UNIT V

Electrical Power Control Systems

In this unit, *electrical power control* systems are studied. The fundamentals of electrical power control are discussed in Chapter 15. This chapter examines several of the fundamental types of *equipment* that are used for electrical power control. This equipment includes *electromechanical* contactors, relays and switches.

Chapter 16 examines the mechanical and electronic *power control* systems that are used with electrical machinery, and the *motor control* systems that are used extensively in day-to-day industrial, commercial, and residential applications. In addition, *programmable logic controllers (PLCs)* are introduced, since they now lay a significant role in machine control.

Chapter 17 discusses electronic control devices such as silicon controlled rectifiers (SCRs), triacs and diacs.

Figure V shows the *electrical power systems model* used in this book, and the major topics of Unit V—Electrical Power Control Systems.

UNIT OBJECTIVES

Upon completion of this unit, you should be able to:

1. Describe the function of standards organizations, such as NEMA, ANSI, and IEEE, in electrical power control.
2. Define important terms used with electrical power control systems.
3. Recognize and sketch symbols used for electrical power control systems.
4. Describe the following types of switches used for electrical power control:
   Toggle Switch
   Rocker Switch
   Pushbutton Switch
   Rotary Switch

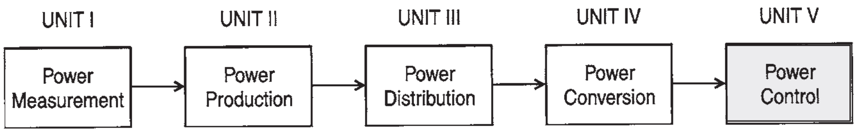

Figure V. Electrical power systems model

Power Control (Chapter 15)
Operational Power Control Systems (Chapter 16)
Control Devices (Chapter 17)

Limit Switch
Temperature Switch
Float Switch
Pressure Switch
Foot Switch
Drum Controller

5. Describe indicating lights used with electrical power control.
6. Recognize and describe various motor starting systems.
7. List the functions of motor starters.
8. Describe the method of assigning size ratings for motor contactors.
9. Describe bimetallic and melting alloy thermal overload devices and their current ratings.
10. Describe the classification system used for motor starters.
11. Describe the method of assigning sizes to manual starters.
12. Describe a combination starter.
13. List criteria used to select motor controllers.
14. List types of motor controller enclosures used by NEMA.
15. Explain the operation of a relay.
16. Explain the operation of a solenoid.
17. Describe an SCR, triac, and diac control devices that may be used for electrical power control.
18. Explain the use of programmable logic controllers and other computerized controllers used for electrical power control applications.
19. Explain the operation of the following power control circuits:
    Start-Stop Control
    Start-Stop Control from Multiple Locations

Start-Stop Control with Safe-Run Feature
Start-Stop Control with Run-Jog Feature
Start-Stop-Jog Control
Forward -Reverse-Stop Control
Full-Voltage Starting
Primary Resistance Starting
Primary Reactor Starting
Autotransformer Starting
Wye-Delta Starting
Part-Winding Starting
Forward-Reverse Starting

20. Describe dynamic braking for direct current (DC) and alternating current (AC) motors.
21. Describe universal motor speed control circuit operation.
22. Describe frequency conversion systems.
23. Describe silicon controlled rectifiers (SCRs), triacs and diacs.

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Chapter 15

Power Control

The *control* of electrical power is a very important part of electrical power system operation. Control is the most complex part of electrical systems. It is, therefore, necessary to limit the discussion in this chapter primarily to some of the common types of electromechanical equipment used for electrical power control. Control equipment is used in conjunction with many types of electrical loads. Electrical motors (mechanical loads) use about 50 percent of all electrical *motor-control* equipment. In most cases, similar equipment is used to control electrical lighting and heating loads.

IMPORTANT TERMS

Chapter 15 deals with power control equipment. After studying this chapter, you should have an understanding of the following terms:

NEMA
ANSI
IEEE
Across-the-Line Starter Auxiliary Contact
Dynamic Braking
Normally Open Contact
Normally Closed Contact
Magnetic Contactor
Drum Controller
Jogging
Manual Starter
Overload Relay
Plugging
Normally Closed Pushbutton
Normally Open Pushbutton

- Reduced-Voltage Starting
- Control Relay
- Safety Switch
- Solenoid
- Timing Relay
- Switches
    - SPST
    - SPDT
    - DPST
    - DPDT
    - 4-Way
    - 3PST
    - 3PDT
- Rotary Switch
- Limit Switch
- Temperature Switch
- Float Switch
- Pressure Switch
- Foot Switch
- Pilot Lights
    - Full-Voltage
    - Transformer-Operated
    - Series Resistor
    - Illuminated Pushbutton
- Combination Starter
- Controller Enclosures-NEMA

POWER CONTROL STANDARDS, SYMBOLS, AND DEFINITIONS

A great amount of fundamental knowledge is needed in order to fully understand electrical power control. Individuals who are concerned with electrical power control systems should have a good knowledge of the *standards, symbols,* and *definitions* that govern electrical power control.

NEMA Standards

The National Electrical Manufacturers' Association (NEMA) has developed standards for electrical control systems. NEMA standards are used extensively to obtain information about the construction and performance of various electrical power control equipment. These standards provide information concerning the voltage, frequency, power, and current ratings for various equipment.

ANSI and IEEE Standards

Two well-known organizations publish standards that are of importance to industry. These organizations are the American National Standards Institute (ANSI) and the Institute of Electrical and Electronic Engineers (IEEE). The standards published by these organizations are for the use of the manufacturing industries, as well as power consumers, and in some cases the general public. These standards are subject to review periodically; therefore, industrial users should keep up to date by obtaining the revisions.

