motor starter coils. The operating voltage of modules can be alternating current or direct current and are generally either 120 or 24 volts. The I/O track in Figure 66–7A can handle eight modules. Since each module can accommodate sixteen devices, this I/O track can control 128 inputs or outputs.

I/O Capacity One factor which determines the size and cost of a programmable logic controller is its I/O capacity. Many small units are designed to handle only 32 inputs or outputs. Large units can handle several hundred. The controller shown in Figure 66–2 is designed to handle eight I/O tracks. Since each I/O track has 128 inputs or outputs, the controller has an I/O capacity of 1024. I/O tracks with many inputs and outputs are shown in Figure 66–8.

The Input Module The central processing unit of a programmable logic controller is extremely sensitive to voltage spikes and electrical noise. For this reason the input I/O uses opto-isolation to electrically separate the incoming signal from the CPU. Another job performed by the input I/O is debouncing any switch contacts connected to it.

Figure 66–9 shows a typical circuit used for the input. A metal oxide varistor (MOV) is connected across the ac input to help eliminate any voltage spikes that may occur on the line. A bridge rectifier changes the ac voltage into dc. A resistor is used to limit current to a light emitting diode. When power is applied to the circuit, the LED turns ON. The light is detected by a phototransistor, which signals the CPU that there is a voltage present at the input terminal.

When the module has more than one input, the bridge rectifiers are connected together on one side to form a common terminal. On the other side the rectifiers are labeled 1, 2, 3, and 4. Figure 66–10 shows four bridge rectifiers connected together to form a common terminal.

Figure 66–11 shows a limit switch connected to the input. Notice that the limit switch completes a

Figure 66–8 I/O track with a large number of inputs and outputs. (Courtesy General Electric.)

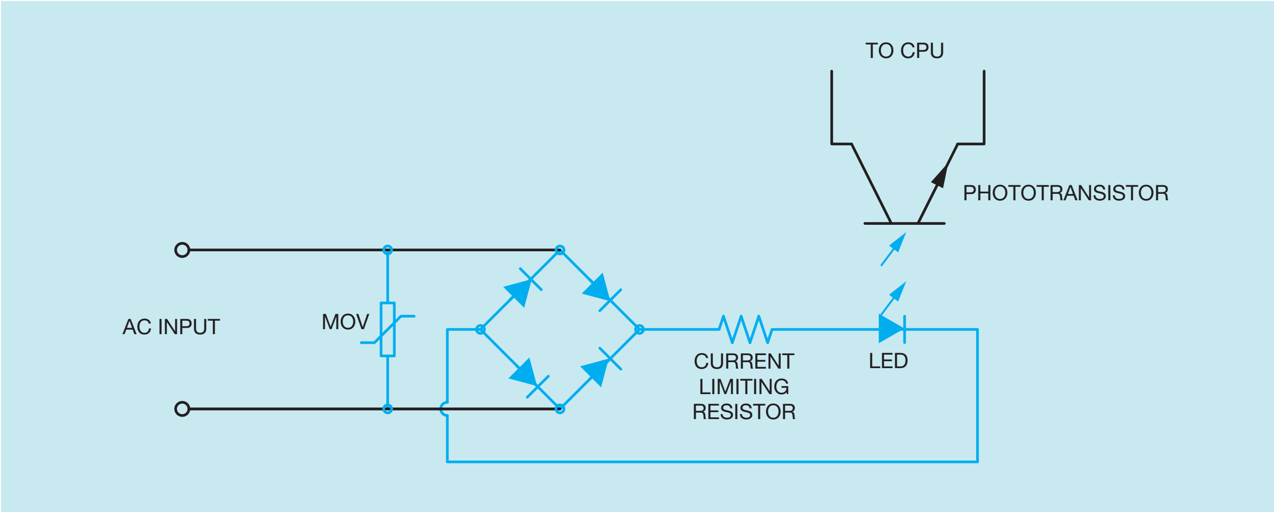


Figure 66–9 Input circuit.

circuit from the ac line to the bridge rectifier. When the limit switch closes, 120-volts ac is applied to the rectifier causing the LED to turn on.

The Output Module

The output module is used to connect the central processing unit to the load. Different manufacturers employ different methods to accomplish this. Some use magnetic relays and others use opto-isolated solid-state relays. The output current rating can range from about 0.5 to 3 A depending on the manufacturer. Voltage ratings are generally 24 to 120 V and can be ac or dc.

Magnetic relay-type outputs have an advantage in that since they complete a circuit with a set of contacts they can control ac or dc currents without a problem. The disadvantage of magnetic relay-type outputs is that they employ moving parts and contacts that wear. When magnetic-type relays are used, the CPU is connected to the coil of the relay and the contacts connect the load to the line (Figure 66–12).

Solid-state-type relays employ optical isolation similar to input modules. In the case of output modules, however, the CPU is connected to a light emitting diode. A solid-state device is then used to connect the load to the line. If the output is designed to control a dc voltage, a power transistor is used to connect the load to the line (Figure 66–13). The transistor is a phototransistor which is operated by the light emitting diode.

If the output is designed to control an ac load, a triac, rather than a power transistor, is used as the control device (Figure 66–14). A photodetector connected to the gate of the triac is used to control the output. When the LED is turned on by the CPU, the photodetector permits current to flow through the gate of the triac and turn it on.

If more than one output is contained in a module, the control devices are connected together on one side to form a common terminal. Figure 66–15 shows an output module that contains four outputs. Notice that one side of each triac has been connected to form a common terminal. On the other side the triacs are labeled 1, 2, 3, and 4. If power transistors are used as the control devices, the emitters or the collectors can be connected to form a common terminal.

Figure 66–16 shows a solenoid coil connected to an ac output module. Notice that the triac is used as a switch to complete a circuit so that current can flow through the coil. The output module does not provide power to operate the load. The power must be provided by an external power source. The amount of current an output can control is limited. Small current loads, such as solenoid coils and pilot lights, can be controlled directly by the I/O output, but large current loads, such as motors, can not. When a large amount of current must be controlled, the output is used to operate the coil of a motor starter or contactor which can be used to control almost anything.

Internal Relays

The actual logic of the control circuit is performed by *internal relays.* An internal relay is an imaginary device that exists only in the logic of the computer. It can have any number of contacts, from one to several

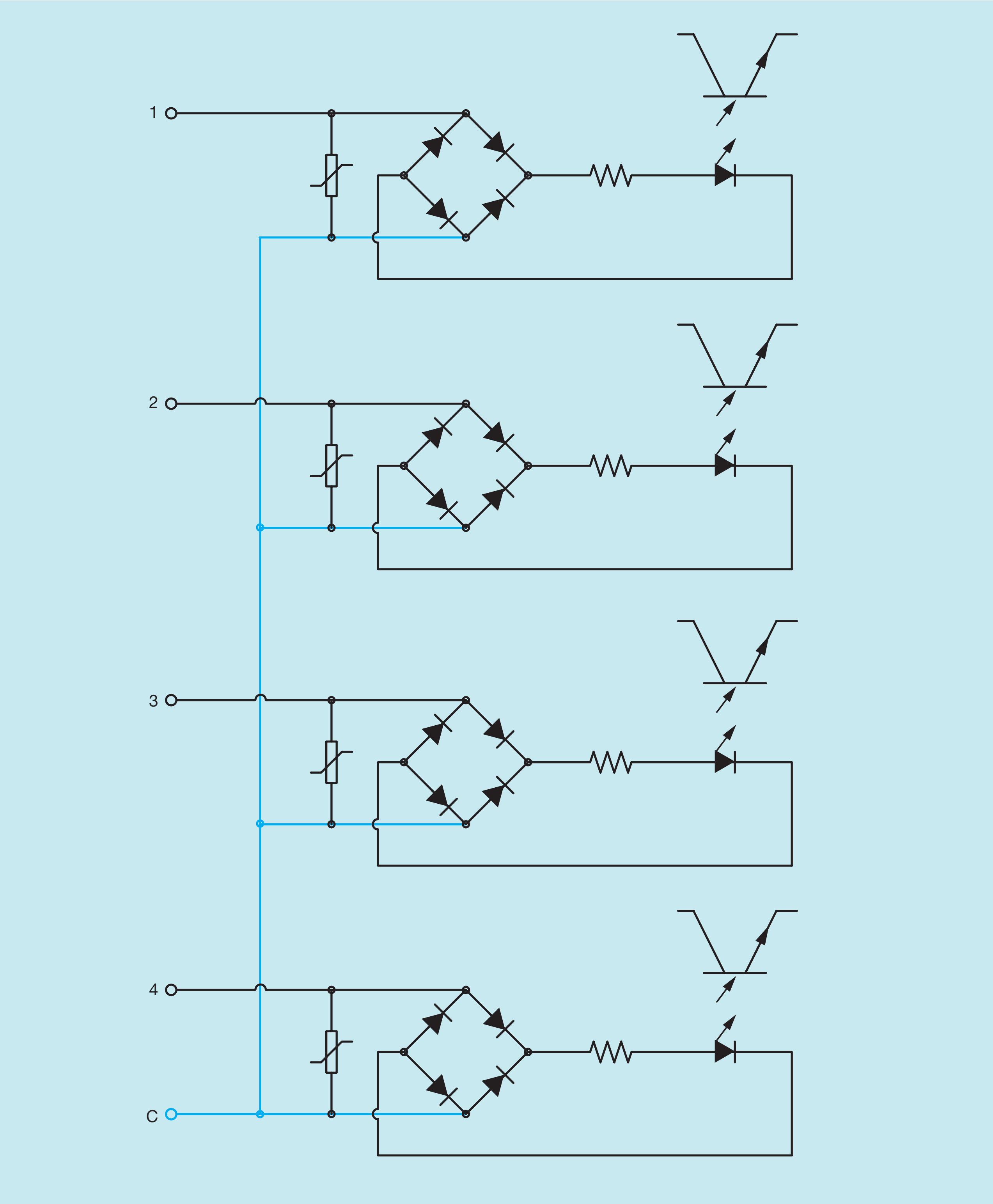


Figure 66–10 Four-input module.

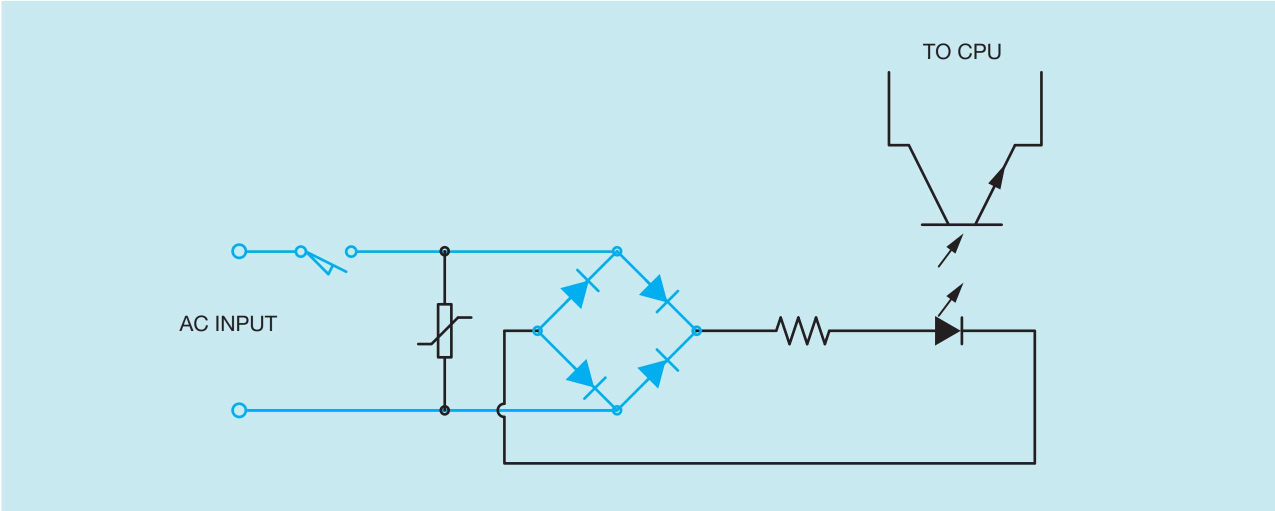


Figure 66–11 Limit switch completes circuit to rectifier.

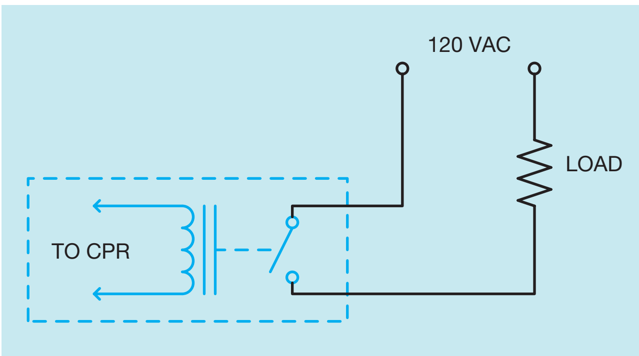


Figure 66–12 A magnetic relay is used to connect the load to the line.

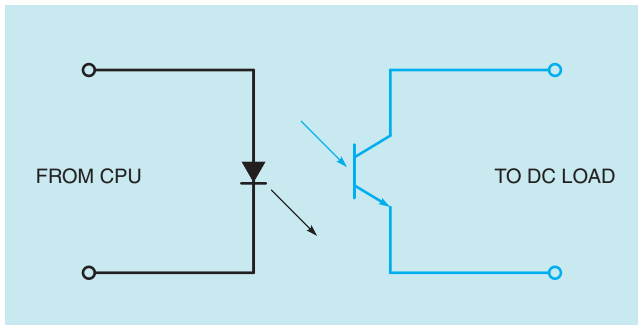


Figure 66–13 Output module used to control a dc module.

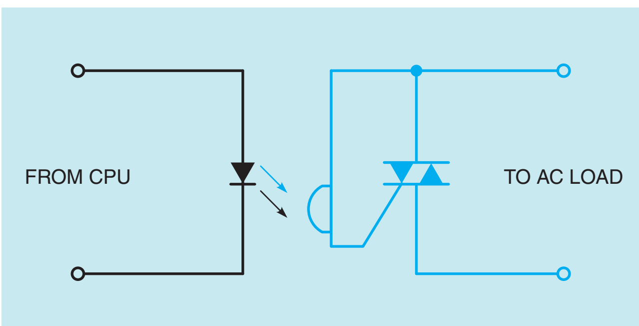


Figure 66–14 Output module used to control an ac module.

hundred, and the contacts can be normally open or normally closed. Internal relays can be programmed into the computer by assigning a coil some number greater than the I/O capacity. For example, assume that the programmable controller has an I/O capacity of 256. If a coil is programmed into the computer and assigned a number greater than 256, 257 for instance, it is an internal relay. Any number of contacts can be controlled by relay 257 by inserting a contact symbol in the program and numbering it 257. If a coil is numbered 256 or less, it can turn on an output when energized.

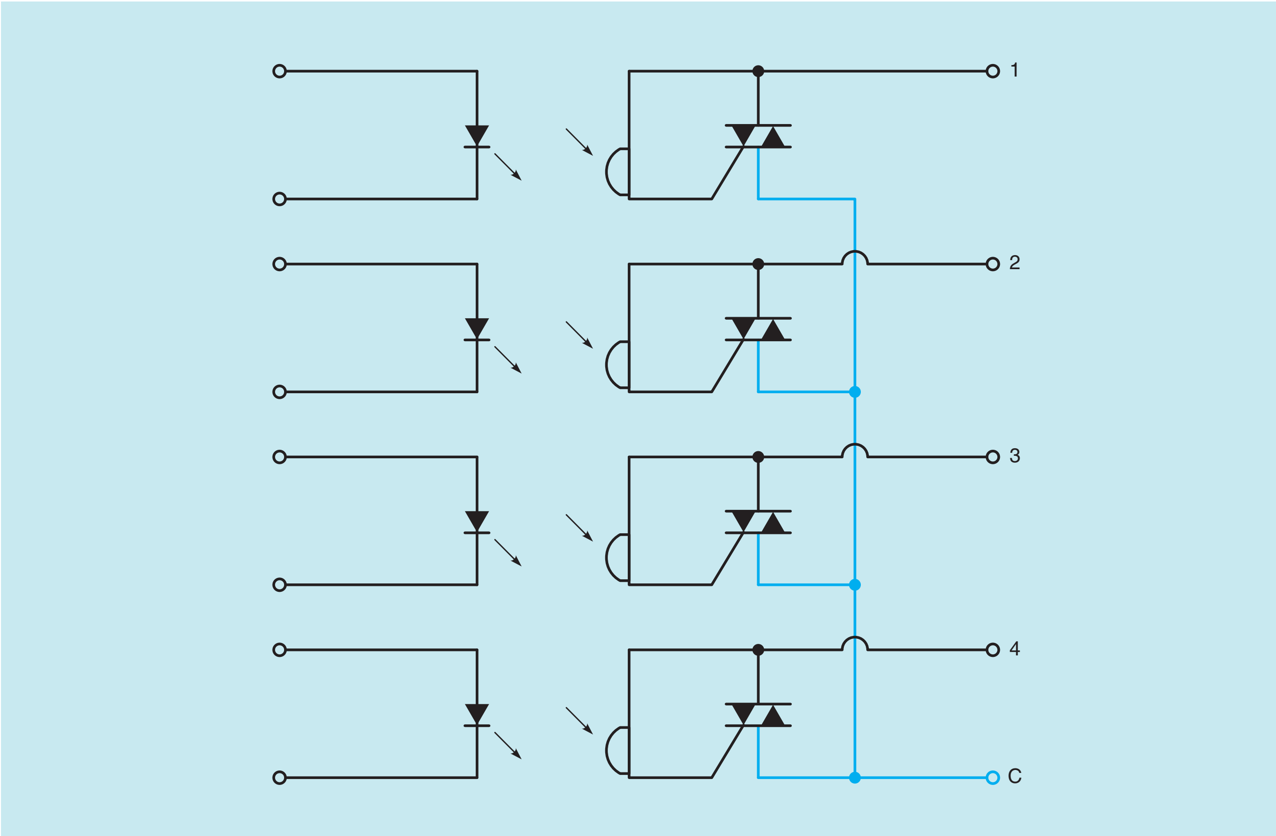


Figure 66–15 Four ac outputs in one module.

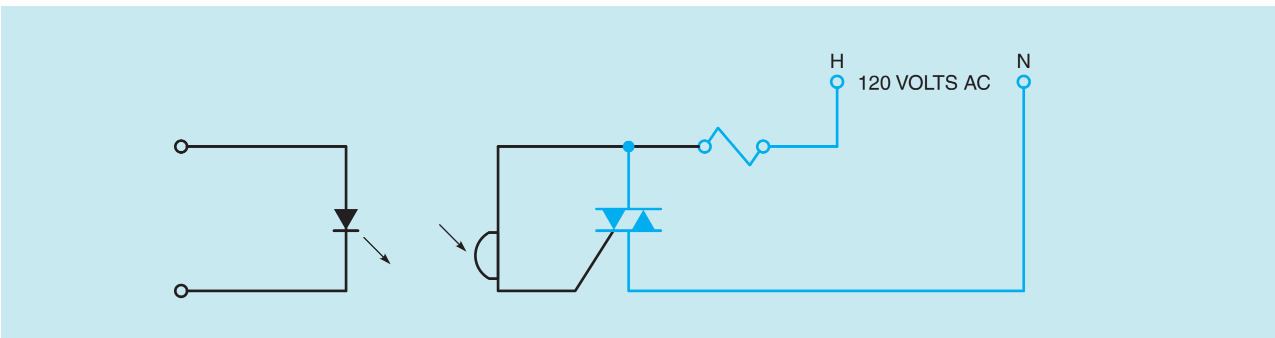


Figure 66–16 An output controls a solenoid.

Inputs are programmed in a similar manner. If a contact is inserted in the program and assigned the number 256 or less, the contact will be changed when a voltage is sensed at that input point. For example, assume that a normally open contact has been programmed into the circuit and assigned number 22. When voltage is applied to input number 22, the contact will close. Since 22 is used as an input in this circuit, care must be taken not to assign number 22 to a coil. Terminal number 22 cannot be used as both an input and an output at the same time.

Counters and Timers

The internal relays of a programmable controller can be used as counters and timers. When timers are used, most of them are programmed in .1 second time intervals. For example, assume that a timer is to be used to provide a delay of 10 seconds. When the delay time is assigned to the timer, the number 00100 is used. This means the timer has been set for 100 tenths of a second which is 10 seconds.

Off-Delay Circuit

The internal timers of a programmable controller function as on-delay relays. A simple circuit can be used, however, to change the sense of the on-delay timer to make it perform as an off-delay timer. Figure 66–17 is this type of circuit. The desired operation of the circuit is as follows. When contact 350 closes, relay coil 12 energizes immediately and turns on a solenoid valve. When contact 350 opens, coil 12 remains energized for 10 seconds before it de-energizes and turns off the solenoid.