These standards were developed from input from manufacturers, consumers, government agencies, and scientific, technical, and professional organizations. Often these published standards are used by industry as well as governmental agencies. It should be noted that the National Electrical Code, discussed previously, is an American National Standards Institute standard.

Definitions

There are several basic definitions that are used when dealing with electrical power control. These definitions are particularly important when interpreting control diagrams and standards. A listing of several of the important power control definitions follows. You should study these definitions.

Across-the-line-Control—A method of motor starting in which a motor is connected directly across the power lines when it is started.

Automatic Starter—A self-acting starter that is completely controlled by control switches, or some other sensing mechanism.

Auxiliary Contact—A contact that is part of a switching system. It is used in addition to the main contacts, and is operated by the main contacts.

Braking—A control method that is used to rapidly stop and hold a motor.

Circuit Breaker—An automatic device that opens under abnormally high current conditions, and can be manually or automatically reset.

Contact—A current-conducting part of a control device. It is used to open or close a circuit.

Contactor—A control device that is used to repeatedly open or close an electric power circuit.

Controller—A device or group of devices that systematically controls the delivery of electric power to the load or loads connected to it.

Disconnect—A control device or group of devices that will open, so that electrical current in a circuit will be interrupted.

Drum Controller—A set of electrical contacts mounted on the surface of a rotating cylinder. It is usually used for controlling the on-off forward-reverse condition of a load.

Electronic Control—A usually solid-state device that performs part of the control function of a system.

Full Voltage Control—A control system that connects equipment directly across the power lines when the equipment is started.

Fuse—A circuit-protection device that disconnects a circuit when an overcurrent condition occurs. It is self-destructing and must be replaced.

Horsepower—The power output or mechanical work rating of an electrical motor.

Jogging—Momentary operation that causes a small movement of the load that is being controlled.

Magnetic Contactor—A contactor which is operated electromagnetically and usually controlled by pushbuttons activated by an operator.

Manual Controller—An electric control device that functions when operated by mechanical means, usually by an operator.

Master Switch—A switch that controls the power delivered to other parts of a system.

Motor—A device (mechanical load) for converting electrical power to mechanical power in the form of rotary motion.

Multispeed Starter—An electrical power-control device that provides for varying the speed of a motor.

Overload Relay—Overcurrent protection for a load. While it is in operation, it maintains the interruption of the load from the power supply until it is reset or replaced.

Overload Relay Reset—A pushbutton that is used to reset a thermal overload relay after the relay has been overloaded.

Pilot Device—A control device that directs the operation of another device or devices.

Plugging—A braking method that causes a motor to develop a retarding force in the reverse direction.

Pushbutton—A button-type control switch that is manually operated for actuating or disconnecting some load device.

Pushbutton Station—A housing for the pushbuttons that are used to control equipment.

Reduced-voltage Starter—A control device that applies a reduced voltage to a motor when it is started.

Relay—A control device that is operated by one electrical circuit to control a load that is part of another electrical circuit.

Remote Control—A system in which the control of an electrical load takes place from some distant location.

Safety Switch—An enclosed, manually operated, disconnecting switch used to turn a load off when necessary.

Solenoid—An electromagnetically actuated control device that is used to produce linear motion for performing various control functions.

Starter—An electric controller that is used to start, stop, and protect the motor that is connected to it.

Timer—A control device that provides variable time periods, so that a control function may be performed.

Symbols

One should have an understanding of the electrical symbols that are commonly used with power control systems. A few of these are somewhat different from basic electrical symbols. Some typical symbols are shown in Figure 15-1. You should especially observe the symbols that are used for the various types of switches and pushbuttons.

POWER CONTROL USING SWITCHES

An important, but often overlooked, part of electrical power control is the various types of switches used. This section will examine the many types of switches that are used to control electrical power. The primary function of a switch is to turn a circuit on or off; however, many more complex switching functions can be performed using switches. The emphasis in this section will be on switches that are used for motor control. Keep in mind that other load devices can also be controlled in a similar manner by switches.

Toggle Switches

Among the simplest types of switches are toggle switches. The symbols for several kinds of toggle switches are shown in Figure 15-2. You

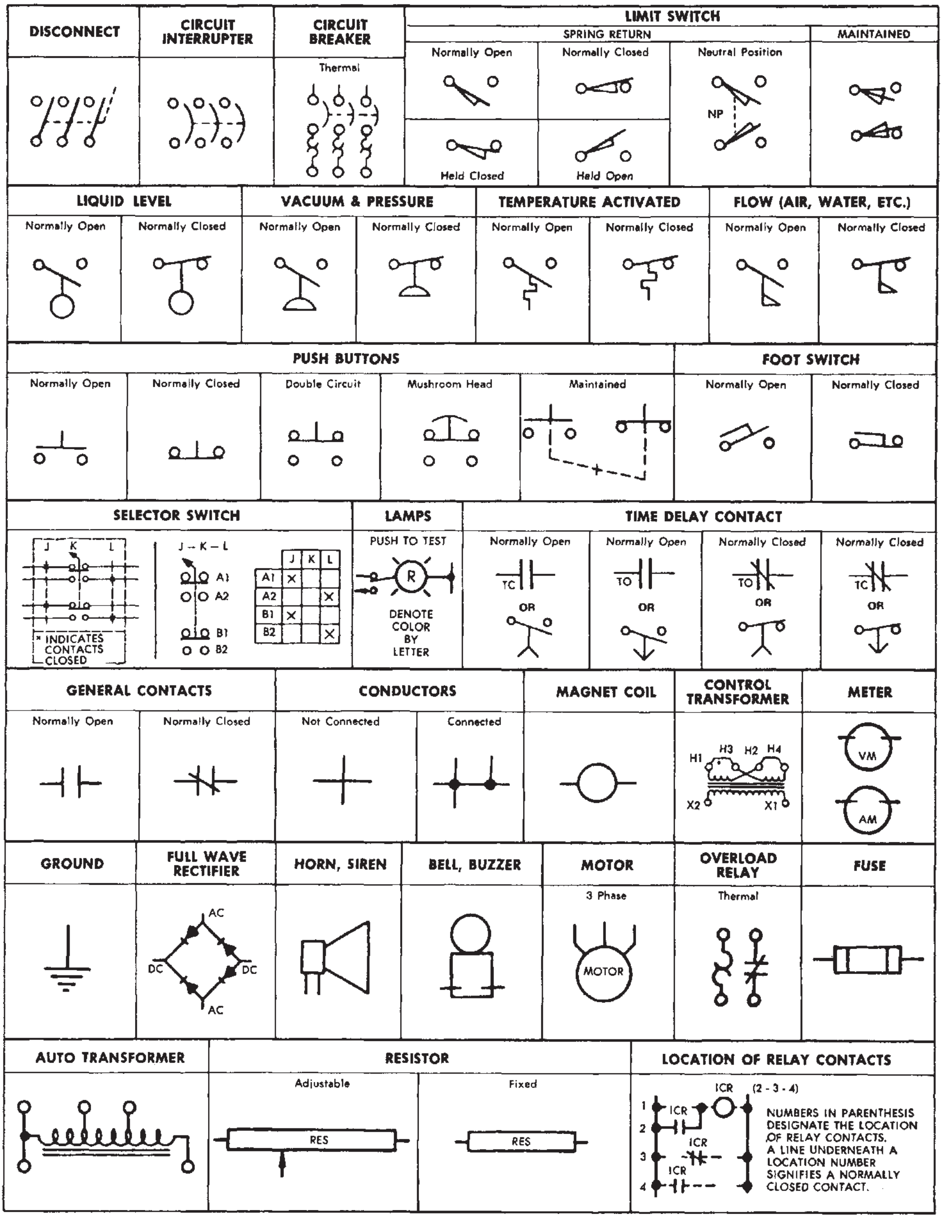

Figure 15-1. Common power control symbols (*Courtesy Furnas Electric Co.*)

should become familiar with the symbols that are used for various types of toggle switches and with the control functions that they can accomplish.

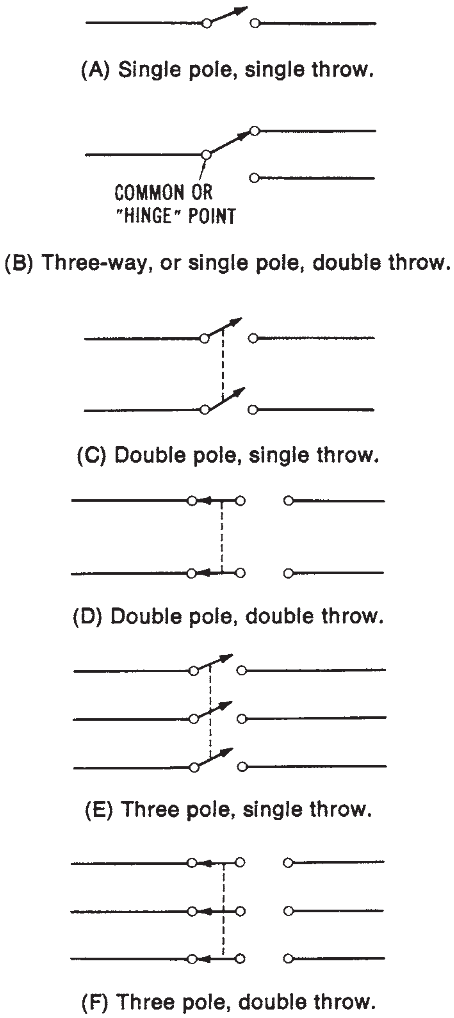

Figure 15-2. Types of toggle switches: (A) Single pole, single throw (SPST), (B) Three-way or single pole, double throw (SPDT), (C) Double pole, single throw (DPST), (D) Double pole, double throw (DPDT), (E) Three pole, single throw (3PST), (F) Three pole, double throw (3PDT)

Rocker Switches

Another type of switch is called a rocker switch. Rocker switches are used for on-off control. They may be either momentary-contact, for accomplishing temporary control, or sustained contact, for causing a load to remain in an on or off condition until the switch position is manually changed.

Pushbutton Switches

Pushbutton switches are commonly used. Many motor-control applications use pushbuttons as a means of starting, stopping, or reversing a motor; the pushbuttons are manually operated to close or open the control circuit of the motor. There are several types of pushbuttons used in the control of motors. Figure 15-3 diagrams some pushbutton styles. Pushbuttons are usually mounted in enclosures.

Ordinarily, pushbuttons are either the normally closed (NC) or normally open (NO) type. An NC pushbutton is closed until it is depressed manually.