This logic is accomplished as follows:

A. When contact 350 closes, internal relay 400 energizes.
B. When coil 400 energizes, normally open contact 400 closes and completes a circuit to coil 12, and normally closed contact 400 connected in series with timer TO-1 opens.
C. When relay coil 12 energizes, both normally open 12 contacts close, and the I/O output at terminal 12 connects the solenoid coil to the power line.
D. When contact 350 opens, internal relay 400 de-energizes.
E. This causes both 400 contacts to change back to their original positions.
F. When normally open contact 400 returns to its open state, a continued current path to coil 12 is maintained by the now closed contact 12 connected parallel to it.

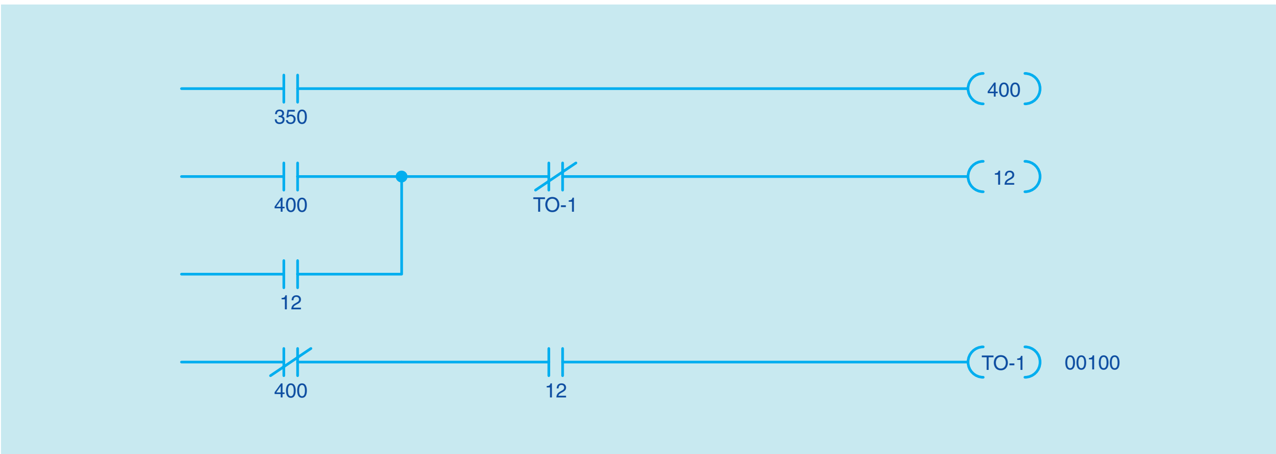


Figure 66–17 Off-delay circuit.

G. When normally closed contact 400 returns to its closed position, a circuit is completed through the now closed contact 12 to coil TO-1.
H. When coil TO-1 energizes, a 10second timer starts. At the end of this time period, contact TO-1 opens and de-energizes coil 12.
I. When coil 12 de-energizes, both 12 contacts return to the open position and the I/O output turns the solenoid off.
J. Timer TO-1 de-energizes when contact 12 opens and the circuit is back in its original start condition.

The number of internal relays and timers contained in a programmable controller is determined by the memory capacity of the computer. As a general rule, PCs that have a large I/O capacity will have a large memory, and machines that have less I/O capacity will have less memory. The use of programmable controllers has steadily increased since their invention in the late 1960s. A PC can replace hundreds of relays and occupy only a fraction of the space. The circuit logic can be changed easily and quickly without requiring extensive hand rewiring. They have no moving parts or contacts to wear out, and their down time is less than an equivalent relay circuit. A programmable controller used to control a dc drive unit is shown in Figure 66–18.

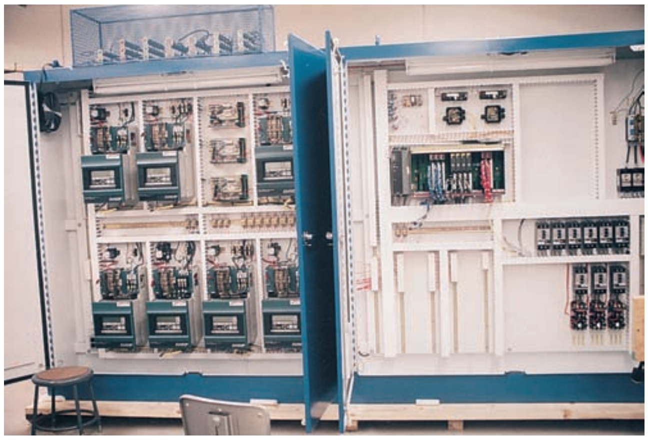


Figure 66–18 DC drive unit controlled by a programmable. (Courtesy Reliance Electric.)

The programming methods presented in this text are for one type of programmable controller. Although there are about as many different methods of programming a programmable controller as there are manufacturers, the concepts presented here are basic to all controllers. It will be necessary, however, to consult the instruction manual when using a particular brand of controller.

Review Questions

1. What industry first started using programmable controllers?
2. Name two differences between PCs and home or business computers.
3. Name the four basic sections of a programmable controller.
4. In what section of the programmable controller is the actual circuit logic performed?
5. What device is used to program the PC?
6. What device separates the programmable controller from the outside circuits?
7. What two functions are performed by an input I/O?
8. If an output I/O controls dc voltage. What electronic device controls the circuit?
9. If an output I/O controls ac voltage, what electronic device controls the circuit?
10. What is an internal relay?

UNIT 67
PROGRAMMING A PLC

OBJECTIVES

After studying this unit, the student will be able to:

- Convert a relay schematic to a schematic used for programming a PC.
- Enter a program into a programmable controller.

In this unit a relay schematic will be converted into a diagram used to program a programmable controller. The process to be controlled is shown in Figure 67–1. A tank is used to mix two liquids. The control circuit operates as follows:

A. When the start button is pressed, solenoids A and B energize. This permits the two liquids to begin filling the tank.

B. When the tank is filled, the float switch trips. This de-energizes solenoids A and B and starts the motor used to mix the liquids together.

C. The motor is permitted to run for one minute. After one minute has elapsed, the motor turns off and solenoid C energizes to drain the tank.

D. When the tank is empty, the float switch de-energizes solenoid C.

E. A stop button can be used to stop the process at any point.

F. If the motor becomes overloaded, the action of the entire circuit will stop.

G. Once the circuit has been energized it will continue to operate until it is manually stopped.

Circuit Operation

A relay schematic that will perform the logic of this circuit is shown in Figure 67–2. The logic of this circuit is as follows:

A. When the start button is pushed, relay coil CR is energized. This causes all CR contacts to close. Contact CR-1 is a holding contact used to maintain the circuit to coil CR when the start button is released.

B. When contact CR-2 closes, a circuit is completed to solenoid coils A and B. This permits the two liquids that are to be mixed together to begin filling the tank.

C. As the tank fills, the float rises until the float switch is tripped. This causes the normally closed float switch contact to open and the normally open contact to close.

D. When the normally closed float switch opens, solenoid coils A and B de-energize and stop the flow of the two liquids into the tank.

E. When the normally open contact closes, a circuit is completed to the coil of a motor starter and the coil of an on-delay timer. The motor is used to mix the two liquids together.

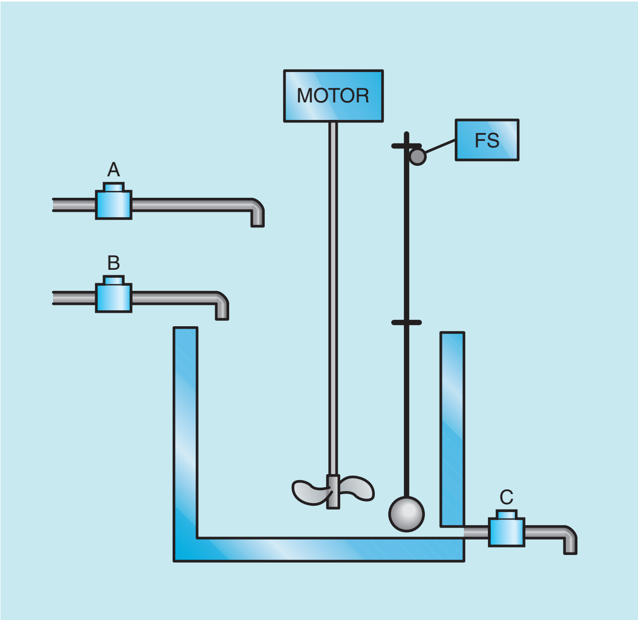


Figure 67–1 Tank used to mix two liquids.

F. At the end of the one minute time period, all of the TR contacts change position. The normally closed TR-2 contact connected in series with the motor starter coil opens and stops the operation of the motor. The normally open TR-3 contact closes and energizes solenoid coil C which permits liquid to begin draining from the tank. The normally closed TR-1 contact is used to assure that valves A and B cannot be re-energized until solenoid C de-energizes.

G. As liquid drains from the tank, the float drops. When the float drops far enough, the float switch trips and its contacts return to their normal positions. When the normally open float switch contact reopens and de-energizes coil TR, all TR contacts return to their normal positions.

H. When the normally open TR-3 contact reopens, solenoid C de-energizes and closes the drain valve. Contact TR-2 recloses, but the motor cannot restart because of the normally open float switch contact.

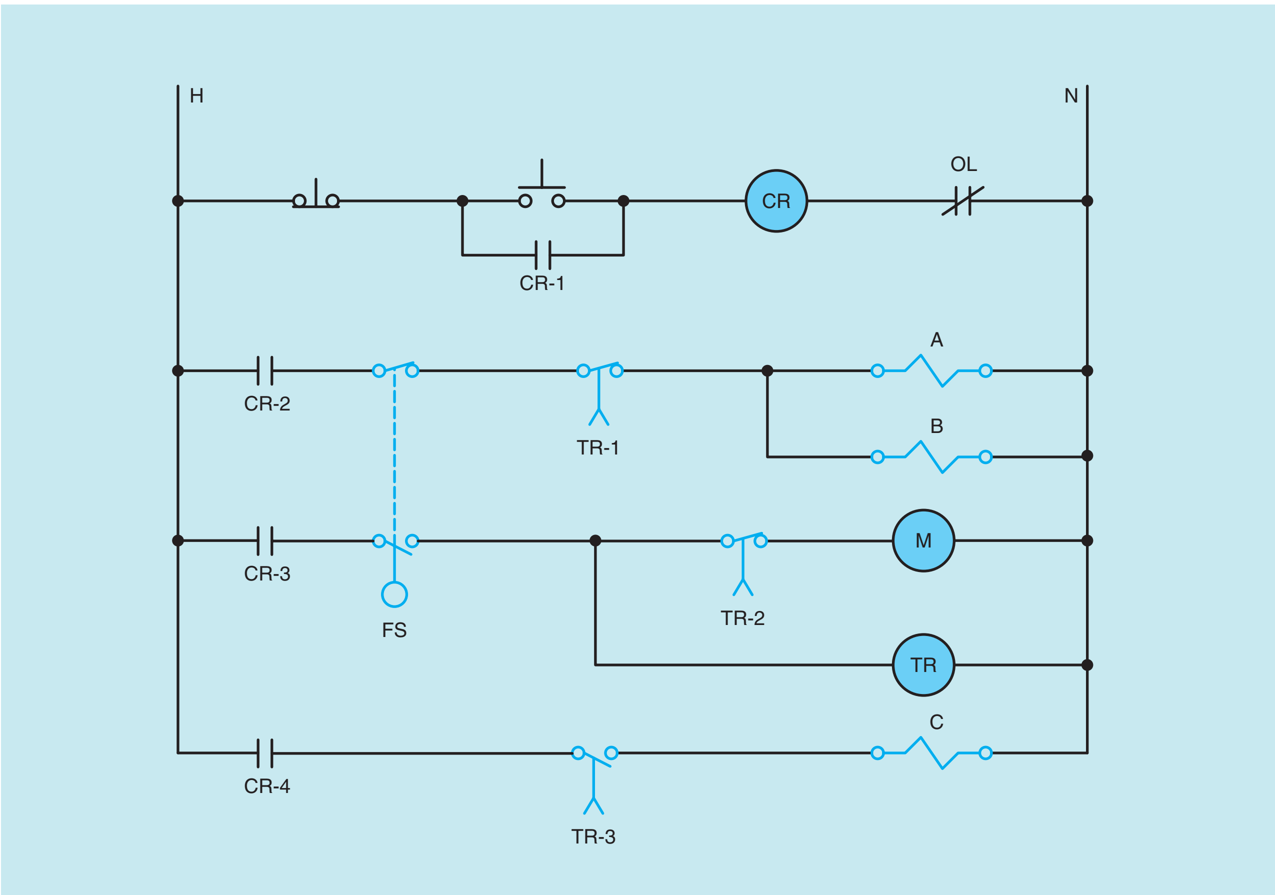


Figure 67–2 Relay schematic.

When contact TR- 1 recloses, a circuit is completed to solenoids A and B. This permits the tank to begin refilling, and the process starts over again.

I. If the stop button or overload contact opens, coil CR de-energizes and all CR contacts open. This de-energizes the entire circuit.

Developing a Program

This circuit will now be developed into a program which can be loaded into the programmable controller. Figure 66–3 shows a program being developed on a computer. Assume that the controller has an I/O capacity of 32, that I/O terminals 1 through 16 are used as inputs, and that terminals 17 through 32 are used as outputs.

Before a program can be developed for input into a programmable logic controller, it is necessary to assign which devices connect to the input and output terminals. This circuit contains four input devices and four output devices. It is also assumed that the motor starter for this circuit contains an overload relay that contains two contacts instead of one. One contact is normally closed and is connected in series with the coil of the motor starter. The other contact is normally open and is used to supply an input to a programmable logic controller. If the motor becomes overloaded, the normally closed contacts will open and disconnect the motor from the line. The normally open contacts will close and provide a signal to the programmable logic controller that the motor has tripped on overload. The input devices are as follows:

Figure 67–3 A program being developed on a programming terminal. (Courtesy GE Fanuc.)

a. Normally closed STOP push button

b. Normally open START push button

c. Normally open overload contact

d. A float switch that contains both a normally open and normally closed contact.

The four output devices are:

a. Solenoid valve A

b. Solenoid valve B

c. Motor starter coil M

d. Solenoid valve C

The connection of devices to the inputs and outputs is shown in Figure 67–4. The normally closed STOP button is connected to input #1, the normally open START button is connected to input #2, the normally open overload contact is connected to input #3, and the float switch is connected to input #4.

The outputs for this PLC are 17 through 32. Output #17 is connected to solenoid A, output #18 is connected to solenoid B, output #19 is connected to the coil of the motor starter, and output #20 is connected to solenoid C. Note that the outputs ***do not*** supply the power to operate the output devices. The outputs simply complete a circuit. One side of each output device is connected to the ungrounded or hot side of a 120 V ac power line. Neutral is connected to the common terminal of the four outputs. A good way to understand this is to imagine a set of contacts controlled by each output as shown in Figure 67–5. When programming the PLC, if a coil is given the same number as one of the outputs it will cause that contact to close and connect the load to the line.

Unfortunately, programmable logic controllers are not all programmed the same way. Almost every manufacturer employs a different set of coil numbers to perform different functions. It is necessary to consult the manual before programming a PLC with which you are not familiar. In order to program the PLC in this

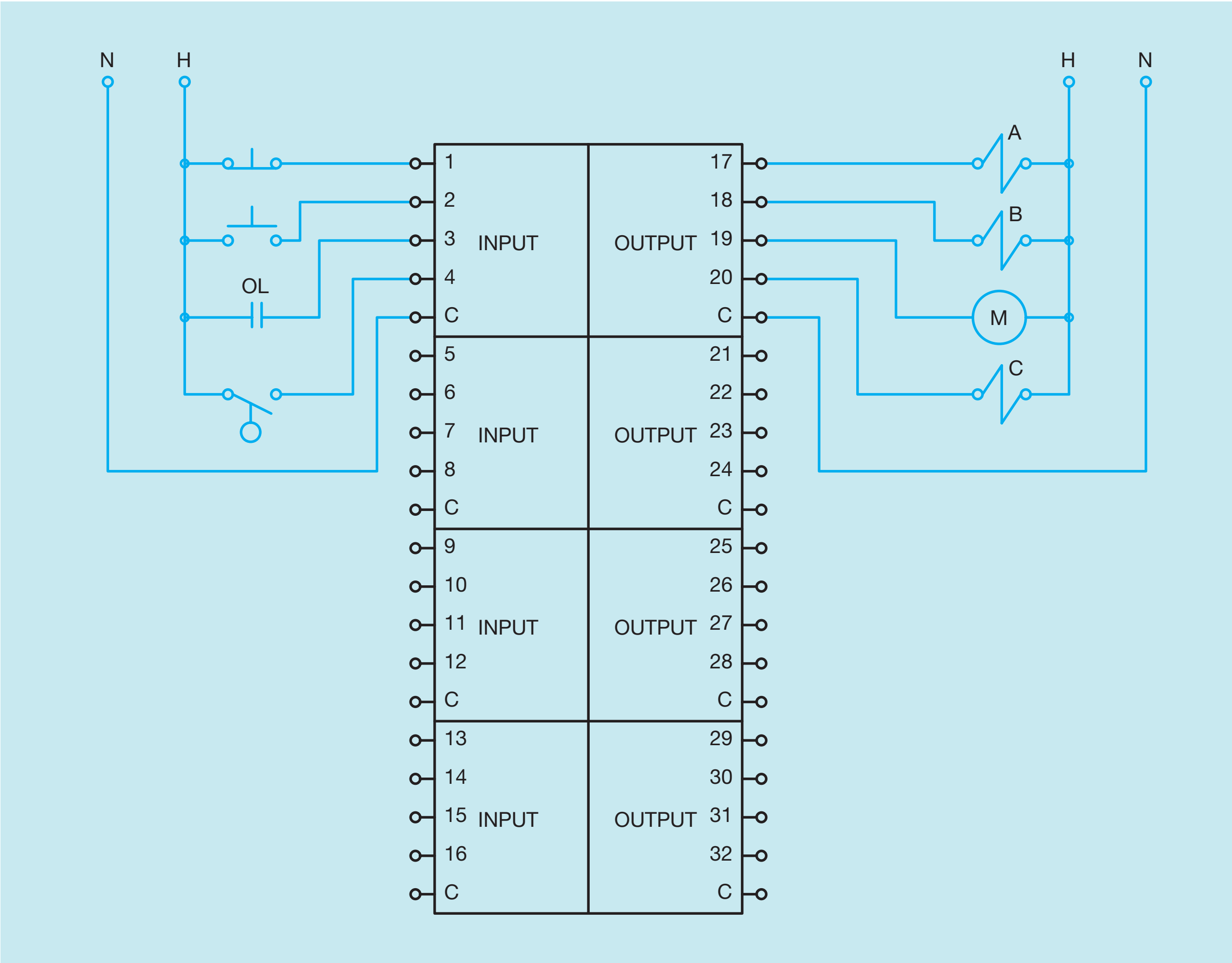


Figure 67–4 Components connected to I/O track.

example, refer to the information in Figure 67–6. This chart indicates that numbers 1 through 16 are inputs. Any contact assigned a number between 1 and 16 will be examined each time the programmable logic controller scans the program. If an input has a low (0 V) state, the contact assigned that number will remain in the state it was programmed. If the input has a high (120 V) state, the program will interpret that contact as having changed state. If it was programmed as open, the PLC will now consider it as closed.

Outputs are 17 through 32. Outputs are treated as coils by the PLC. If a coil is given the same number as an output, that output will turn on (close the contact) when the coil is energized. Coils that control outputs can be assigned internal contacts as well. Internal contacts are contacts that exist in the logic of the program only. They do not physically exist. Since they do not physically exist, a coil can be assigned as many internal contacts as desired and they can be normally open or normally closed.

The chart in Figure 67–6 also indicates that internal relays number from 33 to 103. Internal relays are like internal contacts. They do not physically exist. They exist as part of the program only. They are programmed into the circuit logic by inserting a coil symbol in the program and assigning it a number between 33 and 103.

Timers and counters are assigned coil numbers 200 through 264 and retentive relays are numbered 104 through 134.

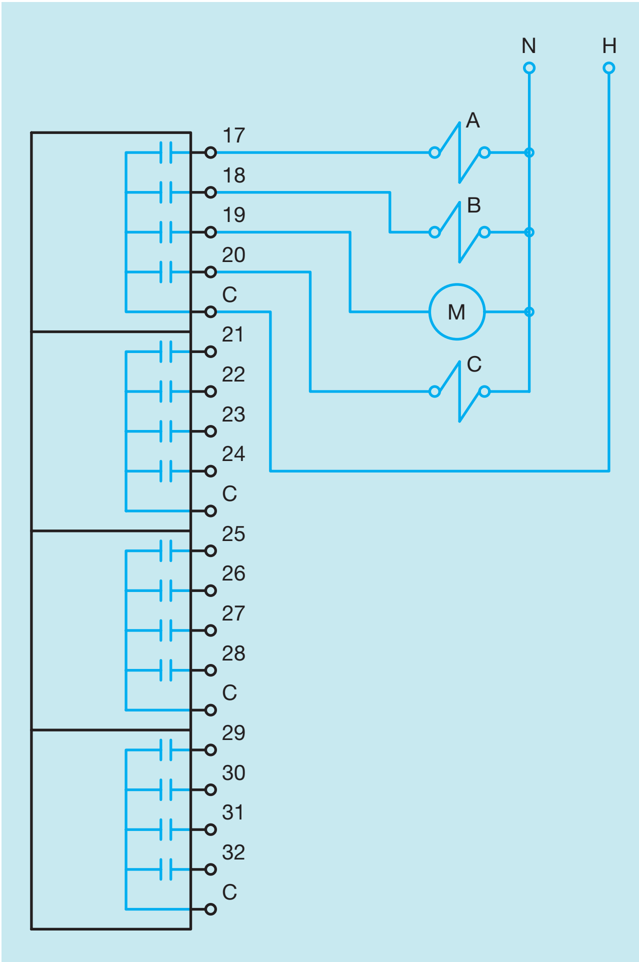


Figure 67–5 Output modules complete a circuit to connect the load to the line.