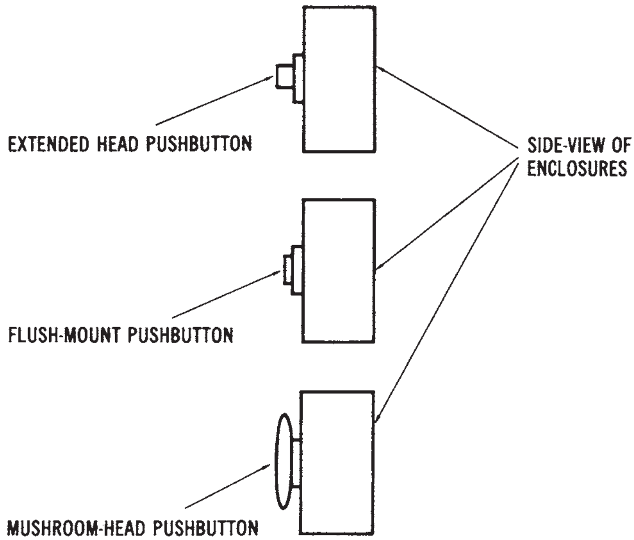

Figure 15-3. Pushbutton styles

It will open a circuit when it is depressed. The NO pushbutton is open until it is manually depressed, and then, once it is depressed, it will close a circuit. The "start" pushbutton of a motor control station is an NO type, while the "stop" switch is an NC type.

Rotary Switches

Another common type of switch is the rotary switch. Many different switching combinations can be wired using a rotary switch. The shaft of a rotary switch is attached to sets of moving contacts. When the rotary shaft is turned to different positions, these moving contacts touch different sets of stationary contacts, which are mounted on ceramic segments. The shaft can lock into place in any of several positions. A common type of rotary switch is shown in Figure 15-4. Rotary switches are usually controlled by manually turning the rotary shaft clockwise or counterclockwise. A knob is normally fastened to the end of the rotary shaft to permit easier turning of the shaft.

Limit Switches

Limit switches are made in a variety of sizes. Limit switches are merely on/off switches that use a mechanical movement to cause a change in the operation of the electrical control circuit of a motor or other load de-

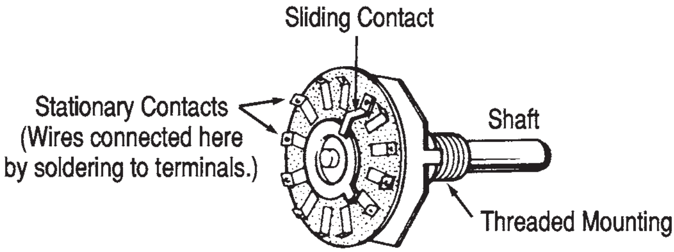

Figure 15-4. Rotary switch

vice. The electrical current developed as a result of the mechanical movement is used to limit movement of the machine, or to make some change in its operational sequence. Limit switches are often used in sequencing, routing, sorting, or counting operations in industry. Ordinarily, they are used in conjunction with hydraulic or pneumatic controls, electrical relays, or other motor-operated machinery, such as drill presses, lathes, or conveyor systems.

In its most basic form, a limit switch converts mechanical motion into an electrical control current. Part of the limit switch is the cam, an external part which is usually mounted on a machine. The cam applies force to the actuator of the limit switch. The actuator is the part of the limit switch that causes the internal NO or NC contacts to change state. The actuator operates by either linear or rotary motion of the cam, which applies force to the limit switch. Two other terms associated with limit switches are *pretravel* and *overtravel.* Pretravel is the distance that the actuator must move to change the normally open or normally closed state of the limit-switch contacts. Overtravel is the distance the actuator moves beyond the point at which the contacts change state. Both pretravel and overtravel settings are important in machine setups where limit switches are used.

Temperature Switches

Temperature switches are among the most common types of control devices used in industry. The control element of a temperature switch contains a specific amount of liquid. The liquid increases in volume when the temperature increases. Thus, changes in temperature can be used to change the position of a set of contacts within the temperature-switch enclosure. Temperature switches may be adjusted throughout a range of temperature settings.

Float Switches

Float switches are used when it is necessary to control the level of a liquid. The float switch has its operating lever connected to a rod and float assembly. The float assembly is placed into a tank of liquid, where the motion of the liquid controls the movement of the operating lever of the float switch. The float switch usually has a set of NO and NC contacts, which are controlled by the position of the operating lever. The contacts are connected to a pump-motor circuit. In operation, the NO contacts are connected in series with a pump-motor control circuit. When the liquid level is reduced, the float switch will be lowered to a point where the operating lever will be moved far enough that the contacts will be caused to change to a closed state. The closing of the contacts will cause the pump motor to turn on. More liquid will then be pumped into the tank until the liquid level has risen high enough to cause the float switch to turn the pump motor off.

Pressure Switches

Another type of electrical control device is called a pressure switch. A pressure switch has a set of electrical contacts that change states as the result of a variation in the pressure of air, hydraulic fluid, water, or some other medium. Some pressure switches are diaphragm operated. They rely upon the intake or expelling of a medium, such as air, which takes place in a diaphragm assembly within the pressure-switch enclosure. Another type of pressure switch uses a piston mechanism to initiate the action of opening or closing the switch contacts. In this type of switch, the movement of a piston is controlled by the pressure of the medium (air, water, et cetera).

Foot Switches

A foot switch is a switch that is controlled by a foot pedal. This type of switch is used for applications in which a machine operator has to use both hands during the operation of the machine. The foot switch provides an additional control position for the operation of a machine, for times when the hands cannot be used.

Drum-controller Switches

Drum controllers are special-purpose switches, which are ordinarily used to control large motors. They may be used with either single-phase or three-phase motors. The usual functions of a drum-controller switch are start/stop control or the forward/reverse/stop control of electrical motors. Contacts are moved as the handle of the controller is turned to provide machine control.