INPUTS	1 - 16
OUTPUTS	17 - 32
INTERNAL RELAYS	33 - 103
TIMERS AND COUNTERS	200 - 264
RETENTATIVE RELAYS	104 - 134

Figure 67–6 Numbers that correspond to specific PLC functions.

Converting the Program

Developing a program for a programmable logic controller is a little different than designing a circuit with relay logic. There are several rules that must be followed with almost all programmable logic controllers.

1. Each line of logic must end with a coil.
2. Coils cannot be connected in parallel.
3. The program will be scanned in the order that it is entered.
4. Generally, coils cannot be assigned the same number. (Some programmable logic controllers require reset coils to reset counters and timers. These reset coils can be assigned the same number as the counter or timer they reset.)

The first two lines of logic for the circuit shown in Figure 67–2 can be seen in Figure 67–7. Notice that contact symbols are used to represent inputs instead of logic symbols such as push buttons, float switches, etc. The programmable logic controller recognizes all inputs as open or closed contacts. It does not know what device is connected to which input. This is the reason that you must first determine which devices connect to which input before a program can be developed. Also notice that input #1 is shown as a normally open contact. Referring to Figure 67–4, it can be seen that input #1 is connected to a normally closed push button. The input is programmed as normally open because the normally closed push button will supply a high voltage to input #1 in normal operation. Since input #1 is in a high state, the PLC will change the state of the open contact and consider it closed. When the STOP push button is pressed, the input voltage will change to low and the PLC will change the contact back to its original open state and cause coil 33 to de-energize.

Referring to the schematic in Figure 67–2, a control relay is used as part of the circuit logic. Since the control relay does not directly cause any output device to turn on or off, an internal relay will be used. The chart in Figure 67–6 indicates that internal relays number between 33 and 103. Coil #33 is an internal relay and does not physically exist. Any number of contacts can be

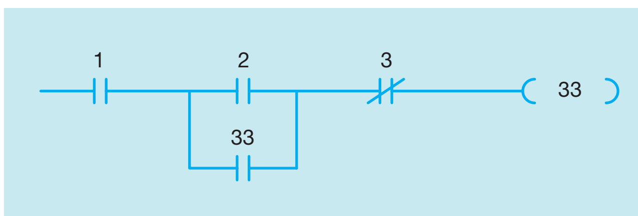


Figure 67–7 Lines 1 and 2 of the program.

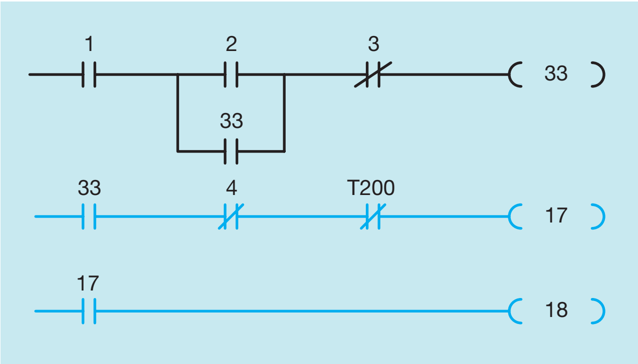


Figure 67–8 Lines 3 and 4 of the circuit are added.

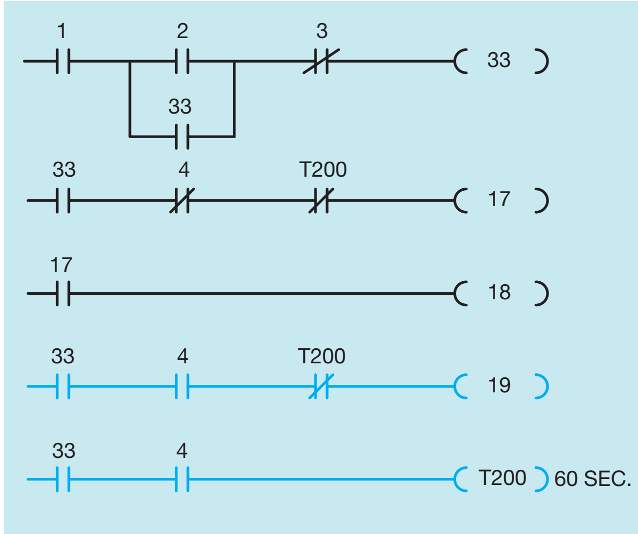


Figure 67–9 Lines 5 and 6 are added to the program.

assigned to this relay and they can be open or closed. The #33 contact connected in parallel with input #2 is the holding contact, labeled CR-1 in Figure 67–2.

The next two lines of logic are shown in Figure 67–8. The third line of logic in the schematic in Figure 67–2 contains a normally open CR-2 contact, a normally closed float switch contact, a normally closed on delay timed contact and solenoid coil A. The fourth line of logic contains solenoid coil B connected in parallel with solenoid coil A. Line 3 in Figure 67–8 uses a normally open contact, assigned the number 33 for contact CR-2. A normally closed contact symbol is assigned the number 4. Since the float switch is connected to input #4, it will control the action of this contact. As long as input #4 remains in a low state, the contact will remain closed. If the float switch should close, input #4 will become high and the number 4 contact will open. The next contact is timed contact TR-1. The chart in Figure 67–6 indicates that timers and counters are assigned numbers 200 through 264. In this circuit, timer TR will be assigned #200. Line 3 ends with coil #17. When coil 17 becomes energized, it will turn on output 17 and connect solenoid coil A to the line.

The schematic in Figure 67–2 shows that solenoid coil B is connected in parallel with solenoid coil A. Programmable logic controllers do not permit coils to be connected in parallel. Each line of logic must end with its own coil. Since solenoid coil B is connected in parallel with A, they both operate at the same time. This logic can be accomplished by assigning an internal contact the same number as the coil controlling output 17. Notice in Figure 67–8 that when coil 17 energizes it will cause contact 17 to close and energize output 18 at the same time.

In Figure 67–9, lines 5 and 6 of the schematic are added to the program. A normally open contact assigned number 33 is used as contact CR-3. A normally open contact assigned the number 4 is controlled by the float switch, and a second normally closed timed contact controlled by timer 200 is programmed in line 5. The output coil is assigned the number 19. When this coil energizes it turns on output 19 and connects motor starter coil M to the line.

Line 6 contains timer coil TR. Notice in Figure 67–2 that coil TR is connected in parallel with contact TR-2 and coil M. As was the case with solenoid coils A and B, coil TR cannot be connected in parallel with coil M. According to the schematic in Figure 67–2, coil TR is actually controlled by contacts CR-3 and the normally open float switch. This logic can be accomplished as shown in Figure 67–9 by connecting coil T200 in series with contacts assigned the numbers 33 and 4. Float switches do not normally contain this many contacts, but since the physical float switch is supplying a high or low voltage to input 4, any number of contacts assigned the number 4 can be used.

The last line of the program is shown in Figure 67–10. A normally open contact assigned the number 33 is used for contact CR-4 and a normally open contact controlled by timer T200 is used for the normally open timed contact labeled TR-3. Coil 20 controls the operation of solenoid coil C.

The circuit shown in Figure 67–2 has not been converted to a program that can be loaded into a programmable logic controller. The process is relatively simple if the rules concerning PLCs are followed.

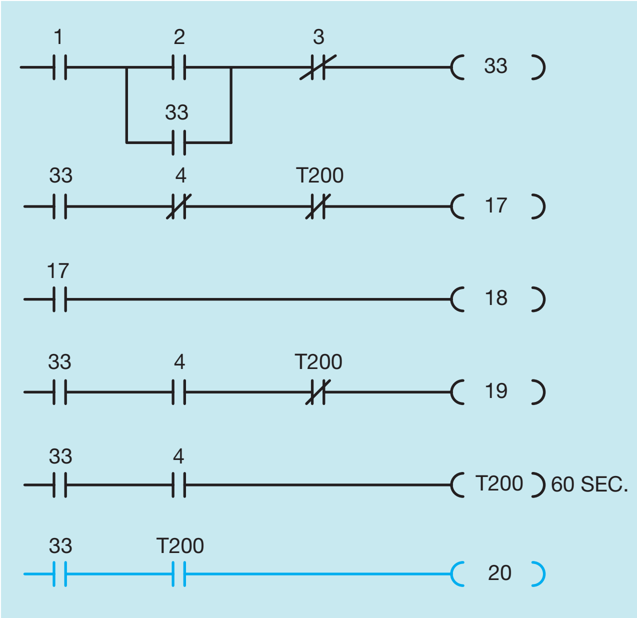


Figure 67–10 Line 7 of the program.

Programming in Boolean

The preceding example circuit was developed for one specific type of programmable controller. It was intended as an example of how to develop and enter a program into the logic of the CPU using a programmable terminal similar to the one shown in Figure 66–4. There may be times when it is necessary to use a small programming device which is hand held or which attaches directly to the CPU when entering a program. Units of this type are shown in Figure 67–11. This programming unit can be used with the SERIES ONE group of programmable controllers manufactured by GE Fanuc Automation. The following program will be developed for entry into the SERIES ONE using the hand-held programmer.

Developing the Program

The following program will be used as a trouble annunciator: A pressure switch is to be connected to the input of a programmable controller. When the pressure rises to a preset point, an audible alarm will be sounded and a warning light will flash off and on. When the operator acknowledges the trouble, the audible alarm will be silenced, but the warning light will continue to flash on and off until the pressure returns to a safe level.

Parameters of the Programmable Controller

Before the program can be developed, the parameters of the programmable controller being used must be known. Because the SERIES ONE programmable controller is being used in this example, its parameters will be discussed. An operations and programming guide for the SERIES ONE is shown in Figure 67–12 (Page 476). All coil and I/O references must be entered in *OCTAL. OCTAL* is a number system which contains only eight digits, 0 through 7. The numbers 8 and 9 are not used because they do not exist as far as the computer is concerned. This does not mean that the numbers 8 and 9 cannot be used when entering times for a timer. This applies only to the way inputs, outputs, and internal relays are identified. For example, any programmable controller that is octal base will not use the numbers 8 or 9. The I/O points for this unit are 000 through 157. Assume the first I/O module used with this controller contains eight units, and these eight units are inputs. The inputs will number from 0 to 7. Now, assume the next set of I/O's is an output module. Numbers 10 through 17 can be used as an output. Notice that numbers 8 and 9 are omitted. The programming guide indicates that a total of 144 internal coils exists. Coils 160 through 337 are nonretentive and coils 340 through 373 are retentive. There are a total of 64 timers and counters which begin with 600 and go through 677. Remember that there are no 8s or 9s. After timer 607 is used, the next timer will be 610.

The circuit shown in Figure 67–13 (Page 478) will be programmed into the controller using the small programming unit. The contacts labeled 0 and 1 are inputs. Contact 0 is connected to the normally open pressure switch which is used to sense the high pressure condition. Contact 1 is connected to the normally open push button used to acknowledge the fault and to turn off the audible alarm. Coils 10 and 11 are outputs. Coil 10 is connected to the warning light and coil 11 is connected to the audible alarm. Coils T600 and T601 are timers used to produce the flashing action of the warning light. In this circuit, the warning light will be on for 0.5 second and off for 0.5 second. Coil 160 is an internal relay.

Figure 67–11 Small programming unit attaches directly to the PLC.

Operation of the Circuit

The circuit operates in the following manner: When the pressure switch closes, all 0 inputs change position. This provides a current path to timer T600 which begins timing. A current path is provided to output 10 which turns on the warning light, and a current path is provided to the audible alarm turning it on. The normally open 0 contact connected in series with coil 160 closes. At the end of a half second, timer T600 times out and changes the position of all T600 contacts. The normally closed contact connected in series with the warning light opens and turns off output 10. The normally open T600 contact closes and permits timer T601 to begin timing. At the end of a half second, timer T601 opens its normally closed contact connected in series with timer T600. This causes timer T600 to reset and return all of its contacts to their

normal position. The normally closed T600 contact permits output 10 to turn on again, and the normally open T600 contact resets timer T601. When timer T601 resets, its contact returns to its normal position, and timer T600 begins timing again.

This condition continues until the operator presses the acknowledge button causing input contact 1 to close. Contact 1 completes a current path to internal relay 160. When internal relay 160 energizes, the normally open 160 contact closes and seals the circuit around contact 1. The normally closed 160 contact opens and turns off the audible alarm. At this time in the circuit, the audible alarm has been turned off, but the warning light is flashing on and off at half-second intervals. This will continue until the pressure drops to a safe level and input 0 reopens all of its contacts causing the circuit to reset to its normal position.

Entering the Program

Now that the circuit has been developed, it must be entered into the memory of the CPU. When using a small programming terminal as shown in Figure 67–11, the program must be entered in a language called *Boolean.* When programming in Boolean, to connect one contact in series with another, the AND function must be used. To connect a contact in parallel with another, the OR function is used, To change a contact from open to closed, the NOT function is used. To start a line of the program, the STR function must be used, To end a line of the program, the OUT function is used except when programming a special function such as a timer or counter. When ending a line of the program with a timer, the TMR function is used; when ending the line with a counter, the CNT function is used. Each component of the program must be entered into memory using the ENT key. Some of the keys on this programming unit use serve two functions. The AND key, for example, is also used to enter the number 7 into the program. The NOT key is also used to enter the number 0 into the program. The second function keys are very similar to the dual purpose keys on a typewriter where the shift key is used to access the second function of a key. The same is true for this unit. The SHF key is used to cause the keys to perform their second function. Once the SHF key has been pressed, it will remain in effect until the ENT key is pressed. There is no need to hold the SHF key down when entering more than one digit into the program.

The first line of logic will be entered as follows:

STR SHF 0 ENT
AND NOT TMR SHF 601 ENT
TMR SHF 600 ENT
SHF .5 ENT

Notice that the STR command is used to start the line of logic. The SHF key must be pressed in order to permit the number 0 to be entered. The ENT command causes that instruction to be entered into the logic of the CPU. The AND function causes the next contact entered to be connected in series with the first contact, and the NOT command instructs the CPU that the contact is to be normally closed instead of normally open. The TMR command instructs the programmable controller that the contact is to be controlled by a timer. Since this line of logic is ended with a timer instead of a normal output or internal relay, the TMR command is used again to instruct the CPU that the last coil is a timer and not an internal relay or output. The CPU can interpret this last timer command to be a coil instead of a contact because directly following this command, the time of the timer had been entered instead of a tie command such as AND or OR. The time is entered with the use of a decimal point in this controller instead of assuming each time interval to be 0.1 second. Different programmable controllers use different methods to enter the time.

The second line of logic is entered as follows:

STR SHF 0 ENT
AND NOT TMR SHF 600 ENT
OUT SHF 10 ENT

The third line of logic is entered as follows:

STR TMR SHF 600 ENT
TMR SHF 601 ENT
SHF .5 ENT

The fourth line of logic is entered as follows:

STR SHF 0 ENT
AND NOT SHF 160 ENT
OUT SHF 11 ENT

The fifth and sixth lines of logic will be entered together because the sixth line of logic is connected in parallel with the fifth:

STR SHF 1 ENT
OR SHF 160 ENT
AND SHF 0 ENT
OUT SHF 160 ENT

This completes the programming of the circuit into the CPU.

MEMORY TYPE	VALID REFERENCES (OCTAL)	QUANTITY (DECIMAL)
SERIES ONE		
I/O Points	000-157	112 total
Internal Coils		144 total
Non-Retentive	160-337	112
Retentive Coils	340-373	28
Initial Reset	374	1
O.I. Second Clock	375	1
Disable All Outputs	376	1
Back-Up Battery Status	377	1
Shift Registers	400-577	128 steps
Timer/Counters	600-677	64 (1)
Sequencers	600-677	64 (1000 steps)
SERIES ONE PLUS		
I/O Points	000-157 700-767	168 total
Internal Coils		144 total
Non-Retentive	160-337	112
Retentive Coils	340-373	28
Initial Reset	374	1
O.I. Second Clock	375	1
Disable All Outputs	376	1
Back-Up Battery Status	377	1
Shift Registers	400-577 (2)	128 steps
Timer/Counters	600-677	64 (1)
Sequencers	600-677	64 (1000 steps)
Data Registers	400-577 (2)	64 (16-bit)

(1) Total maximum number of Timers and/or Counters
(2) Shift register and data register references are identical, however, shift registers operate on bits, while data registers (located in a totally different area of memory) operate on bytes

MODE SWITCH

POSITION	FUNCTION
RUN	CPU scans logic, outputs enabled
PROG	Enter/Edit logic, no scanning
LOAD	Controls transfer to and from external device (recorder, printer, PROM writer)

STATUS INDICATORS

ON/OFF	Operating state of I.O. internal coils or shift registers.
RUN	ON=CPU in RUN mode
BATT	ON=Lithium battery voltage low
PWR	ON=Power supply DC voltage normal
CPU	ON=CPU internal fault Watchdog timer timed out low DC voltage

LOGIC AND EDITING KEYS

KEY	DESCRIPTION
F	(Series One Plus Only) Entered before a 2-digit number to select a data operation.
R	(Series One Plus Only) Entered before a 3-digit data register or 2-digit group reference when programming data operations.
AND	Places logic in series with previous logic.
OR	Places logic in parallel with previous logic.
STR	Starts a new line or group of logic.
NOT	Specifies a normally closed contact when used with AND/OR.
OUT	Ends line of logic with a coil, can be an output.
TMR	Specifies a timer function.
CNT	Specifies a counter function.
SR	Specifies a shift register function.
MCS	Begins a master control relay function.
MCR	Ends a master control relay function.
SET	Specifies a latched coil or used to force an I/O reference on.
RST	Turns off a latched coil or forces an I/O reference off.
DEL	Included in sequence for removing (deleting) an instruction from program memory.
INS	Included in sequence for adding (inserting) an instruction in program memory.
ENT	Causes logic to be placed in program memory.
CLR	Removes (clears) previous logic entry, acknowledges error codes, causes memory address to be displayed when monitoring a program.
SHF	Selects shifted functions (upper label above keys).
SCH	Used when initiating a search function.
PRV	Selects previous logic or function, and when monitoring, selects the previous group of 8 references.
NXT	Selects the next logic function. When monitoring, selects the next group of 8 references.
0 to 9	SHIFTED FUNCTION. Selects numerical values.
•	SHIFTED FUNCTION. Selects decimal point when entering numerical values, (timers using XXX.X seconds).
MON	SHIFTED FUNCTION. Selects monitor operation.
CHECK	SHIFTED FUNCTION. Initiates verify operation with peripheral.
READ	SHIFTED FUNCTION. Initiates loading of CPU memory from a peripheral.
WRITE	SHIFTED FUNCTION. Initiates writing (recording) program in CPU memory to a peripheral.

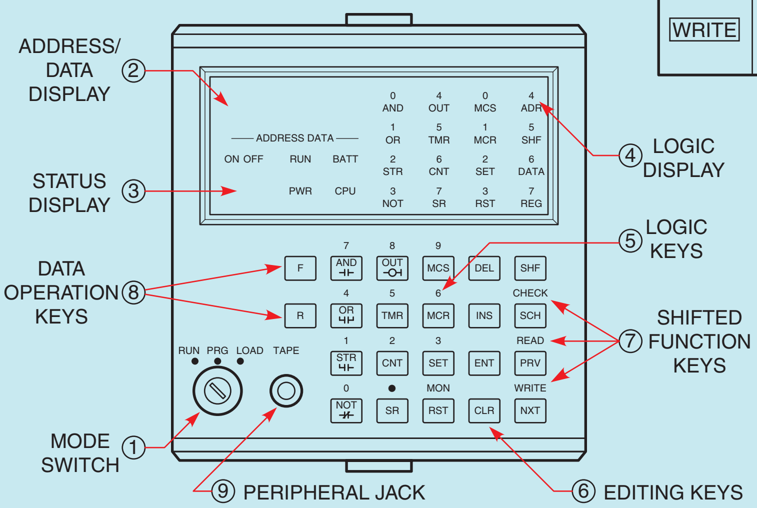


Figure 67–12 Programming guide for a SERIES ONE programmable controller. (Courtesy GE Fanuc Automation North America Inc.)

PROGRAMMER OPERATION

OPERATION	KEYSTROKES	MODE* R	P	L
Clear all memory.	[CLR] [SHF] [0] [0] [0] [DEL] [NXT]		X	
Display present address.	[CLR]	X	X	
Display present function.	[NXT]	X	X	
Next function.	[NXT]	X	X	
Previous function.	[PRV]	X	X	
Go to first function in program memory (address 0000).	[SHF] [NXT]	X	X	
Go to specific memory address.	[SHF] (Address) [NXT]	X	X	
Search for a specific function.	(Function) [SHF] (Ref.No.) [SCH] [NXT]	X	X	
Search for a specific reference number.	[SHF] (Ref. No.) [SCH] [NXT]	X	X	
Insert function before the displayed function (or address).	(Function) [SHF] (Ref.No.) [INS] [NXT]		X	
Delete function.	(Address) [DEL] [PRV]		X	
Edit a program.	(Address) (Function) [SHF] (Ref.No.) [ENT]		X	
Check program for errors. If none, next empty address is displayed.	[CLR] [SCH]	X	X	
Change T/C preset.	(Address) [SHF] (preset) [ENT]	X		
Mon. ON/OFF state of contact or coil.	Observe ON/OFF LED when coil or contact is selected.	X		
Monitor group of 8 consecutive references (I/O, internal coils, SR coils).	[SHF] (Beginning Ref.No.) [MON]	X		
Monitor timer or counter accumulate register.	[SHF] (T/C No.) [MON]	X		
Force a reference ON (will be overridden by user logic).	[SET] [SHF] (Ref.No.) [ENT]	X		
Force a reference OFF (will be overridden by user logic).	[RST] [SHF] (Ref.No.) [ENT]	X		
Enter a function into program memory.	(Function) [SHF] (Ref.No.) [ENT]		X	
Write to tape, printer, or PROM writer.	(Optional Program ID) [WRITE]			X
Load program memory from tape.	(Optional Program ID) [READ]			X
Verify data on tape or in PROM writer RAM against program memory.	(Optional Program ID) [WRITE]			X

*R=RUN, P=PROGRAM, L=LOAD

Figure 67–12 *continued*

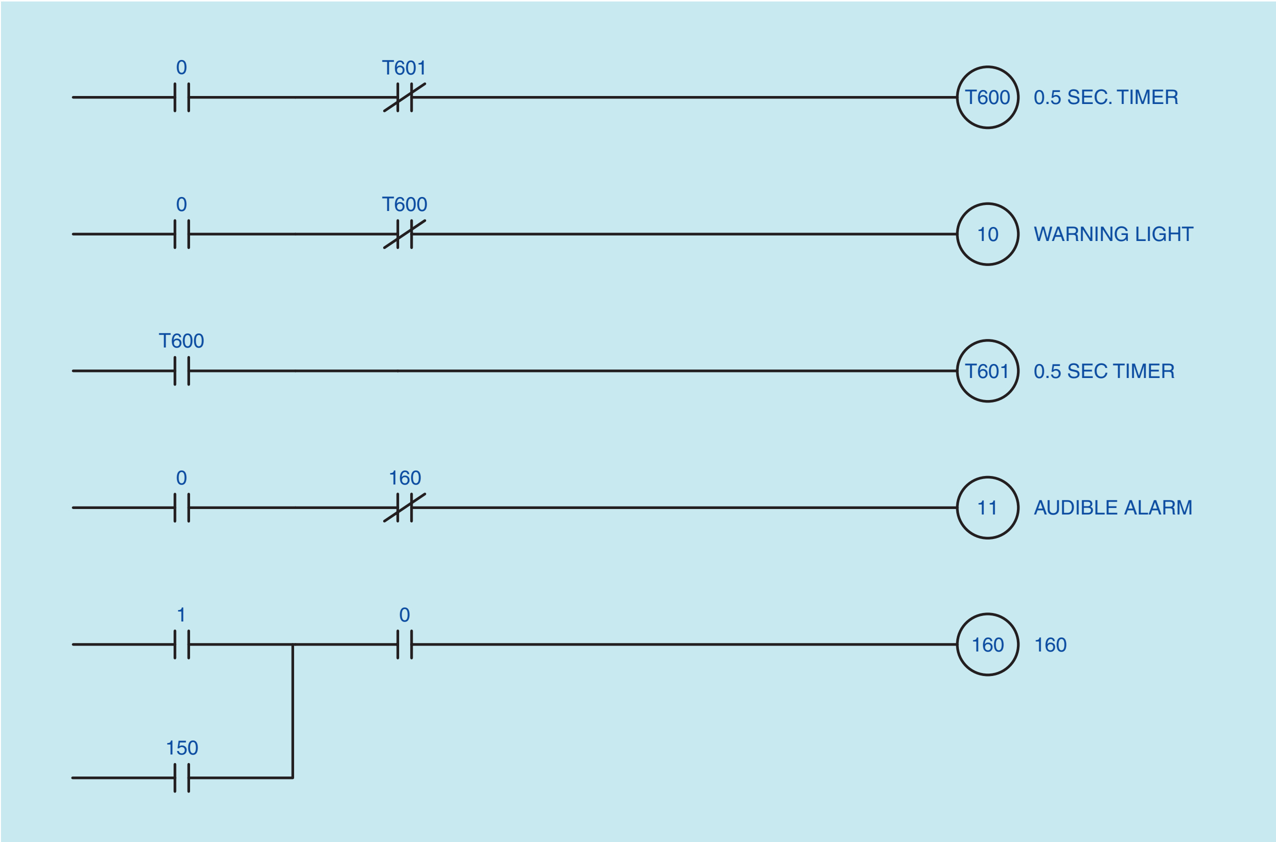


Figure 67–13 Warning light and alarm circuit.

Review Questions

1. Why are NEMA symbols representing such components as push buttons, limit switches, and float switches not used in a programmable controller schematic?
2. Explain how to program an internal relay into the controller.
3. Why are the contacts used to represent stop buttons and overload contacts programmed normally open?
4. Why is the output I/O used to energize a motor starter instead of energizing the motor directly?
5. A timer is to be programmed for a delay of 3 minutes. What number is used to set this timer?
6. When programming in Boolean, what command is used to connect two circuit components together in series?
7. When programming in Boolean, what command is used to connect two circuit components together in parallel?
8. When programming in Boolean, what command is used to change a contact from normally open to normally closed?
9. Why are the numbers 8 and 9 not used in an *OCTAL* based system?

UNIT 68

ANALOG SENSING FOR PROGRAMMABLE CONTROLLERS

OBJECTIVES

After studying this unit, the student will be able to:

- Describe the differences between analog and digital inputs.
- Discuss precautions that should be taken when using analog inputs.
- Describe the operation of a differential amplifier.

Many of the programmable controllers found in industry are designed to accept analog as well as digital inputs. Analog means continuously varying. These inputs are designed to sense voltage, current, speed, pressure, temperature, humidity, etc. When an analog input is used, a special module mounts on the I/O track of the PC. An analog sensor may be designed to operate between a range of settings, such as 50 to 300 C°, or 0 to 100 psi. These sensors are used to indicate between a range of values instead of merely operating in an on or off mode. An analog pressure sensor designed to indicate pressures between 0 and 100 psi would have to indicate when the pressure was 30 psi, 50 psi, or 80 psi. It would not just indicate whether the pressure had or had not reached 100 psi. A pressure sensor of this type can be constructed in several ways. One of the most common methods is to let the pressure sensor operate a current generator which produces currents between 4 and 20 milliamperes. It is desirable for the sensor to produce a certain amount of current instead of a certain amount of voltage because it eliminates the problem of voltage drop on lines. For example, assume a pressure sensor is designed to sense pressures between 0 and 100 psi. Also assume that the sensor produces a voltage output of 1 volt when the pressure is 0 psi and a voltage of 5 volts when the pressure is 100 psi. Since this is an analog sensor, when the pressure is 50 psi, the sensor should produce a voltage of 3 volts. This sensor is connected to the analog input of a programmable controller Figure 68 – 1. The analog input has a sense resistance of 250Ω. If the wires between the sensor and the input of the programmable controller are short enough (so that there is almost no wire resistance), the circuit will operate without a problem. Because the sense resistor in

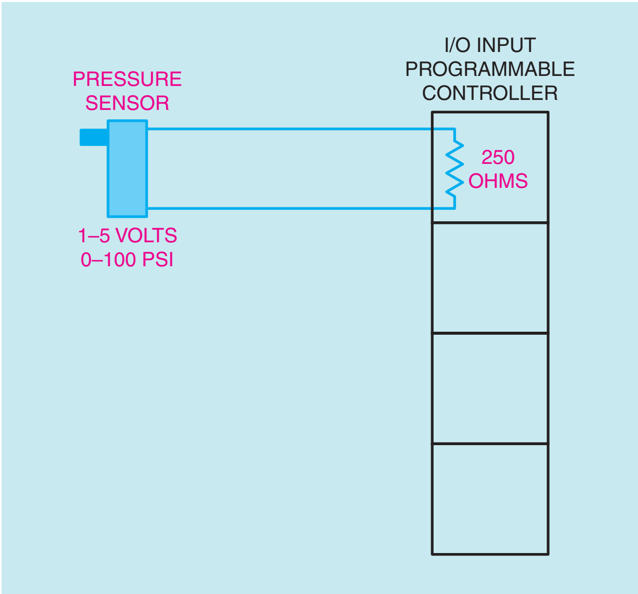


Figure 68–1 The pressure sensor produces one to five volts.

the input of the programmable controller is the only resistance in the circuit, all of the output voltage of the pressure sensor will appear across it. If the pressure sensor produces a 3-volt output, 3 volts will appear across the sense resistor.

If the pressure sensor is located some distance away from the programmable controller, however, the resistance of the two wires running between the pressure sensor and the sense resistor can cause inaccurate readings. Assume that the pressure sensor is located far enough from the programmable controller so that the two conductors have a total resistance of 50 Ω (Figure 68–2). This means that the total resistance of the circuit is now 300 Ω (250 + 50 = 300). If the pressure sensor produces an output voltage of 3 volts when the pressure reaches 50 psi, the current flow in the circuit will be 0.010 amp (3/300 = 0.010). Since there is a current flow of 0.010 through the 250 Ω sense resistor, a voltage of 2.5 volts will appear across it. This is substantially less than the 3 volts being produced by the pressure sensor.

If the pressure sensor is designed to operate a current generator with an output of 4 to 20 mA, the resistance of the wires will not cause an inaccurate reading at the sense resistor. Since the sense resistor and the resistance of the wire between the pressure sensor and the programmable controller form a series circuit, the current must be the same at the point in the circuit. If the pressure sensor produces an output current of 4 mA when the pressure is 0 psi and a current of 20 mA when the pressure is 100 psi, at 50 psi it will produce a current of 12 mA. When a current of 12 mA flows through the 250 sense resistor, a voltage of 3 volts will be dropped across it (Figure 68–3). Because the pressure sensor produces a certain amount of current instead of

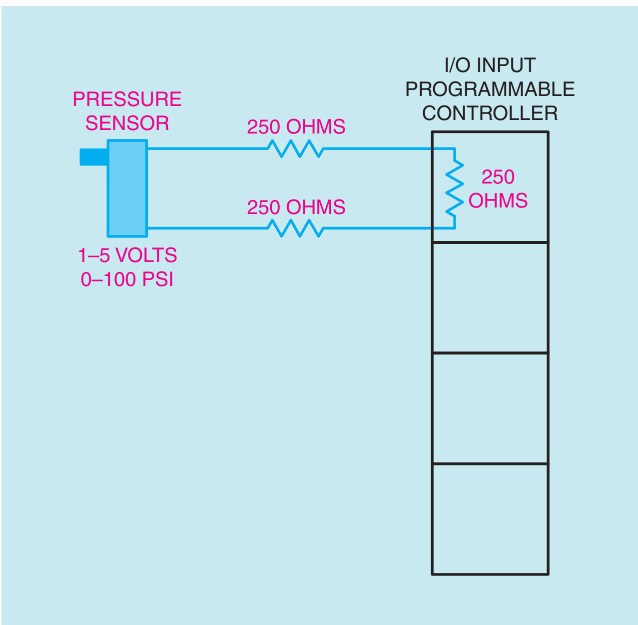


Figure 68–2 Resistance in the lines can cause problems.

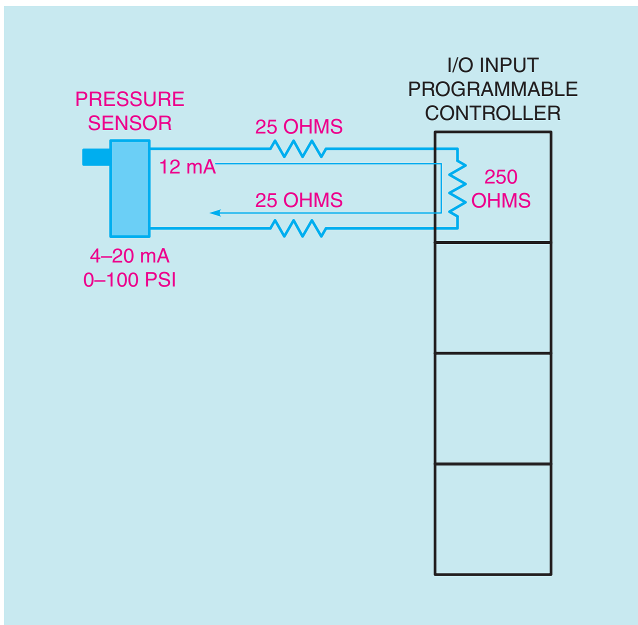


Figure 68–3 The current must be the same in a series circuit.

a certain amount of voltage with a change in pressure, the amount of wire resistance between the pressure sensor and programmable controller is of no concern.

Installation

Most analog sensors can produce only very weak signals—0 to 10 volts or 4 to 20 milliamps are common. In an industrial environment where intense magnetic fields and large voltage spikes abound, it is easy to lose the input signal in the electrical noise. For this reason, special precautions should be taken when installing the signal wiring between the sensor and the input module. These precautions are particularly important when using analog inputs, but they should also be followed when using digital inputs.

Keep Wire Runs Short

Try to keep wire runs as short as possible. A long wire run has more surface area of wire to pick up stray electrical noise.

Plan the Route of the Signal Cable

Before starting, plan how the signal cable should be installed. *Never run signal wire in the same conduit with power wiring.* Try to run signal wiring as far away from power wiring as possible. When it is necessary to cross power wiring, install the signal cable so that it crosses at a right angle as shown in Figure 68–4.

Use Shielded Cable

Shielded cable is used for the installation of signal wiring. One of the most common types, shown in Figure 68–5, uses twisted wires with a Mylar foil shield. The ground wire must be grounded if the shielding is to operate properly. This type of shielded cable can provide a noise reduction ratio of about 30,000 : 1.

Another type of signal cable uses a twisted pair of signal wires surrounded by a braided shield. This type of cable provides a noise reduction of about 300 : 1.

Common coaxial cable should be avoided. This cable consists of a single conductor surrounded by a braided shield. This type of cable offers very poor noise reduction.

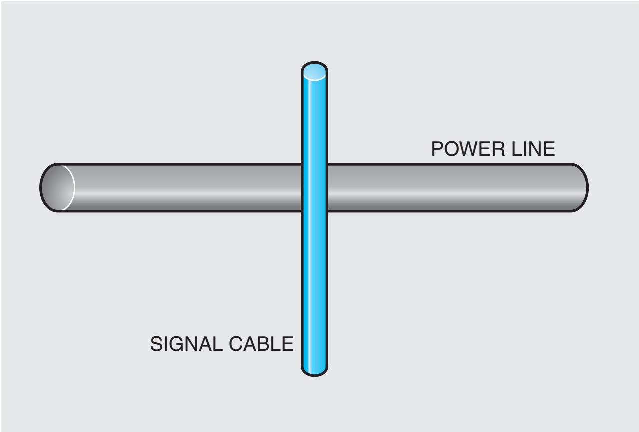


Figure 68–4 Signal cable crosses power line at right angle.

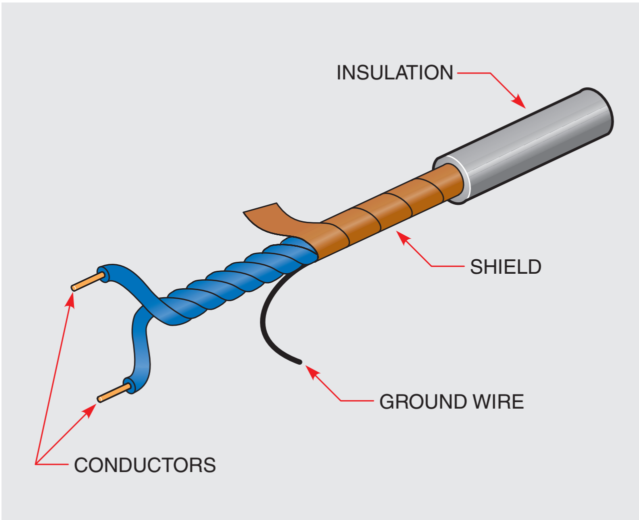


Figure 68–5 Shielded cable.

Grounding

Ground is generally thought of as being electrically neutral, or zero at all points. However, this may not be the case in practical application. It is not uncommon to find that different pieces of equipment have ground levels that are several volts apart (Figure 68–6).

To overcome this problem large cable is sometimes used to tie the two pieces of equipment together. This forces them to exist at the same potential. This method is sometimes referred to as the brute-force method.

Where the brute-force method is not practical, the shield of the signal cable is grounded at only one end. The preferred method is generally to ground the shield at the sensor.

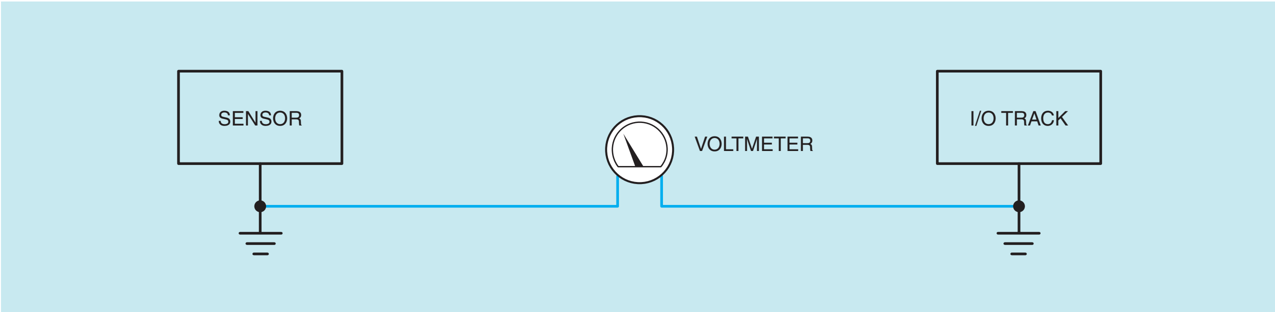


Figure 68–6 All grounds are not equal.

The Differential Amplifier

An electronic device that is often used to help overcome the problem of induced noise is the differential amplifier (Figure 68–7). This device detects the voltage difference between the pair of signal wires and amplifies this difference. Since the induced noise level should be the same in both conductors, the amplifier will ignore the noise. For example, assume an analog sensor is producing a 50-millivolt signal. This signal is applied to the input module, but induced noise is at a level of 5 volts. In this case the noise level is 100 times greater than the signal level. The induced noise level, however, is the same for both of the input conductors. Therefore, the differential amplifier ignores the 5-volt noise and amplifies only the voltage difference which is 50 millivolts.

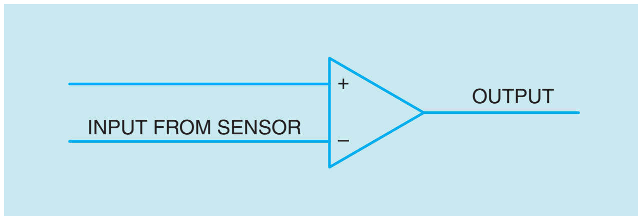


Figure 68–7 Differential amplifier detects difference in signal level.

Review Questions

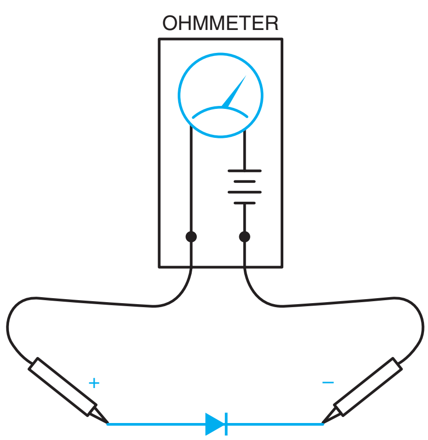
1. Explain the difference between digital inputs and analog inputs.
2. Why should signal wire runs be kept as short as possible?
3. When signal wiring must cross power wiring, how should the wires be crossed?
4. Why is shielded wire used for signal runs?
5. What is the brute-force method of grounding?
6. Explain the operation of the differential amplifier.