Pilot Lights for Switches

Pilot lights usually operate in conjunction with switches. Motor-control devices often require that some visual indication of the operating condition of the motor be provided. Pilot lights of various types are used to provide such a visual indication. They usually indicate either an on or off condition. For instance, a pilot light could be wired in parallel with a motor to indicate when it is on. Some types of pilot lights are:

1. *Full-voltage Across-the-line Lights*—These are relatively inexpensive lights, but they do not last as long as other types.
2. *Transformer-operated Lights*—These use a relatively low voltage to activate the lamp, but they require the expense of an additional transformer, which ordinarily reduces the operating voltage to 6 volts.
3. *Resistor-type Lights*—These lights use a series resistor to reduce the voltage across the lamp.
4. *Illuminated Pushbutton*—In these, the functions of the pushbutton and the pilot-light device are combined into one item of equipment, which reduces the mounting-space requirement.

CONTROL EQUIPMENT FOR ELECTRIC MOTORS

There are several types of electromechanical equipment used for the control of electric-motor power. The selection of power-control equipment will affect the efficiency of the power-system operation and the performance of the machinery. It is very important to use the proper type of equipment for each power-control application. This section will concentrate on the types of equipment used for motor control.

Motor-starting Control

A motor-starting device is a type of power control used to accelerate a motor from a "stopped" condition to its normal operating speed. There are many variations in motor starter design, the simplest being a manually operated on/off switch connected in series with one or more power lines. This type of starter is used only for smaller motors that do not draw an excessive amount of current.

Another type of motor starter is the magnetic starter, which relies upon an electromagnetic effect to open or close the power-source circuit of the motor. Often, motor starters are grouped together for the control of adjacent equipment in an industrial plant. Such groupings of motor starters and associated control equipment are called control centers. Control centers provide a relatively easy access to the power distribution system, since they are relatively compact, and the control equipment is not scattered throughout a large area. Motor-starting systems will be discussed in greater detail in Chapter 16.

Function of Motor Starters

Various types of motor starters are used for control of motor power. The functions of a starter vary in complexity; however, motor starters usually perform one or more of the following functions:

1. On and off control.
2. Acceleration.
3. Overload protection.
4. Reversing the direction of rotation.

Some starters control a motor by being connected directly across the power input lines. Other starters reduce the level of input voltage that is applied to the motor when it is started, so as to reduce the value of the starting current. Ordinarily, motor overload protection is contained in the same enclosure as the magnetic contactor.

Sizes of Motor Contactors

The contactors used with motor starters are rated according to their current capacity. The National Electrical Manufacturers Association (NEMA) has developed standard sizes for magnetic contactors according to their current capacity. Table 15-1 lists the NEMA standard sizes for magnetic contactors. By looking at this chart, you can see that a NEMA size 1 contactor has a 30-ampere current capacity if it is open (not mounted in a metal enclosure), and a 27-ampere capacity if it is enclosed. The corresponding maximum horsepower ratings of loads for each of the NEMA contactor sizes are also shown in Table 15-1.

Manual Starters

Some motors use manual starters to control their operation. This type

Table 15-1. Sizes of Magnetic Contactors

			Maximum Horsepower Rating of Load					
	Ampere Rating		Single-Phase		Three-Phase			
NEMA Size	Open	Enclosed	115 V	230 V	115 V	200 V	230 V	460 V
00	10	9	0.33	1	0.75	1.5	1.5	2
0	20	18	1	2	2	3	3	5
1	30	27	2	3	3	7.5	7.5	10
2	50	45	3	7.5	7.5	10	15	25
3	100	90	7.5	15	15	25	30	50
4	150	135	—	—	25	40	50	100
5	300	270	—	—	—	75	100	200
6	600	540	—	—	—	150	200	400
7	900	810	—	—	—	—	300	600
8	1350	1215	—	—	—	—	450	900
9	2500	2250	—	—	—	—	800	1600

of starter provides starting, stopping, and overload protection similar to that of a magnetic contactor. However, manual starters must be mounted near the motor that is being controlled. Remote-control operation is not possible, as it would be with a magnetic contactor. This is due to the small control current that is required by the magnetic contactor. Magnetic contactors also provide a low-voltage protection by the dropout of the contacts when a low-voltage level occurs. Manual starters remain closed until they are manually turned off. They are usually limited to small sizes.

Motor Overload Protection

Both manual and magnetic starters can have overload protection contained in their enclosures. It is common practice to place either bimetallic or melting-alloy overload relays in series with the motor branch circuit power lines. These devices are commonly called heaters. An overload protective relay is selected according to the current rating of the motor circuit to which it is connected. An identification number is used on overload protective devices. This number is used to determine the current that will cause the overload device to “trip” or open the branch circuit. Some typical overload protection or heater tables are given in Tables 15-2 and 15-3.

Table 15-2 is used for melting-alloy-type devices. The Table Number (26142) is selected according to the type and size of controller, the size of motor, and the type of power distribution (single-phase or three-phase). For example, a heater with an H37 code number is used with a motor that has a full-load current of 18.6 to 21.1 amperes.

Table 15-3 is used with bimetallic overload relays. They are selected in the same manner as melting-alloy relays. However, this table shows the trip amperes of the heater. A heater with a *K53* code number has a 13.9 trip-ampere rating. Thus, a current in excess of 13.9 amperes would cause the heater element to trip. This would open the motor branch circuit by removing the power from the motor.