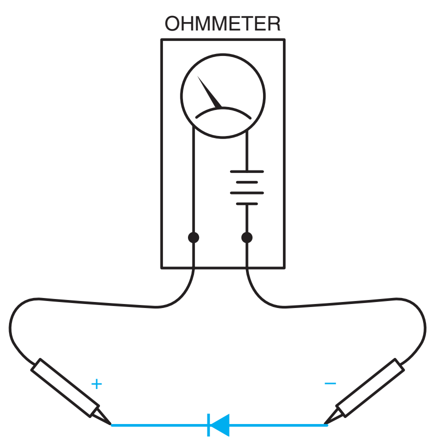
APPENDIX

Testing Solid-State Components

1. Testing a Diode

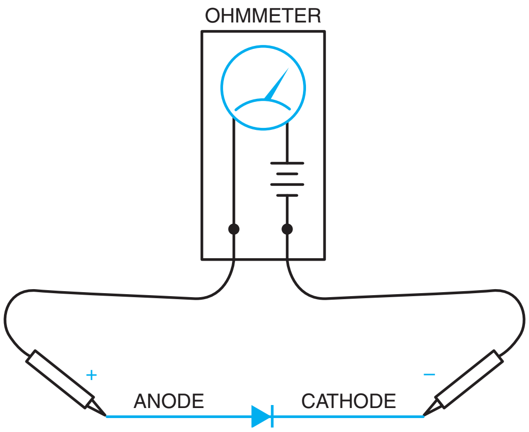
1. Connect the ohmmeter leads to the diode. Notice if the meter indicates continuity through the diode or not.
2. Reverse the diode connection to the ohmmeter. Notice if the meter indicates continuity through the diode or not. The ohmmeter should indicate continuity through the diode in only one direction. NOTE: If continuity is not indicated in either direction, the diode is open. If continuity is indicated in both directions, the diode is shorted.



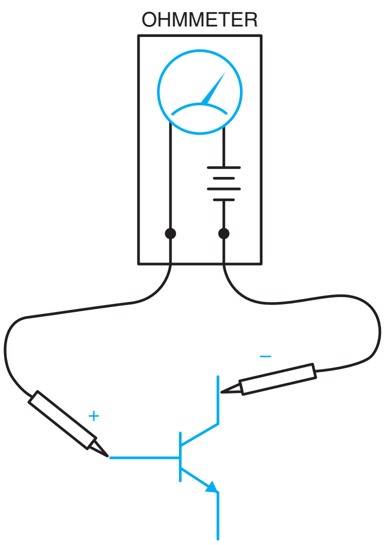


2. Testing a Transistor

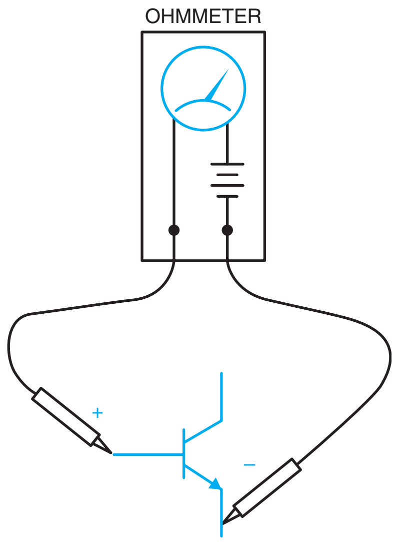
1. Using a diode, determine which ohmmeter lead is positive and which is negative. The ohmmeter will indicate continuity through the diode only when the positive lead is connected to the anode and the negative lead is connected to the cathode.



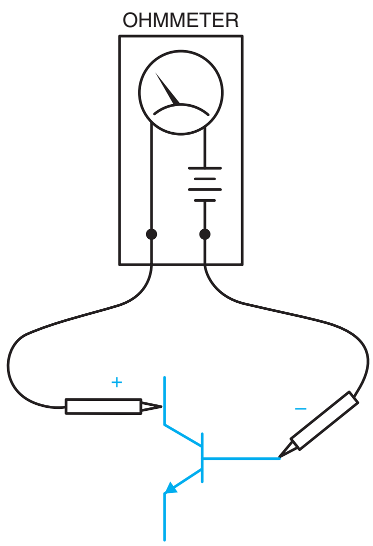
2. If the transistor is an NPN, connect the positive ohmmeter lead to the base and the negative lead to the collector. The ohmmeter should indicate continuity. The reading should be about the same as the reading obtained when the diode was tested.



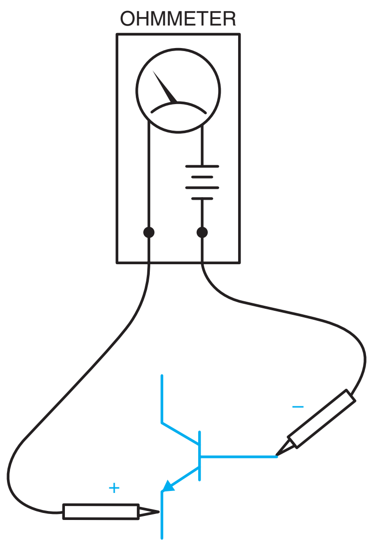
3. With the positive ohmmeter lead still connected to the base of the transistor, connect the negative lead to the emitter. The ohmmeter should again indicate a forward diode junction. NOTE: If the ohmmeter does not indicate continuity between the base-collector or the base-emitter, the transistor is open.



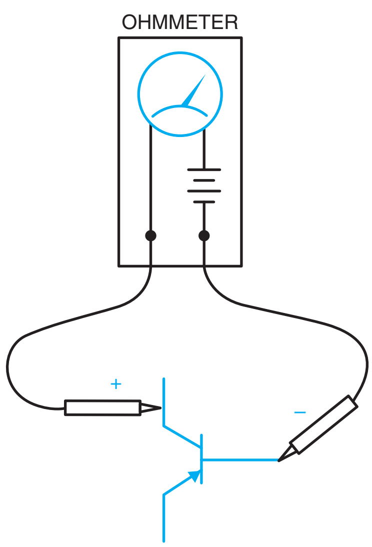
4. Connect the negative ohmmeter lead to the base and the positive lead to the collector. The ohmmeter should indicate infinity or no continuity.



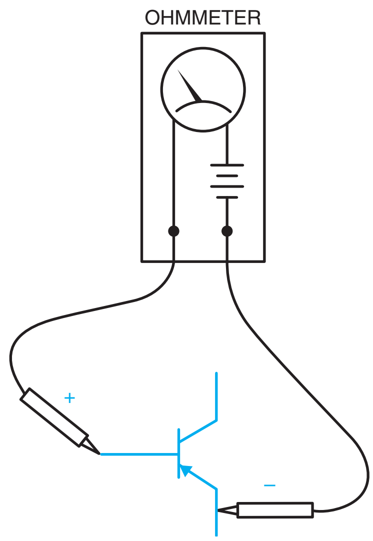
5. With the negative ohmmeter lead connected to the base, reconnect the positive lead to the emitter. There should, again, be no indication of continuity. NOTE: If a very high resistance is indicated by the ohmmeter, the transistor is "leaky" but it may still operate in the circuit. If a very low resistance is seen, the transistor is shorted.



6. To test a PNP transistor, reverse the polarity of the ohmmeter leads and repeat the test. When the negative ohmmeter lead is connected to the base, a forward diode junction should be indicated when the positive lead is connected to the collector or emitter.

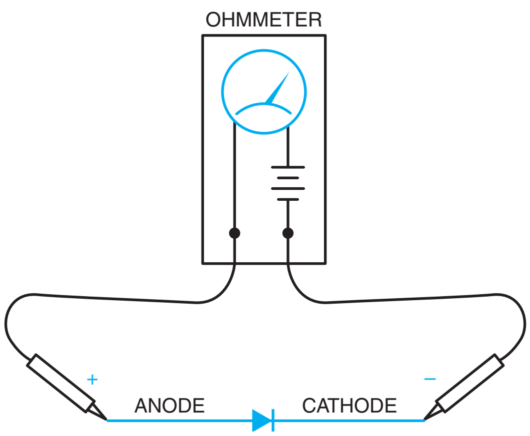


7. If the positive ohmmeter lead is connected to the base of a PNP transistor, no continuity should be indicated when the negative lead is connected to the collector or the emitter.

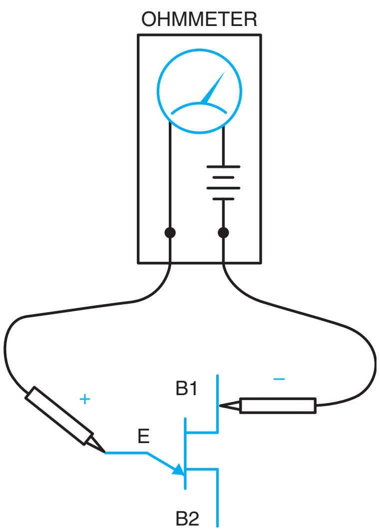


3. Testing a Unijunction Transistor

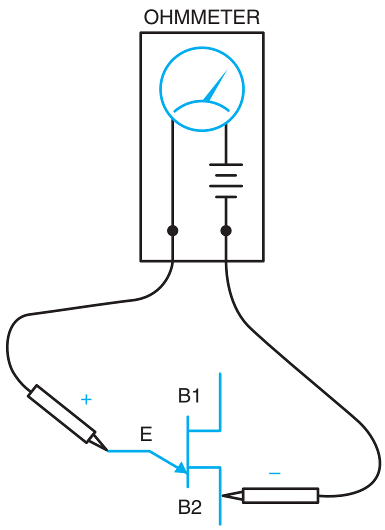
1. Using a junction diode, determine which ohmmeter lead is positive and which is negative. The ohmmeter will indicate continuity when the positive lead is connected to the anode and the negative lead is connected to the cathode.



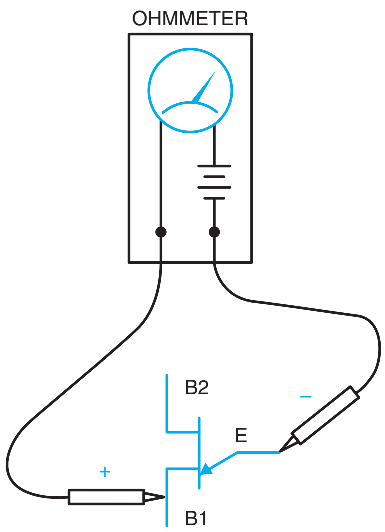
2. Connect the positive ohmmeter lead to the emitter lead and the negative lead to base #1. The ohmmeter should indicate a forward diode junction.



3. With the positive ohmmeter lead connected to the emitter, reconnect the negative lead to base #2. The ohmmeter should again indicate a forward diode junction.

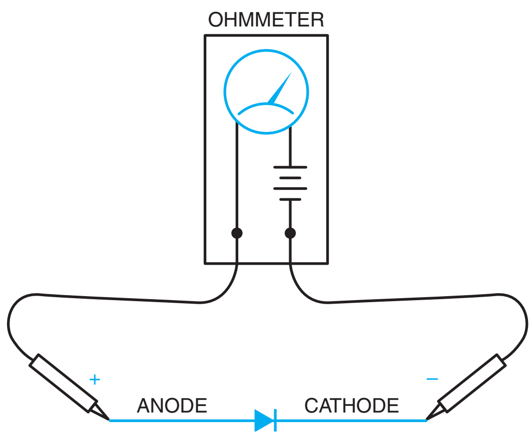


4. If the negative ohmmeter lead is connected to the emitter, no continuity should be indicated when the positive lead is connected to base #1 or base #2.

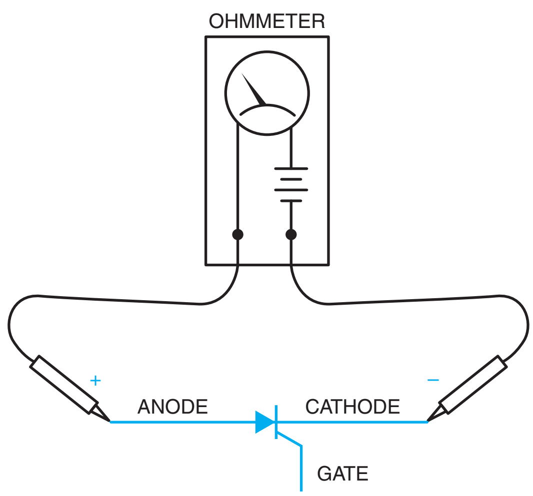


4. Testing an SCR

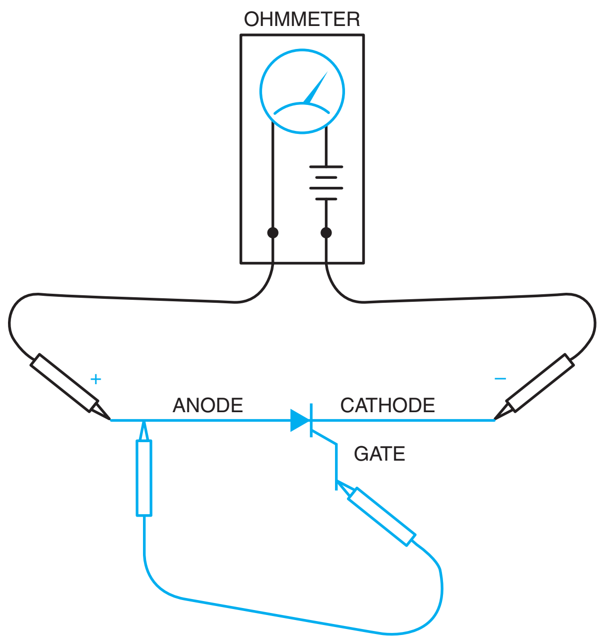
1. Using a junction diode, determine which ohmmeter lead is positive and which is negative. The ohmmeter will indicate continuity only when the positive lead is connected to the anode of the diode and the negative lead is connected to the cathode.



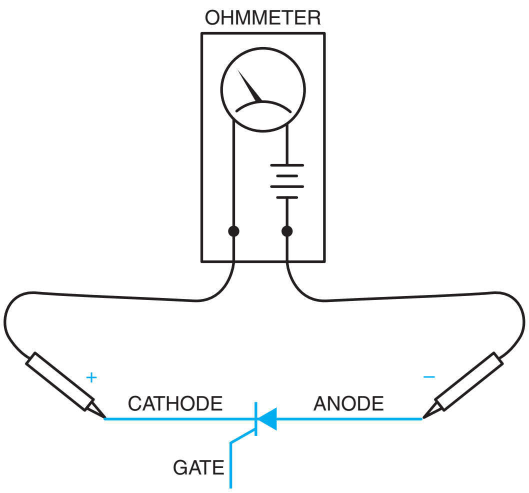
2. Connect the positive ohmmeter lead to the anode of the SCR and the negative lead to the cathode. The ohmmeter should indicate no continuity.



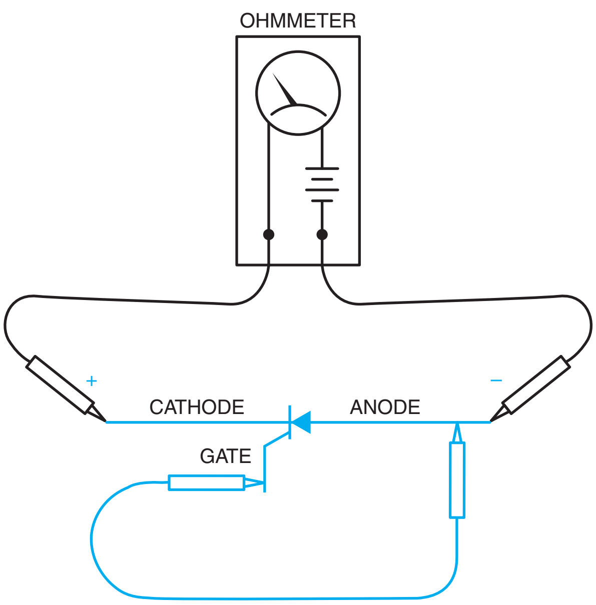
3. Using a jumper lead, connect the gate of the SCR to the anode. The ohmmeter should indicate a forward diode junction when the connection is made. NOTE: If the jumper is removed, the SCR may continue to conduct or it may turn off. This will be determined by whether or not the ohmmeter can supply enough current to keep the SCR above its holding current level.



4. Reconnect the SCR so that the cathode is connected to the positive ohmmeter lead and the anode is connected to the negative lead. The ohmmeter should indicate no continuity.

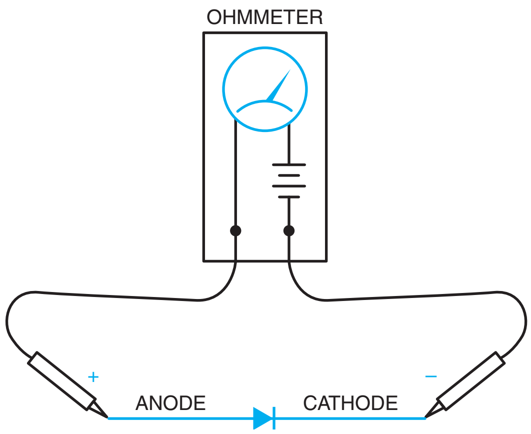


5. If a jumper lead is used to connect the gate to the anode, the ohmmeter should indicate no continuity. NOTE: SCRs designed to switch large currents (50 amperes or more) may indicate some leakage current with this test. This is normal for some devices.

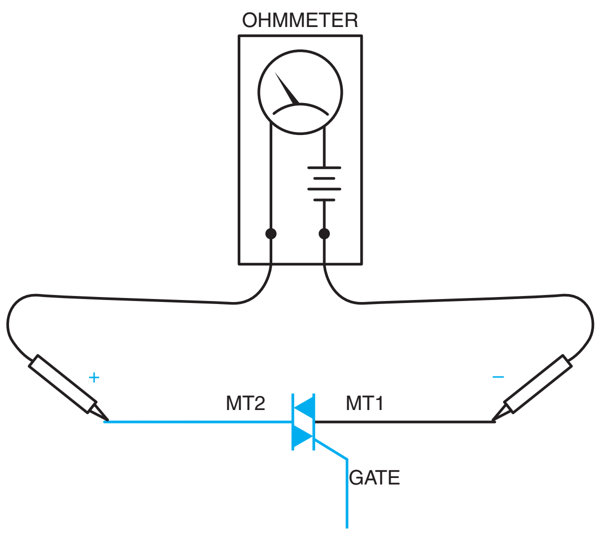


5. Testing a Triac

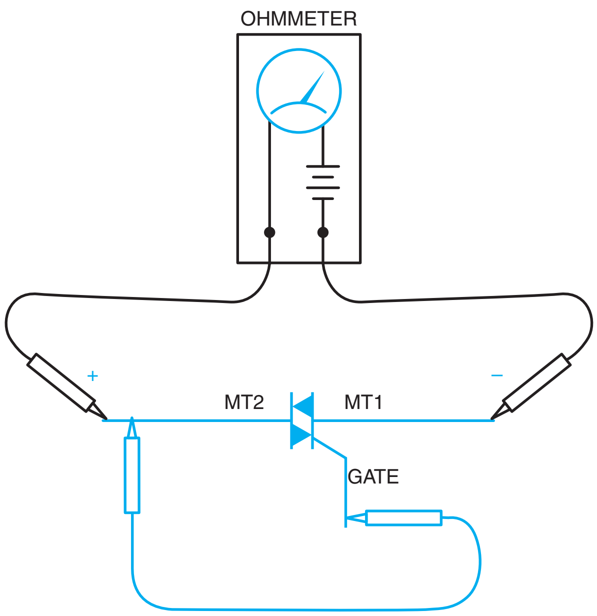
1. Using a junction diode determine which ohmmeter lead is positive and which is negative. The ohmmeter will indicate continuity only when the positive lead is connected to the anode and the negative lead is connected to the cathode.



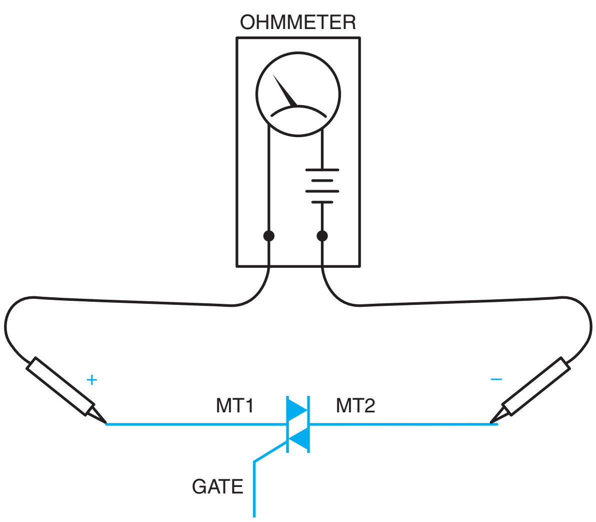
2. Connect the positive ohmmeter lead to MT2 and the negative lead to MT 1. The ohmmeter should indicate no continuity through the triac.