Table 15-2. Melting Allow Devices

Table 26142					
Full Load Motor Amps.	*Heater Code*	*Full Load Motor Amps.*	*Heater Code*	*Full Load Motor Amps.*	*Heater Code*
12.6 - 14.5	H33	21.2 - 22.2	H38	34.6 - 38.9	H43
14.6 - 16.0	H34	22.3 - 23.6	H39	39.0 - 44.7	H44
16.1 - 16.9	H35	23.7 - 26.2	H40	44.8 - 48.8	H45
17.0 - 18.5	H36	26.3 - 30.1	H41	48.9 - 54.2	H46
18.6 - 21.1	H37	30.2 - 34.5	H42	54.3 - 60.0	H48

Table 15-3. Bimetallic Devices

Table 62K					
Trip Amperes	*Heater Code*	*Trip Amperes*	*Heater Code*	*Trip Amperes*	*Heater Code*
1.95	K21	5.59	K36	17.0	K56
2.12	K22	6.39	K37	18.3	K57
2.31	K23	6.88	K39	19.8	K58
2.49	K24	7.78	K41	21.0	K60
2.75	K26	8.42	K42	22.5	K61
3.05	K27	9.54	K43	24.1	K62
3.29	K28	10.1	K49	25.7	K63
3.69	K29	11.5	K50	28.3	K64
4.01	K31	12.6	K52	31.1	K67
4.32	K32	13.9	K53	34.6	K68
4.77	K33	15.1	K54		
5.14	K34	16.0	K55		

Classes of Motor Starters

The types of motor starters that are commercially available are divided into five classes. These classes, which were established by NEMA, are:

1. Class A—Alternating current (AC), manual or magnetic, air-break or oil-immersed starters that operate on 600 volts or less.
2. Class B—Direct current (DC), manual or magnetic, air-break starters that operate on 600 volts or less.
3. Class C—AC, intermediate voltage starters.
4. Class D—DC, intermediate voltage starters.
5. Class E—AC, magnetic starters that operate on 2200 volts to 4600 volts. Class E1 uses contacts, and Class E2 uses fuses.

Sizes of Manual Starters

A uniform method has also been established for sizing manual motor starters. Some examples of the sizes of full-voltage manual starters are:

1. Size M-O—For single-phase 115-volt motors up to 1 horsepower.
2. Size M-1—For single-phase 115-volt motors up to 2 horsepower.
3. Size M-1P—For single-phase 115-volt motors up to 3 horsepower.

These sizes are summarized in Table 15-4.

Table 15-4. Sizes of Manual Starters

Maximum Horsepower Rating of Load					
Starter Size	*Single-Phase 115 V*	*230 V*	*Three-Phase 200-230 V*	*460-575 V*	*Ampere Rating*
M-O	1	2	3	5	20
M-1	2	3	7.5	20	30
M-1P	3	5	—	—	30

Combination Starters

A popular type of motor starter used in control applications is the combination starter. These starters incorporate protective devices such as fused-disconnect switches, air-type circuit breakers, or a system of fuses and circuit breakers mounted in a common enclosure. They are used on systems of 600 volts or less.

Criteria for Selecting Motor Controllers

There are several important criteria that should be considered when selecting electric motor controllers. Among these are:

1. The type of motor-AC or DC, induction or wound rotor.
2. The motor ratings-voltage, current, duty cycle, and service factor.
3. Motor operating conditions-ambient temperature and type of atmosphere.
4. Utility company regulations-power factor, demand factor, load requirements, and the local codes.
5. Type of mechanical load connected to motor-torque requirement.

In order to become more familiar with the criteria listed above, you must be able to interpret the data on a motor nameplate. The information contained on a typical nameplate is summarized as follows:

Manufacturing Co.—The company that built the motor.
Motor Type—A specific type of motor, that is: split-phase AC, universal, three-phase induction, et cetera.
Identification Number—Number assigned by the manufacturer.
Model Number—Number assigned by the manufacturer.
Frame Type—Frame size defined by NEMA.
Number of Phases (AC)—Single-phase or three-phase.
Horsepower—The amount produced at rated speed.
Cycles (AC)—Frequency the motor should be used with (usually 60 Hz).
Speed (r/min)—The amount at rated hp, voltage, and frequency.
Voltage Rating-Operating voltage of motor.
Current Rating (amperes)—Current drawn at rated load, voltage, and frequency.
Thermal Protection—The type of overload protection used.
Temperature Rating (°C)—Amount of temperature that the motor will rise over ambient temperature, when operated.
Time Rating—Time the motor can be operated without overheating (usually continuous).
Amps—Current drawn at rated load, voltage, and frequency.

Motor-controller Enclosures

The purpose of a motor-controller enclosure is obvious. The operator is protected against accidental contact with high voltages that could cause death or shock. In some cases, however, the enclosures are used to protect the control equipment from its operating environment, which may contain water, heavy dust, or combustible materials. The categories of motor-controller enclosures have been standardized by NEMA. The following list, courtesy of Furnas Electric Company, summarizes various classifications.

NEMA 1 General-Purpose enclosures protect personnel from accidental electrical contact with the enclosed apparatus. These enclosures satisfy indoor applications in normal atmospheres that are free of excessive moisture, dust, and explosive materials.

NEMA 3 (3R) Weatherproof enclosures protect the control from weather hazards. These enclosures are suitable for applications on ship docks, canal locks, and construction work, and for application in subways and tunnels. The door seals with a rubber gasket. They are furnished with conduit hub and pole mounting bracket.

NEMA 4 Weathertight enclosures are suitable for application outdoors on ship docks and in dairies, breweries, et cetera. This type meets standard hose test requirements. They are sealed with a rubber gasket in the door. NEMA 4X Corrosion Resistant fiberglass enclosures are virtually maintenance free. These U.L.-listed units are adaptable to any conduit system by means of readily available metal, fiberglass, or PVC conduit hubs, and are suitable for NEMA 3, 3R, 3S, 4, and 12 applications because they are dust-tight, rain-tight, water-tight, and oil-tight.

NEMA 12 Industrial-Use enclosures also satisfy dust-tight applications. These enclosures exclude dust, lint, fibers, and oil or coolant seepage. The hinged cover seals with a rubber gasket.

NEMA 13 Oil-tight pushbutton enclosures protect against dust, seepage, external condensation, oil, water, and coolant spray.

NEMA 7. For atmospheres containing hazardous gas, NEMA 7 enclosures satisfy Class 1, Group C or D applications, as outlined in Section 500 of the *National Electrical Code Standard of the National Board of Fire Underwriters for Electrical Wiring and Apparatus.* These cast aluminum enclosures are designed for use in atmospheres containing ethylether vapors, ethylene, cyclopropane, gasoline, hexane, naptha, benzine, butane, propane, alcohol, acetone, benzol, lacquer solvent vapors, or natural gas. Machined surfaces between the cover and the base provide the seal.

NEMA 9, For atmospheres containing explosive dust, NEMA 9 enclosures satisfy Class II, Group E, F, and G applications, as outlined by the *National Electri-*

cal Code for metal dust, carbon black, coal, coke, flour, starch, or grain dusts. The enclosure is cast aluminum with machined surfaces between cover and base to provide seal.

NEMA TYPES 1B1, 1B2, IB3 Flush Types provide behind-the-panel mounting into machine bases, columns, or plaster walls to conserve space and to provide a more pleasant appearance. NEMA 1B1 mounts into an enclosed machine cavity, NEMA 1B2 includes its own enclosure behind the panel to exclude shavings and chips that might fall from above. NEMA IB3 for plaster walls includes an adjustment to compensate for wall irregularities.

OTHER ELECTROMECHANICAL POWER CONTROL EQUIPMENT

There are so many types of electromechanical power control equipment used today that it is almost impossible to discuss each type. However, some of the very important types will be discussed in the following paragraphs.

Relays

Relays represent one of the most widely used control devices available today. The electromagnet of a relay contains a stationary core. Mounted close to one end of the core is a movable piece of magnetic material called the armature. When the coil is activated electrically, it produces a magnetic field in the metal core. The armature is then attracted to the core, which in turn produces a mechanical motion. When the coil is de-energized, the armature is returned to its original position by spring action.

The armature of a relay is generally designed so that electrical contact points respond to its movement. Activation of the relay coil will cause the contact points to "make" or "break," according to the design of the relay. A relay could be described as an electromagnetic switching mechanism. There are an almost endless number of special-purpose relays and switch combinations used for electrical power control. Figure 15-5 shows a simplified diagram of the construction of a relay that is used to control a motor.

Relays use a small amount of current to create an electromagnetic field that is strong enough to attract the armature. When the armature is attracted, it either opens or closes the contacts. The contacts then either turn on or turn off circuits that are using large amounts of current. The minimal current that must flow through the relay coil, in order to create a magnetic field strong enough to "attract" the armature, is known as the

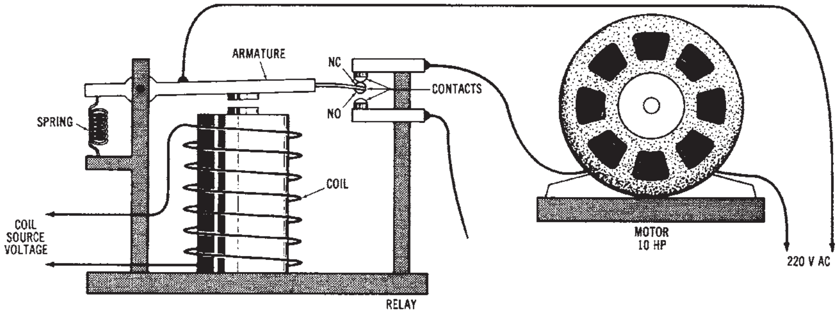

Figure 15-5. Simplified diagram of the construction of a relay that is used to control a motor

"pickup" or "make" current. The current through the relay coil that allows the magnetic field to become weak enough to release the armature is known as the "break" or "dropout" current.

There are two types of contacts used in conjunction with most relays—normally open (NO) and normally closed (NC). The NO contacts remain open when the relay coil is de-energized, and are closed only when the relay is energized. The NC contacts remain closed when the relay is de-energized, and are open only when the coil is energized.

Solenoids

A solenoid, shown in Figure 15-6 is an electromagnetic coil with a movable core that is constructed of a magnetic material. The core, or plunger, is sometimes attached to an external spring. This spring causes the plunger to remain in a fixed position until moved by the electromagnetic field that is created by current through the coil. This external spring also causes the core or plunger to return to its original position when the coil is de-energized.

Solenoids are used for a variety of control applications. Many gas and fuel oil furnaces use solenoid valves to automatically turn the fuel supply on or off upon demand. Most dishwashers use one or more solenoids to control the flow of water.