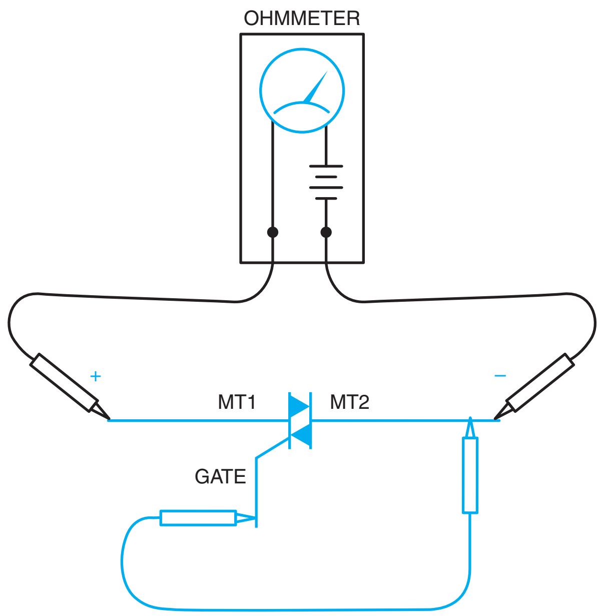
3. Using a jumper lead, connect the gate of the triac to MT2. The ohmmeter should indicate a forward diode junction.



4. Reconnect the triac so that MTl is connected to the positive ohmmeter lead and MT2 is connected to the negative lead. The ohmmeter should indicate no continuity through the triac.



5. Using a jumper lead, again connect the gate to MT2. The ohmmeter should indicate a forward diode junction.



Identifying the Leads of a Three-Phase, Wye-Connected, Dual-Voltage Motor

The terminal markings of a three-phase motor are standardized and used to connect the motor for operation on 240 or 480 volts. Figure A–1 shows these terminal markings and their relationship to the other motor windings. If the motor is to be connected to a 240-volt line, the motor windings are connected parallel to each other as shown in Figure A–2. If the motor is to be operated on a 480-volt line, the motor windings are connected in series as shown in Figure A–3.

As long as these motor windings remain marked with the proper numbers, connecting the motor for operation on a 240- or 480-volt power line is relatively simple. If these numbers are removed or damaged, however, the leads must be reidentified before the motor can be connected. The following procedure can be used to identify the proper relationship of the motor windings.

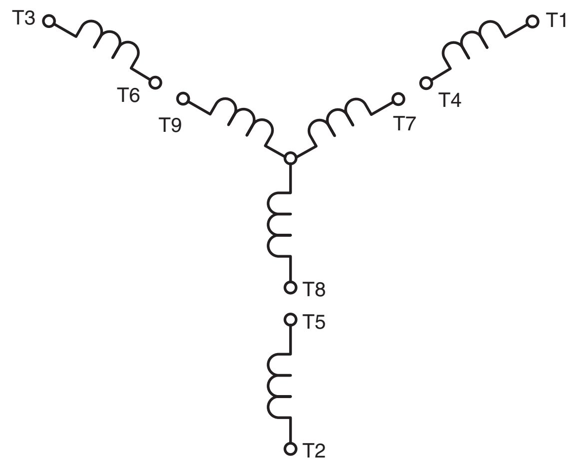


Figure A–1 Standard terminal markings for a three-phase motor.

1. Using an ohmmeter, divide the motor windings into four separate circuits. One circuit will have continuity to three leads, and the other three circuits will have continuity between only two leads (Figure #1). *Caution: the circuits that exhibit continuity between*

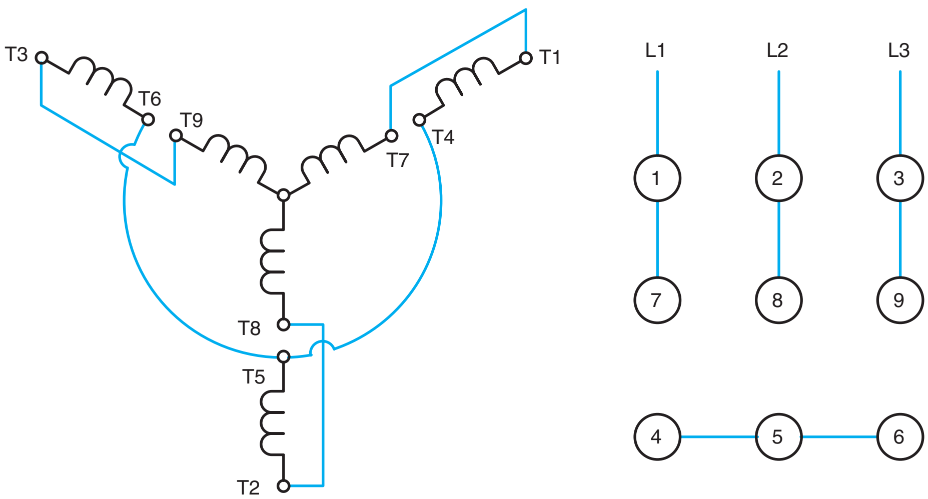


Figure A–2 Low voltage connection.

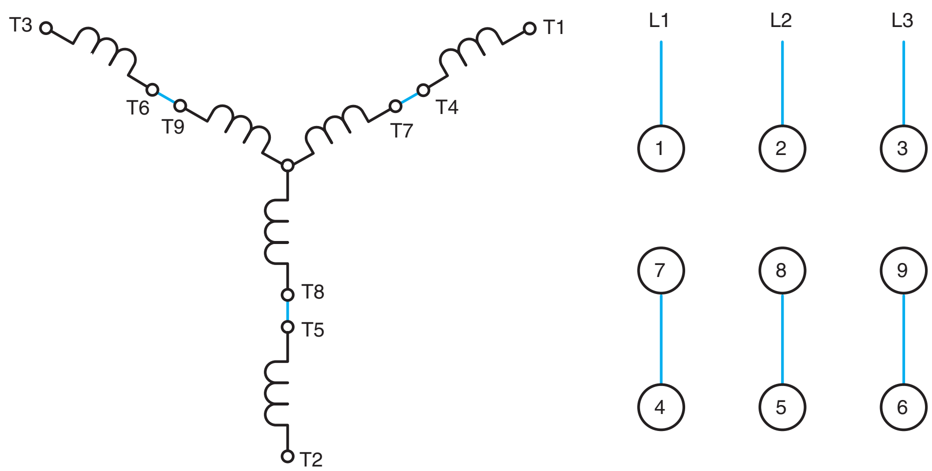


Figure A–3 High voltage connection.

two leads must be identified as pairs, but do not let the ends of the leads touch anything.

2. Mark the three leads that have continuity with each other as T7, T8, and T9. Connect these three leads to a 240-volt, three-phase power source (Figure A–4). (Note: Since these windings are rated at 240 volts each, the motor can be safely operated on one set of windings as long as it is not connected to a load.)

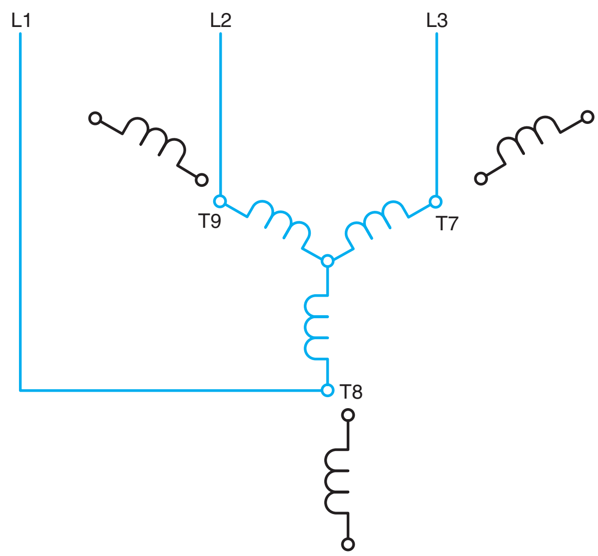


Figure A–4 T7, T8, and T9 connected to a three-phase, 240-volt line.

3. With the power turned off, connect one end of one of the paired leads to the terminal marked T7. Turn the power on, and using an ac voltmeter set for a range not less than 480 volts, measure the voltage from the unconnected end of the paired lead to terminals T8 and T9 (Figure A–5). If the measured voltages are unequal, the wrong paired lead is connected to terminal T7. Turn the power off, and connect another paired lead to T7. When the correct set of paired leads is connected to T7, the voltage readings to T8 and T9 will be equal.
4. After finding the correct pair of leads, a decision must be made as to which lead should be labeled T4 and which should be labeled T1. Since an induction motor is basically a transformer, the phase windings act very similar to a multiwinding autotransformer. If terminal T1 is connected to terminal T7, it will operate similar to a transformer with its windings connected to form subtractive polarity. If an ac voltmeter is connected to T4, a voltage of about 140 volts should be seen between T4 and T8 or T4 and T9 (Figure A–6).

   If terminal T4 is connected to T7, the winding will operate similar to a transformer with its windings connected for additive polarity. If an ac voltmeter is connected to T1, a voltage of about 360 volts will be indicated when the other lead of the voltmeter is connected to T8 or T9 (Figure A–7).

   Label leads T1 and T4 using the preceding procedure to determine which lead is correct. Then disconnect and separate T1 and T4.
5. To identify the other leads, follow the same basic procedure. Connect one end of one of the remaining pairs to T8. Measure the voltage between the unconnected lead and T7 and T9 to determine if it is the correct lead pair for terminal T8. When the correct lead pair is connected to T8, the voltage between the unconnected terminal and T7 or T9 will be equal. Then determine which is T5 or T2 by measuring for a high or low voltage. When T5 is connected to T8, about 360 volts can be measured between T2 and T7 or T2 and T9.
6. The remaining pair can be identified as T3 or T6. When T6 is connected to T9, a voltage of about 360 volts can be measured between T3 and T7 or T3 and T8.

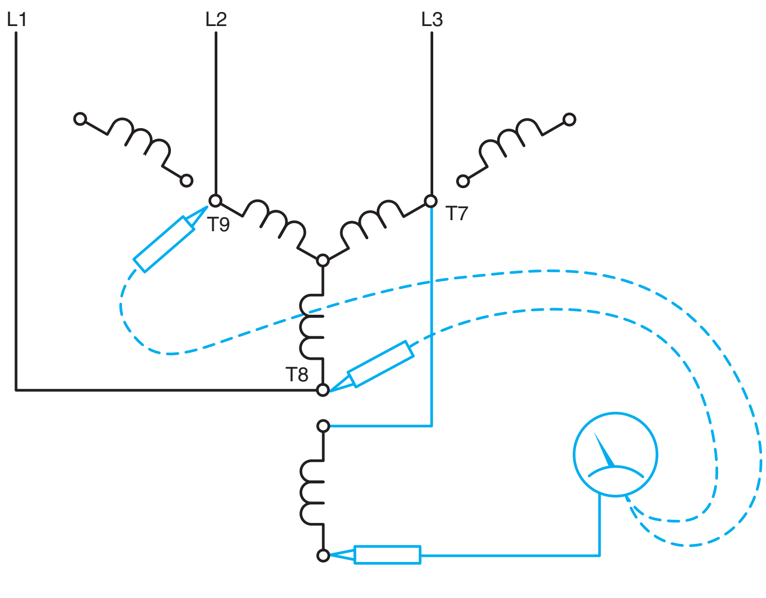


Figure A–5 Measure voltage from unconnected paired lead to T8 and T9.

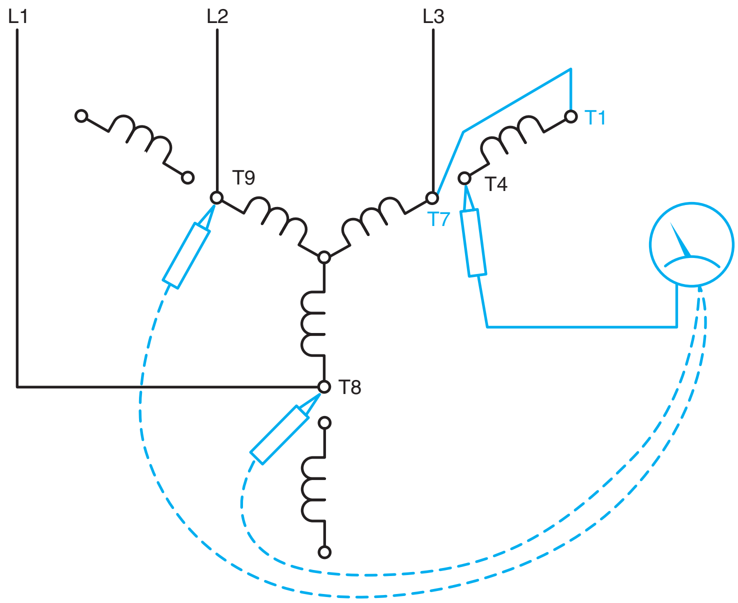


Figure A–6 T1 connected to T7.

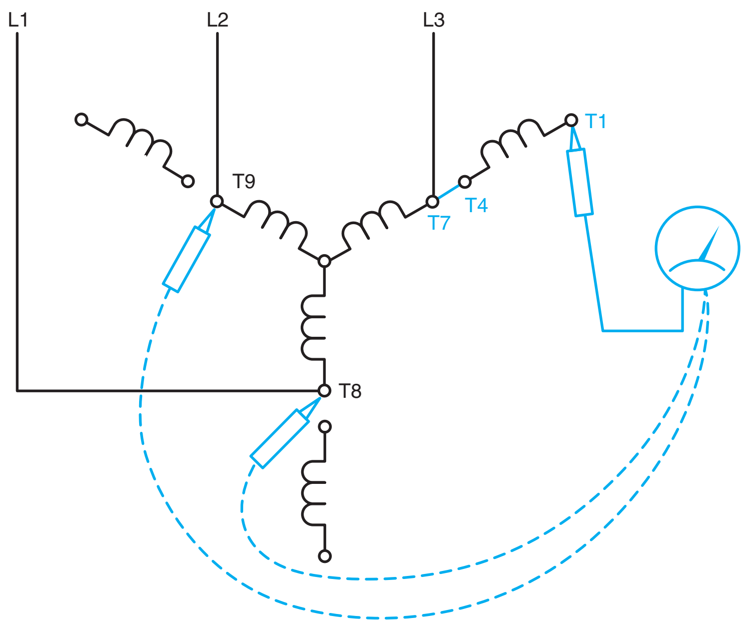
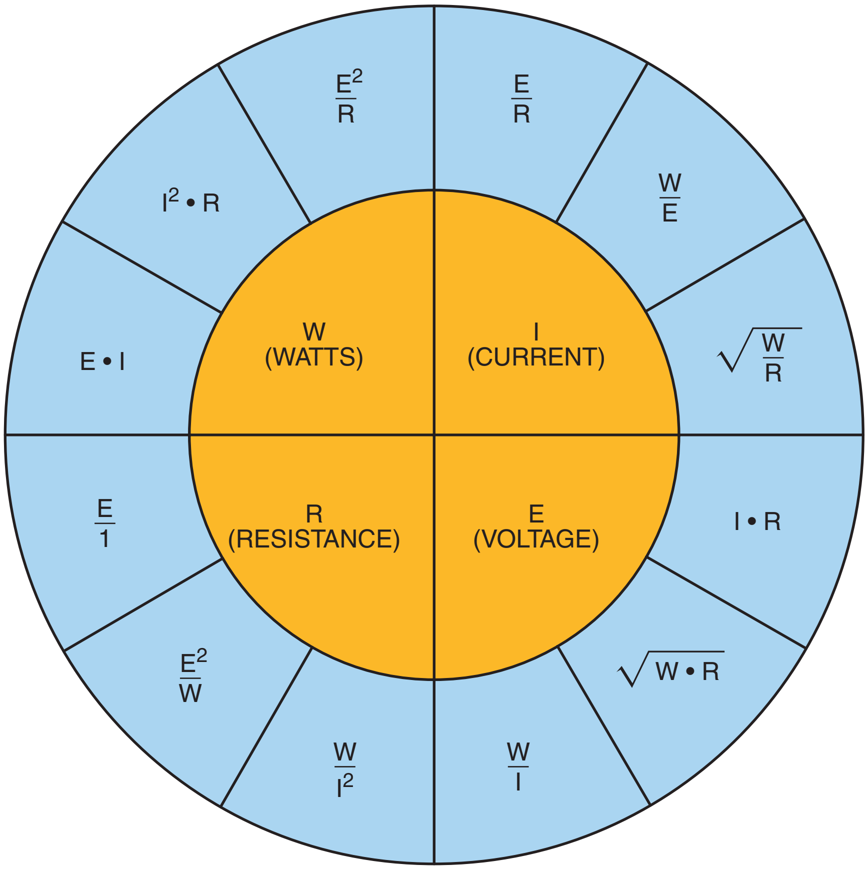
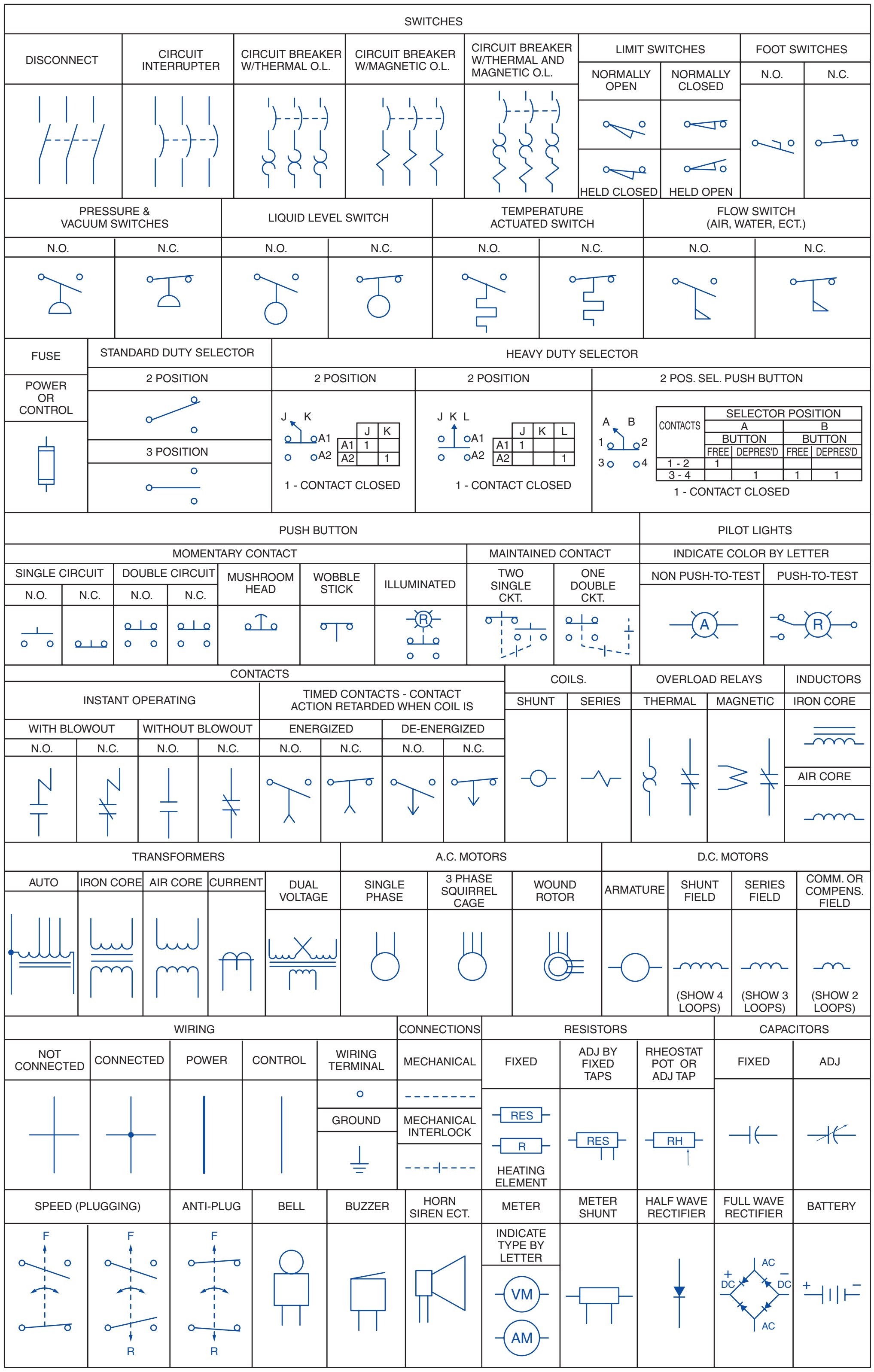


Figure A–7 T4 connected to T7.

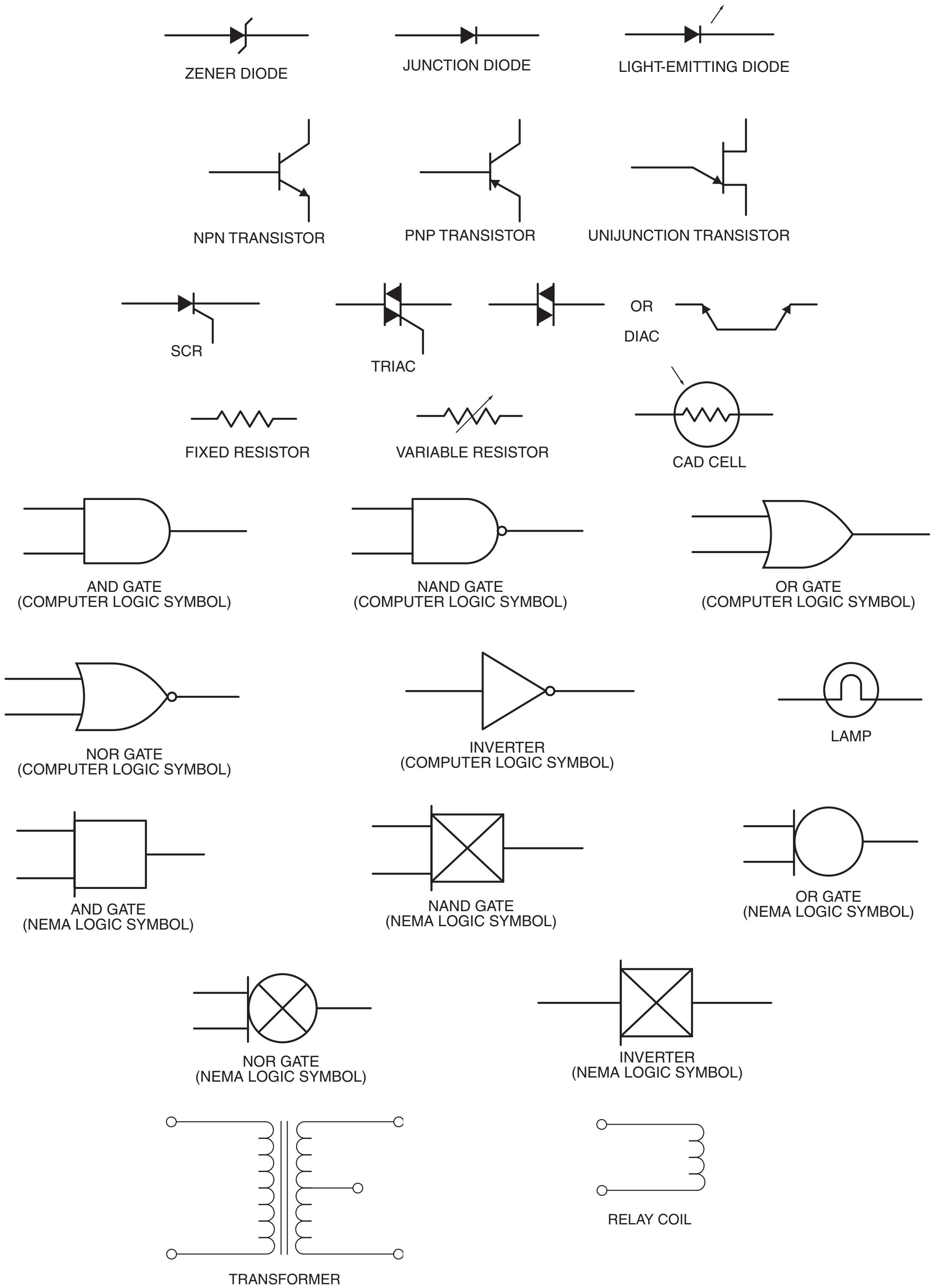
Ohm's Law Formulas



Standard Wiring Diagram Symbols

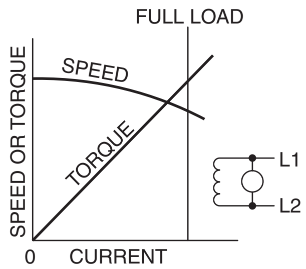


Electronic Symbols

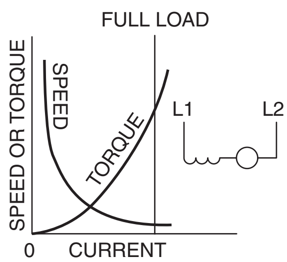


Motor Types and Line Diagrams

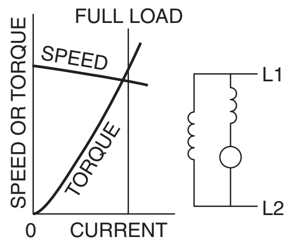
Dc Shunt Motor. Main field winding is designed for parallel connection to the armature; stationary field; rotating armature with commutator; has a no-load speed; full speed at full load is less than no-load speed; torque increases directly with load.



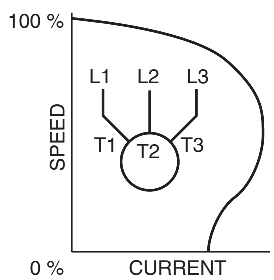
Dc Series Motor. Main field winding is designed for series connection to the armature; stationary field; rotating armature with commutator; does not have a no-load speed; requires solid direct connection to the load to prevent runaway at no-load; speed decreases rapidly with increase in load; torque increases as square of armature current; main motor for crane hoists; excellent starting torque.



Dc Compound Motor. Main field both shunt (parallel) and series; stationary fields; rotating armature with commutator; combination shunt and series fields produce characteristics between straight shunt or series dc motor; good starting torque; main motor for dc driven machinery (mills or presses).

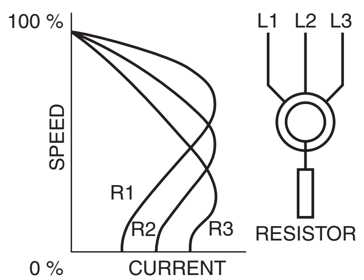


Ac Squirrel Cage Motor. Single or three phase; single phase requires a starting winding; three phase, self starting; stationary stator winding; no electrical connection to short-circuited rotor; torque produced from magnetic reaction of stator and rotor fields; speed a function of supply frequency and number of electrical poles wound on stator; considered as constant speed even though speed decreases slightly with increased load; good starting torque; high inrush currents during starting on full voltage; rugged construction; easily serviced and maintained; high efficiency; good running power factor when delivering full load; requires motor control for stator windings only.

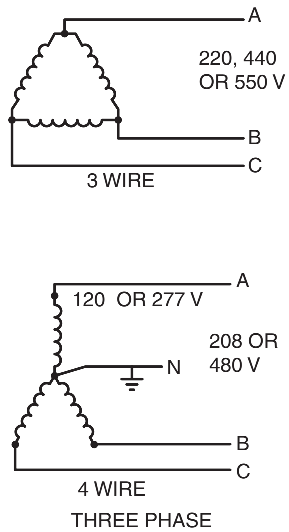


Ac Wound-Rotor Induction Motor. Characteristics similar to squirrel cage motor; stationary stator winding; rotor windings terminate on slip rings; external addition of resistance to rotor circuit for speed control; good starting torque; high inrush current during starting on full voltage; low efficiency when resistor is inserted in rotor windings; good running power factor; requires motor controls for stator and rotor circuits.

Ac Synchronous Motor. Stationary ac stator windings; rotating dc field winding; no starting torque unless motor has starting winding; generally poor starting torque; constant speed when motor up to speed and dc field winding energized; can provide power factor correction with proper dc field excitation; requires special motor control for both ac and dc windings to prevent the dc field winding from being energized until a specified percent of running speed has been obtained.



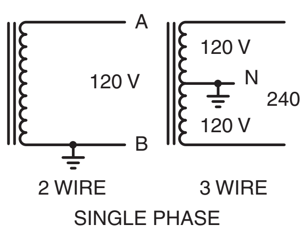
Three-phase. Three-wire delta 230/460 volts, 580 volts; four-wire wye 208/440, 277/480 volts neutral line grounded; primary industrial power distribution; main motor drives, integral horsepower motors, lighting, heating, fractional horsepower motors, and business machines; used as three-phase or single-phase power supply.



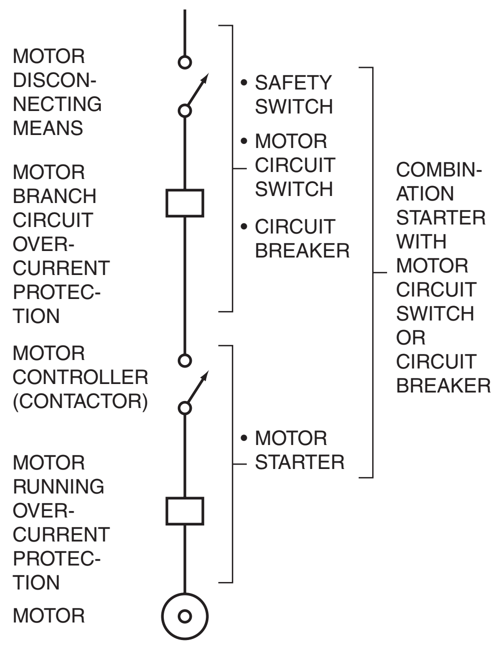
Power Supplies

All electrical power supplied as ac or dc; primarily ac; generation, transmission, and some distribution of power at high voltage (above 5000 volts) or medium voltage (600 to 5000 volts); most power distribution of voltage for industrial and residential use is 600 volts and under; ac power generally at 60-Hertz frequency; ac distribution at use location single or three phase.

Single-phase. Two wire, 120 volts, one line grounded; 120/240 volts, three-wire center-line grounded; residential distribution, lighting, heat, fractional horsepower motors and business machines.



Motor Circuit Elements



GLOSSARY

Accelerating Relay Any type of relay used to aid in starting a motor or to accelerate a motor from one speed to another. Accelerating relays may function by: motor armature current (current limit acceleration); armature voltage (counter emf acceleration); or definite time (definite time acceleration).

Accessory (control use) A device that controls the operation of magnetic motor control. (Also see Master Switch, Pilot Device, and Push Button.)

Across-the-line Method of motor starting which connects the motor directly to the supply line on starting or running. (Also called Full Voltage Control.)

Alternating Current (Ac) Current changing both in magnitude and direction; most commonly used current.

Alternator A machine used to generate alternating current by rotating conductors through a magnetic field.

Ambient Temperature The temperature surrounding a device.

Ampacity The maximum current rating of a wire or cable.

Ampere Unit of electrical current.

Amplifier A device used to increase a signal.

Amplitude The highest value reached by a signal, voltage, or current.

AND Gate A digital logic gate that must have all of its inputs high to produce an output.

Anode The positive terminal of an electronic device.

Applied Voltage The amount of voltage connected to a circuit or device.

ASA American Standards Association.

Astable Mode The state in which an oscillator can continually turn itself on and off, or continually change from positive to negative output.

Atom The smallest part of an element that contains all the properties of that element.

Attenuator A device that decreases the amount of signal, voltage, or current.

Automatic Self-acting, operating by its own mechanism when actuated by some triggering signal such as a change in current strength, pressure, temperature, or mechanical configuration.

Automatic Starter A self-acting starter which is completely controlled by master or pilot switches or other sensing devices; designed to control automatically the acceleration of a motor during the acceleration period.

Auxiliary Contacts Contacts of a switching device in addition to the main circuit contacts; auxiliary contacts operate with the movement of the main contacts.

Barrier Charge The potential developed across a semiconductor junction.

Base The semiconductor region between the collector and emitter of a transistor. The base controls the current flow through the collector-emitter circuit.

Base Current The amount of current that flows through the base-emitter section of a transistor.

Bias A dc voltage applied to the base of a transistor to preset its operating point.

Bimetal Strip A strip made by bonding two unlike metals together that, when heated, expand at different rates. This causes a bending or warping action.

Blowout Coil Electromagnetic coil used in contactors and starters to deflect an arc when a circuit is interrupted.

Bounceless Switch A circuit used to eliminate contact bounce in mechanical contacts.

Branch Circuit That portion of a wiring system that extends beyond the final overcurrent device protecting the circuit.

Brake An electromechanical friction device to stop and hold a load. Generally electric release spring applied—coupled to motor shaft.

Breakdown Torque (of a motor) The maximum torque that will develop with the rated voltage applied at the rated frequency, without an abrupt drop in speed. (ASA)

Bridge Circuit A circuit that consists of four sections connected in series to form a closed loop.

Bridge Rectifier A device constructed with four diodes, which converts both positive and negative cycles of ac voltage into dc voltage.

Busway A system of enclosed power transmission that is current and voltage rated.

Cad Cell A device that changes its resistance with a change of light intensity.

Capacitance The electrical size of a capacitor.

Capacitive Any circuit or device having characteristics similar to those of a capacitor.

Capacitor A device made with two conductive plates separated by an insulator or dielectric.

Capacitor Start Motor A single-phase induction motor with a main winding arranged for direct connection to the power source and an auxiliary winding connected in series with a capacitor. The auxiliary winding is in the circuit only during starting. (NEMA)

Cathode The negative terminal of a device.

Cathode-Ray Tube (CRT) An electron beam tube in which the beam of electrons can be focused to any point on the face of the tube. The electron beam causes the face of the tube to produce light when it is struck by the beam.

Center-Tapped A transformer that has a wire connected to the electrical midpoint of its winding. Generally the secondary is tapped.

Charge Time The amount of time necessary to charge a capacitor.

Choke An inductor designed to present an impedance to ac current, or to be used as the current filter of a dc power supply.

Circuit Breaker Automatic device that opens under abnormal current in carrying circuit; circuit breaker is not damaged on current interruption; device is ampere, volt, and horsepower rated.

Clock Timer A time-delay device that uses an electric clock to measure the delay period.

Collapse (of a magnetic field) When a magnetic field suddenly changes from its maximum value to a zero value.

Collector The semiconductor region of a transistor which must be connected to the same polarity as the base.

Comparator A device or circuit that compares two like quantities such as voltage levels.

Conduction Level The point at which an amount of voltage or current will cause a device to conduct.

Conductor A device or material that permits current to flow through it easily.

Contact A conducting part of a relay which acts with another conducting part to complete or to interrupt a circuit.

Contactor A device that repeatedly establishes or interrupts an electric power circuit.

Continuity A complete path for current flow.

Controller A device or group of devices that governs, in a predetermined manner, the delivery of electric power to apparatus connected to it.

Controller Function Regulate, accelerate, decelerate, start, stop, reverse, or protect devices connected to an electric controller.

Controller Service Specific application of controller. General Purpose: standard or usual service. Definite Purpose: service condition for specific application other than usual.

Current The rate of flow of electrons. Measured in amperes.

Current Flow The flow of electrons.

Current Rating The amount of current flow a device is designed to withstand.

Current Relay A relay that functions at a predetermined value of current. A current relay may be either an overcurrent relay or an undercurrent relay.

Dashpot Consists of a piston moving inside a cylinder filled with air, oil, mercury, silicon, or other fluid. Time delay is caused by allowing the air or fluid to escape through a small orifice in the piston. Moving contacts actuated by the piston close the electrical circuit.

Definite Time (or Time Limit) Definite time is a qualifying term indicating that a delay in action is purposely introduced. This delay remains substantially constant regardless of the magnitude of the quantity that causes the action.

Definite-Purpose Motor Any motor designed, listed, and offered in standard ratings with standard operating characteristics or mechanical construction for use under service conditions other than usual or for use on a particular type of application. (NEMA)

Delta Connection A circuit formed by connecting three electrical devices in series to form a closed loop. Most often used in three-phase connections.

Device A unit of an electrical system that is intended to carry but not utilize electrical energy.
Diac A bidirectional diode.
Dielectric An electrical insulator.
Digital Device A device that has only two states of operation.
Digital Logic Circuit elements connected in such a manner as to solve problems using components that have only two states of operation.
Digital Voltmeter A voltmeter that uses a direct-reading, numerical display as opposed to a meter movement.
Diode A two-element device that permits current to flow through it in only one direction.
Direct Current (Dc) Current that does not reverse its direction of flow. A continuous nonvarying current in one direction.
Disconnecting Means (Disconnect) A device, or group of devices, or other means whereby the conductors of a circuit can be disconnected from their source of supply.
Drum Controller Electrical contacts made on the surface of a rotating cylinder or section; contacts made also by operation of a rotating cam.
Drum Switch A switch having electrical connecting parts in the form of fingers held by spring pressure against contact segments or surfaces on the periphery of a rotating cylinder or sector.
Duty Specific controller functions. Continuous (time) Duty: constant load, indefinite long time period. Short Time Duty: constant load, short or specified time period. Intermittent Duty: varying load, alternate intervals, specified time periods. Periodic Duty: intermittent duty with recurring load conditions. Varying duty: varying loads, varying time intervals, wide variations.
Dynamic Braking Using a dc motor as a generator, taking it off the line and applying an energy dissipating resistor to the armature. Dynamic braking for an ac motor is accomplished by disconnecting the motor from the line and connecting dc power to the stator windings.
Eddy Currents Circular induced currents contrary to the main currents; a loss of energy that shows up in the form of heat.
Electrical Interlocking Accomplished by control circuits in which the contacts in one circuit control another circuit.
Electric Controller A device, or group of devices, which governs, in some predetermined manner, the electric power delivered to the apparatus to which it is connected.
Electron One of the three major subatomic parts of an atom. The electron carries a negative charge.
Electronic Control Control system using gas and/or vacuum tubes, or solid-state devices.
Emitter The semiconductor region of a transistor which must be connected to a polarity different than the base.
Enclosure Mechanical, electrical, and environmental protection for control devices.
Eutectic Alloy Metal with low and sharp melting point; used in thermal overload relays; converts from a solid to a liquid state at a specific temperature; commonly called solder pot.
Exclusive OR Gate A digital logic gate that will produce an output when its inputs have opposite states of logic level.
Feeder The circuit conductor between the service equipment, or the generator switchboard of an isolated plant and the branch circuit overcurrent device.
Feeler Gauge A precision instrument with blades in thicknesses of thousandths of an inch for measuring clearances.
Filter A device used to remove the ripple produced by a rectifier.
Frequency Number of complete variations made by an alternating current per second; expressed in Hertz. (See Hertz)
Full Load Torque (of a motor) The torque necessary to produce the rated horsepower of a motor at full load speed.
Full Voltage Control (*Across-the-line*) Connects equipment directly to the line supply on starting.
Fuse An overcurrent protective device with a fusible member, which is heated directly and destroyed by the current passing through it to open a circuit.
Gain The increase in signal power produced by an amplifier.
Gate A device that has multiple inputs and a single output; or one terminal of some solid-state devices such as SCRs or triacs.
General-Purpose Motor Any open motor that has a continuous 40C rating and is designed, listed, and offered in standard ratings with standard operating characteristics and mechanical construction for use under usual service conditions without restrictions to a particular application or type of application. (NEMA)

Heat Sink A metallic device designed to increase the surface area of an electronic component to remove heat at a faster rate.

Hertz International unit of frequency, equal to one cycle per second of alternating current.

High Voltage Control Formerly, all control above 600 volts. Now, all control above 5,000 volts. See Medium Voltage for 600- to 5,000-volt equipment.

Holding Contacts Contacts used for the purpose of maintaining current flow to the coil of a relay.

Holding Current The amount of current needed to keep an SCR or a triac turned on.

Horsepower Measure of the time rate of doing work (working rate).

Hysteresis Loop A graphic curve that shows the value of magnetizing force for a particular type of material.

Impedance The total opposition to current flow in an electrical circuit.

Induced Current produced in a conductor by the cutting action of a magnetic field.

Inductor A coil used to introduce inductance into an electrical circuit.

Input Power delivered to an electrical device.

Input Voltage The amount of voltage connected to a device or circuit.

Instantaneous A qualifying term indicating that no delay is purposely introduced in the action of a device.

Insulator A material used to electrically isolate two conductive surfaces.

Integral Whole or complete; not fractional.

Interlock To interrelate with other controllers; an auxiliary contact. A device is connected in such a way that the motion of one part is held back by another part.

Internal Relay Digital logic circuits in a programmable controller that can be programmed to operate in the same manner as control relays.

Inverse Time A qualifying term indicating that a delayed action is introduced purposely. This delay decreases as the operating force increases.

Inverter (Gate) A digital logic gate that has an output opposite its input.

Isolation Transformer A transformer whose secondary winding is electrically isolated from its primary winding.

Jogging (Inching) Momentary operations; the quickly repeated closure of the circuit to start a motor from rest for the purpose of accomplishing small movements of the driven machine.

Jumper A short length of conductor used to make a connection between terminals or around a break in a circuit.

Junction Diode A diode that is made by joining two pieces of semiconductor material.

Kick-Back Diode A diode used to eliminate the voltage spike induced in a coil by the collapse of a magnetic field.

Lattice Structure An orderly arrangement of atoms in a crystalline material.

Led (Light-Emitting Diode) A diode that will produce light when current flows through it.

Limit Switch A mechanically operated device which stops a motor from revolving or reverses it when certain limits have been reached.

Load Center Service entrance; controls distribution; provides protection of power; generally of the circuit breaker type.

Local Control Control function, initiation, or change accomplished at the same location as the electric controller.

Locked Rotor Current (of a motor) The steady-state current taken from the line with the rotor locked (stopped) and with the rated voltage and frequency applied to the motor.

Locked Rotor Torque (of a motor) The minimum torque that a motor will develop at rest for all angular positions of the rotor with the rated voltage applied at a rated frequency. (ASA)

Lockout A mechanical device that may be set to prevent the operation of a push button.

Logic A means of solving complex problems through the repeated use of simple functions which define basic concepts. Three basic logic functions are: and, or, and not.

Low Voltage Protection (LVP) Magnetic control only; nonautomatic restarting; three-wire control; power failure disconnects service; power restored by manual restart.

Low Voltage Release (LVR) Manual and magnetic control; automatic restarting; two-wire control; power failure disconnects service; when power is restored, the controller automatically restarts the motor.

Magnet Brake Friction brake controlled by electromagnetic means.

Magnetic Contactor A contactor that is operated electromechanically.

Magnetic Controller An electric controller; device functions operated by electromagnets.

Magnetic Field The space in which a magnetic force exists.

Maintaining Contact A small control contact used to keep a coil energized; usually actuated by the same coil. Holding contact; Pallet switch.

Manual Controller An electric controller; device functions operated by mechanical means or manually.

Master Switch A main switch to operate contactors, relays, or other remotely-controlled electrical devices.

Medium Voltage Control Formerly known as High Voltage; includes 600- to 5000-volt apparatus; air break or oil-immersed main contactors; high interrupting capacity fuses; 150,000 kVa at 2,300 volts; 250,000 kVA at 4,000–5,000 volts.

Microprocessor A small computer. The central processing unit is generally made from a single integrated circuit.

Mode A state or condition.

Monostable (Mode) The state in which an oscillator or timer will operate through only one sequence of events.

Motor Device for converting electrical energy to mechanical work through rotary motion; rated in horsepower.

Motor Circuit Switch Motor branch circuit switch rated in horsepower; capable of interrupting overload motor current.

Motor Controller A device used to control the operation of a motor.

Motor-Driven Timer A device in which a small pilot motor causes contacts to close after a predetermined time.

Multispeed Motor A motor that can be operated at more than one speed.

Multispeed Starter An electric controller with two or more speeds; reversing or nonreversing; full or reduced voltage starting.

NAND Gate A digital logic gate that will produce a high output only when all of its inputs are in a low state.

Negative One polarity of voltage, current, or a charge.

Negative Resistance The property of a device in which an increase of current flow causes an increase of conductance. The increase of conductance causes a decrease in the voltage drop across the device.

NEMA National Electrical Manufacturers Association.

NEMA Size Electric controller device rating; specific standards for horsepower, voltage, current, and interrupting characteristics.

Neutron One of the principal parts of an atom. The neutron has no charge and is part of the nucleus.

Nonautomatic Controller Requires direct operation to perform function; not necessarily a manual controller.

Noninductive Load An electrical load that does not have induced voltages caused by a coil. Noninductive loads are generally resistive, but can be capacitive.

Nonreversing Operation in one direction only.

NOR Gate A digital logic gate that will produce a high output when any of its inputs are low.

Normally Open and Normally Closed When applied to a magnetically-operated switching device, such as a contactor or relay, or to the contacts of these devices, these terms signify the position taken when the operating magnet is de-energized. The terms apply only to nonlatching types of devices.

Off-Delay Timers A timer in which the contacts change position immediately when the coil or circuit is energized, but delay returning to their normal positions when the coil or circuit is de-energized.

Ohmmeter A meter used to measure resistance.

On-Delay Timer A timer in which the contacts delay changing position when the coil or circuit is energized, but change back immediately to their normal positions when the coil or circuit is de-energized.

Operational Amplifier (OP-AMP) An integrated circuit used as an amplifier.

Optoisolator A device used to connect sections of a circuit by means of a light beam.

Oscillator A device or circuit used to change dc voltage into ac voltage.

Oscilloscope An instrument that measures the amplitude of voltage with respect to time.

Out-of-phase Voltage A voltage that is not in phase when compared to some other voltage or current.

Output Devices Elements such as solenoids, motor starters, and contactors that receive input.

Output Pulse A short duration voltage or current which can be negative or positive, produced at the output of a device or circuit.

Overload Protection Overload protection is the result of a device that operates on excessive current, but not necessarily on short circuit, to cause and maintain the interruption of current flow to the

device governed. NOTE: Operating overload means a current that is not in excess of six times the rated current for alternating-current motors, and not in excess of four times the rated current for direct-current motors.

Overload Relay Running overcurrent protection; operates on excessive current; not necessarily protection for short circuit; causes and maintains interruption of device from power supply. Overload Relay Heater Coil: Coil used in thermal overload relays; provides heat to melt eutectic alloy.

Overload Relay Reset Push button used to reset thermal overload relay after relay has operated.

Panelboard Panel, group of panels, or units; an assembly that mounts in a single panel; includes buses, with or without switches and/or automatic overcurrent protective devices; provides control of light, heat, power circuits; placed in or against wall or partition; accessible from front only.

Parallel Circuit A circuit that has more than one path for current flow.

Peak Inverse/Peak Reverse Voltage The rating of a semiconductor device which indicates the maximum amount of voltage that can be applied to the device in the reverse direction.

Peak-To-Peak Voltage The amplitude of voltage measured from the negative peak of an ac waveform to the positive peak.

Peak Voltage The amount of voltage of a waveform measured from the zero voltage point to the positive or negative peak.

Permanent-split Capacitor Motor A single-phase induction motor similar to the capacitor start motor except that it uses the same capacitance which remains in the circuit for both starting and running. (NEMA)

Permeability The ease with which a material will conduct magnetic lines of force.

Phase Relation of current to voltage at a particular time in an ac circuit. Single Phase: A single voltage and current in the supply. Three Phase: Three electrically-related (120-degree electrical separation) single-phase supplies.

Phase-Failure Protection Phase-failure protection is provided by a device that operates when the power fails in one wire of a polyphase circuit to cause and maintain the interruption of power in all the wires of the circuit.

Phase-Reversal Protection Phase-reversal protection is provided by a device that operates when the phase rotation in a polyphase circuit reverses to cause and maintain the interruption of power in all the wires of the circuit.

Phase Rotation Relay A relay that functions in accordance with the direction of phase rotation.

Phase Shift A change in the phase relationship between two quantities of voltage or current.

Photodetector A device that responds to change in light intensity.

Photodiode A diode that conducts in the presence of light, but not in darkness.

Pilot Device Directs operation of another device. Float Switch: A pilot device that responds to liquid levels. Foot Switch: A pilot device operated by the foot of an operator. Limit Switch: A pilot device operated by the motion of a power-driven machine; alters the electrical circuit with the machine or equipment.

Plugging Braking by reversing the line voltage or phase sequence; motor develops retarding force.

Pneumatic Timer A device that uses the displacement of air in a bellows or diaphragm to produce a time delay.

Polarity The characteristic of a device that exhibits opposite quantities, such as positive and negative, within itself.

Pole The north or south magnetic end of a magnet; a terminal of a switch; one set of contacts for one circuit of main power.

Potentiometer A variable resistor with a sliding contact, which is used as a voltage divider.

Power Factor A comparison of the true power (WATTS) to the apparent power (VOLT AMPS) in an ac circuit.

Power Rating The rating of a device that indicates the amount of current flow and voltage drop that can be permitted.

Pressure Switch A device that senses the presence or absence of pressure and causes a set of contacts to open or close.

Printed Circuit A board on which a predetermined pattern of printed connections has been formed.

Proton One of the three major parts of an atom. The proton carries a positive charge.

Pull-up Torque (of alternating-current motor) The minimum torque developed by the motor during the period of acceleration from rest to the speed at which breakdown occurs. (ASA)

Push Button A master switch; manually-operable

plunger or button for an actuating device; assembled into push-button stations.

RC Time Constant The time constant of a resistor and capacitor connected in series. The time in seconds is equal to the resistance in ohms multiplied by the capacitance in farads.

Reactance The opposition to current flow in an ac circuit offered by pure inductance or pure capacitance.

Rectifier A device that converts alternating current into direct current.

Regulator A device that maintains a quantity at a predetermined level.

Relay Operated by a change in one electrical circuit to control a device in the same circuit or another circuit; rated in amperes; used in control circuits.

Remote Control Controls the function initiation or change of an electrical device from some remote point, or location.

Remote Control Circuit Any electrical circuit that controls any other circuit through a relay or an equivalent device.

Residual Magnetism The retained or small amount of remaining magnetism in the magnetic material of an electromagnet after the current flow has stopped.

Resistance The opposition offered by a substance or body to the passage through it of an electric current; resistance converts electrical energy into heat; resistance is the reciprocal of conductance.

Resistance Start Induction Run Motor One type of split-phase motor that uses the resistance of the start winding to produce a phase shift between the current in the start winding and the current in the run winding.

Resistor A device used primarily because it possesses the property of electrical resistance. A resistor is used in electrical circuits for purposes of operation, protection, or control; commonly consists of an aggregation of units.

- *Starting Resistors* Used to accelerate a motor from rest to its normal running speed without damage to the motor and connected load from excessive currents and torques, or without drawing undesirable inrush current from the power system.
- *Armature Regulating Resistors* Used to regulate the speed of torque of a loaded motor by resistance in the armature or power circuit.
- *Dynamic Braking Resistors* Used to control the current and dissipate the energy when a motor is decelerated by making it act as a generator to convert its mechanical energy to electrical energy and then to heat in the resistor.
- *Field Discharge Resistors* Used to limit the value of voltage that appears at the terminals of a motor field (or any highly inductive circuit) when the circuit is opened.
- *Plugging Resistors* Used to control the current and torque of a motor when deceleration is forced by electrically reversing the motor while it is still running in the forward direction.

Rheostat A resistor that can be adjusted to vary its resistance without opening the circuit in which it may be connected.

Ripple An ac component in the output of a dc power supply caused by improper filtering.

RMS Value The value of ac voltage that will produce as much power when connected across a resistor as a like amount of dc voltage.

Safety Switch Enclosed manually-operated disconnecting switch; horsepower and current rated; disconnects all power lines.

Saturation The maximum amount of magnetic flux a material can hold.

Schematic An electrical diagram which shows components in their electrical sequence without regard for physical location.

Selector Switch A master switch that is manually operated; rotating motion for actuating device; assembled into push-button master stations.

Semiautomatic Starter Part of the operation of this type of starter is nonautomatic while selected portions are automatically controlled.

Semiconductor A material that contains four valence electrons and is used in the production of solid-state devices. The most common types are silicon and germanium.

Semimagnetic Control An electric controller in which functions are partly controlled by electromagnets.

Sensing Device A pilot device that measures, compares, or recognizes a change or variation in the system which it is monitoring; provides a controlled signal to operate or control other devices.

Series-Aiding Two or more voltage producing devices connected in series in such a manner that their voltages add to produce a higher total voltage.

Series Circuit An electric circuit formed by the connection of one or more components in such a manner that there is only one path for current flow.

Service The conductors and equipment necessary to deliver energy from the electrical supply system to the premises served.

Service Equipment Necessary equipment, circuit breakers, or switches and fuses with accessories mounted near the entry of the electrical supply; constitutes the main control or cutoff for supply.

Service Factor (of a general-purpose motor) An allowable overload; the amount of allowable overload is indicated by a multiplier which, when applied to a normal horsepower rating, indicates the permissible loading.

Shaded-Pole Motor A single-phase induction motor provided with an auxiliary short-circuited winding or windings displaced in magnetic position from the main winding. (NEMA)

Shading Loop A large copper wire or band connected around part of a magnetic pole piece to oppose a change of magnetic flux.

Short Circuit An electrical circuit that contains no resistance to limit the flow of current.

Signal The event, phenomenon, or electrical quantity that conveys information from one point to another.

Signal Generator A text instrument used to produce a low-value, ac voltage for the purpose of testing or calibrating electronic equipment.

Silicon-Controlled Rectifier (SCR) A four-layer semiconductor device that is a rectifier and must be triggered by a pulse applied to the gate before it will conduct.

Sine-Wave Voltage A voltage waveform; its value at any point is proportional to the trigonometric sine of the angle of the generator producing it.

Slip Difference between the rotor rpm and the rotating magnetic field of an ac motor.

Snap Action The quick opening and closing action of a spring-loaded contact.

Solder Pot See Eutectic Alloy.

Solenoid A magnetic device used to convert electrical energy into linear motion. A tubular, current-carrying coil that provides magnetic action to perform various work functions.

Solenoid-and-Plunger A solenoid-and-plunger is a solenoid provided with a bar of soft iron or steel called a plunger.

Solenoid Valve A valve operated by an electric solenoid.

Solid-State Devices Electronic components that control electron flow through solid materials such as crystals; e.g., transistors, diodes, integrated circuits.

Special-Purpose Motor A motor with special operating characteristics or special mechanical construction, or both, designed for a particular application and not falling within the definition of a general-purpose or definite-purpose motor. (NEMA)

Split-Phase A single-phase induction motor with auxiliary winding, displaced in magnetic position from, and connected parallel to, the main winding. (NEMA)

Starter A starter is a controller designed for accelerating a motor to normal speed in one direction of rotation. NOTE: A device designed for starting a motor in either direction of rotation includes the additional function of reversing and should be designated as a controller.

Startup The time between equipment installation and the full operation of the system.

Static Control Control system in which solid-state devices perform the functions. Refers to no moving parts or without motion.

Stealer Transistor A transistor used in such a manner as to force some other component to remain in the off state by shunting its current to electrical ground.

Step-Down Transformer A transformer that produces a lower voltage at its secondary winding than is applied to its primary winding.

Step-Up Transformer A transformer that produces a higher voltage at its secondary winding than is applied to its primary winding.

Surge A transient variation in the current and/or potential at a point in the circuit; unwanted, temporary.

Switch A device for making, breaking, or changing the connections in an electric circuit.

Switchboard A large, single panel with a frame or assembly of panels; devices may be mounted on the face of the panels, on the back, or both; contains switches, overcurrent, or protective devices; instruments accessible from the rear and front; not installed in wall-type cabinets. (See Panelboard)

Synchronous Speed The speed of the rotating magnetic field of an ac induction motor.

Tachometer Generator Used for counting revolutions per minute. Electrical magnitude or impulses are calibrated with a dial-gauge reading in rpm.

Temperature Relay A relay that functions at a predetermined temperature in the apparatus protected. This relay is intended to protect some other apparatus such as a motor or controller and does not necessarily protect itself.

Terminal A fitting attached to a circuit or device for convenience in making electrical connections.

Thermal Compound A grease-like substance used to thermally bond two surfaces together for the purpose of increasing the rate of heat transfer from one object to another.

Thermal Protector (as applied to motors) An inherent overheating protective device that is responsive to motor current and temperature. When properly applied to a motor, this device protects the motor against dangerous overheating due to overload or failure to start.

Thermistor A resistor that changes its resistance with a change of temperature.

Thyristor An electronic component that has only two states of operation, on and off.

Time Limit See Definite Time.

Timer A pilot device that is also considered a timing relay; provides adjustable time period to perform function; motor driven; solenoid-actuated; electronic.

Torque The torque of a motor is the twisting or turning force which tends to produce rotation.

Transducer A device that transforms power from one system to power of a second system: for example, heat to electrical.

Transformer An electromagnetic device that converts voltages for use in power transmission and operation of control devices.

Transient See Surge.

Transistor A solid-state device made by combining three layers of semiconductor material. A small amount of current flow through the base-emitter can control a larger amount of current flow through the collector-emitter.

Triac A bidirectional, thyristor device used to control ac voltage.

Trigger Pulses A voltage or current of short duration used to activate the gate, base, or input of some electronic device.

Trip Free Refers to a circuit breaker that cannot be held in the on position by the handle on a sustained overload.

Troubleshoot To locate and eliminate the source of trouble in any flow of work.

Truth Table A chart used to show the output condition of a logic gate or circuit as compared to different conditions of input.

Undervoltage Protection The result when a device operates on the reduction or failure of voltage to cause and maintain the interruption of power to the main circuit.

Undervoltage Release Occurs when a device operates on the reduction or failure of voltage to cause the interruption of power to the main circuit, but does not prevent the reestablishment of the main circuit on the return of voltage.

Unijunction Transistor (UJT) A special transistor that is a member of the thyristor family of devices and operates like a voltage-controlled switch.

Valence Electron The electron in the outermost shell or orbit of an atom.

Variable Resistor A resistor in which the resistance value can be adjusted between the limits of its minimum and maximum value.

Varistor A resistor that changes its resistance value with a change of voltage.

Volt/Voltage An electrical measure of potential difference, electromotive force, or electrical pressure.

Voltage Divider A series connection of resistors used to produce different values of voltage drop across them.

Voltage Drop The amount of voltage required to cause an amount of current to flow through a certain value of resistance or reactance.

Voltage Rating A rating that indicates the amount of voltage that can safely be connected to a device.

Voltage Regulator A device or circuit that maintains a constant value of voltage.

Voltage Relay A relay that functions at a predetermined value of voltage. A voltage relay may be either an overvoltage or an undervoltage relay.

Voltmeter An instrument used to measure a level of voltage.

Volt-Ohm-Milliammeter (VOM) A test instrument so designed that it can be used to measure voltage, resistance, or milliamps.

Watt A measure of true power.

Waveform The shape of a wave as obtained by plotting a graph with respect to voltage and time.

Wye Connection A connection of three components made in such a manner that one end of each component is connected. This connection generally connects devices to a three-phase power system.

Zener Diode A special diode that exhibits a constant voltage drop when connected in such a manner that current flows through it in the reverse direction.

Zener Region The region current enters into when it flows through a diode in the reverse direction.

Zero Switching A feature of some solid-state relays that causes current to continue flowing through the device until the ac waveform returns to zero.

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8.7 Acknowledgment. By opening this package and/or by accessing the Licensed Content on this Website, THE END USER ACKNOWLEDGES THAT IT HAS READ THIS AGREEMENT, UNDERSTANDS IT, AND AGREES TO BE BOUND BY ITS TERMS AND CONDITIONS. IF YOU DO NOT ACCEPT THESE TERMS AND CONDITIONS, YOU MUST NOT ACCESS THE LICENSED CONTENT AND RETURN THE LICENSED PRODUCT TO THOMSON DELMAR LEARNING (WITHIN 30 CALENDAR DAYS OF THE END USER'S PURCHASE) WITH PROOF OF PAYMENT ACCEPTABLE TO DELMAR LEARNING, FOR A CREDIT OR A REFUND. Should the End User have any questions/comments regarding this Agreement, please contact Thomson Delmar Learning at delmarhelp@thomson.com.

Delmar's Virtual Laboratory in Industrial Motor Controls

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Basic Installation Instructions

It is recommended that virus protection, disk-security, and other open programs be turned off prior to installing the Virtual Laboratory in Industrial Motor Control software. Student data may be stored to a floppy disk or hard drive. The installation options are described below.

Installing and Starting the Virtual Laboratory in Industrial Motor Control Software

1. Insert the Virtual Laboratory in Industrial Motor Control CD-ROM into the CD-ROM drive.
2. Launch the IMC installer by double-clicking the file called install.exe on the CD-ROM.
3. Or, click **Start/Settings/Control Panels;** then double-click the **Add/Remove Programs** control panel. Click **Install,** and follow the on-screen instructions.
4. Choose whether you want to run the program from the CD-ROM or to install the entire program to a hard disk. Note: Installing the CD-ROM minimum version requires 25 MB of free hard-disk space. Installing the entire program requires 450 MB of free hard-disk space, but this will enhance the program's performance.
5. Choose whether you want to store student data to the installation directory on the hard drive or to data diskettes. Note: if the data diskette option is chosen, students must have their data diskettes to logon and to use the program.
6. Choose the location for the IMC program. The default location is C:\IMC. Use the Browse feature to change location.
7. After installation is complete, click **Start/Programs/Delmar's Industrial Motor Control/Delmar's Industrial Motor Control.**

Basic Operating Instructions

Starting Virtual Laboratory in Industrial Motor Control CD-ROM Network version

1. Double-click the IMC icon to start the program.
2. The opening screen shows the title and copyright. Click anywhere on the screen to continue or wait a few moments until the opening screen automatically advances to the log-on screen.
3. Following the opening screen is a list of students registered to use the program. When the program is started for the first time, this list will be empty.
4. The first time a student uses Virtual Laboratory in Industrial Motor Control, he or she will need to register. On subsequent log-ons, the students will have to select their name and key in their password.

Steps for Student Registration

1. Click the **Add Name** button on the class list screen.
2. The student types his or her first and last names, creates a password, and re-types the password. A mouse click or pressing the Tab key will advance the cursor through text fields.
3. When finished entering log-on information, click OK.
4. The program records the student's log-on information for future use and advances the student to the Main Menu.
5. When a student returns to Virtual Laboratory in Industrial Motor Control software after initially logging on, he or she will need to select his or her name from the student list, enter the password, and click OK.

Additional Controls

The following controls are available on most screens and are found on the lower right side of the screen.

Main Menu button – This button takes you back to the main menu of the program.

Glossary button – This button advances you to the glossary where you can look up definitions of words related to industrial motor control and, where available, see schematic drawings and photographs.

Reports button – This button takes you to the Reporting section showing data on the students' work.

Help button – Clicking the Help button accesses Help information for the current screen.

Exit button – This button brings up a prompt asking if you want to exit the program