Specialized Relays

There are many types of relays used for electrical power control. General-purpose relays are used for low-power applications. They are rel-

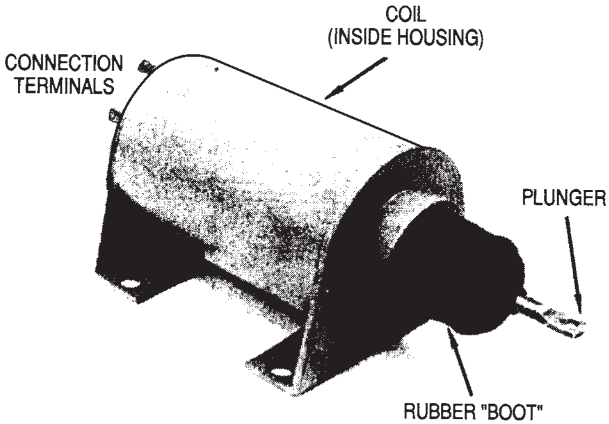

Figure 15-6. A solenoid

atively inexpensive and small in size. Many small, general-purpose relays are mounted in octal base (8-pin) plug-in sockets. Latching relays are another type of relay. They are almost identical to the relays discussed previously, but they have a latching mechanism that holds the contacts in position after the power has been removed from the coil. A latching relay usually has a special type of unlatching coil connected in series with a pushbutton stop switch. Solid-state relays are used when improved reliability, or a rapid rate of operation, is necessary. Electromagnetic relays will wear out after prolonged use, and have to be replaced periodically. Solid-state relays, like other solid state devices, have a long life expectancy. They are not sensitive to shock, vibration, dust, moisture, or corrosion. Timing relays are used to turn a load device on or off after a specific period of time.

The operation of a pneumatic timing relay is dependent upon the movement of air within a chamber. Air movement is controlled by an adjustable orifice that controls the rate of air movement through the chamber. The air-flow rate determines the rate of movement of a diaphragm or piston assembly. This assembly is connected to the contacts of the relay. Therefore, the orifice adjustment controls the air-flow rate, which determines the time from the activation of the relay until a load connected to it is turned on or off. There are other types of timing relays, such as solid-state, thermal, oil-filled, dashpot, and motor-driven timers. Timing relays are useful for sequencing operations that require a time delay between operations. A typical application would be as follows: (1) a "start" push-button is pressed, (2) a timing relay is activated, (3) after a 5-second time delay, a motor is turned on.

ELECTRONIC POWER CONTROL

Solid-state power controllers are capable of replacing electromagnetic circuit breakers and relays used for electrical power control. The introduction of computerized control for industrial equipment has brought about a new technology of machine control. Many industrial machines, such as automated manufacturing and robotic equipment, are now controlled by computerized circuits. An understanding of the basic principles of electrical control is, however, still very important for technicians.

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Chapter 16

Operational Power Control Systems

Chapter 15 dealt with the equipment used for electrical power control. Now, the *operational power control systems* will be discussed in Chapter 16. Some specific applications of the equipment and devices that were studied in Chapter 15 will be investigated in this chapter.

IMPORTANT TERMS

Chapter 16 deals with operational power control systems. After studying this chapter, you should have an understanding of the following terms:

- Start-Stop Pushbutton
- Normally Open (NO) Pushbutton
- Normally Closed (NC) Pushbutton
- Overload Protection
- Jogging
- Limit Switch
- High-Low Speed Selection
- Magnetic Contactor
- Full-Voltage Starting
- Primary Resistance Starting
- Primary Reactor Starting
- Wye-Delta Starting
- Autotransformer Starting
- Part-Winding Starting
- Direct Current (DC) Starting Systems
- Forward-Reverse-Stop Control
  - Three-phase Alternating Current (AC) Motors

BASIC CONTROL SYSTEMS

Electrical power control systems are used with many types of loads. The most common electrical loads are motors, so our discussion will deal mainly with electric *motor control.* However, many of the basic control systems are also used to control lighting and heating loads. Generally, the controls for lighting and heating loads are less complex.

Several *power control circuits* are summarized in Figures 16-1 through 16-9. Figure 16-1 is a *start-stop pushbutton* control circuit with *overload protection* (OL). Notice that the *"start"* pushbutton is normally open (NO), and the *"stop"* pushbutton is normally closed (NC). *Single-phase lines* L1 and L2 are connected across the control circuit. When the start pushbutton is pushed, a *momentary* contact is made between points 2 and 3. This causes the NO contact (M) to close. A complete circuit between L1 and L2 results, which causes the electromagnetic *coil* M to be energized. When the NC stop pushbutton is pressed, the circuit between L1 and L2 will open. This causes contact M to open and turn the circuit off.

The circuit of Figure 16-2 is the same type of control as the circuit given in Figure 16-1. In the circuit of Figure 16-2, the *start-stop control* of a load can be accomplished from *three* separate locations. Notice that the start pushbuttons are connected in *parallel,* and the stop pushbuttons are connected in *series.* The control of one load, from as many locations as is desired, can be accomplished with this type of control circuit.

The next circuit (Figure 16-3) is the same as the circuit in Figure 16-1, except that a "safe-run" switch is provided. The "safe" position assures that the start pushbutton will not activate the load. A "start-safe" switch circuit often contains a key, which the machine operator uses to turn the control circuit on or off.

Figure 16-4 is also like the circuit of Figure 16-1, but with a "jog-run" switch added in series with the NO contact (M). In the "run" position, the circuit will operate just like the circuit of Figure 16-1. The "jog" position is used so that a complete circuit between L1 and L2 will be achieved and sustained only while the start pushbutton is pressed. With the selector switch in the "jog" position, a motor can be rotated a small amount at a time, for positioning purposes. *Jogging* or *inching* is defined as the momentary operation of a motor to provide small movements of its shaft.

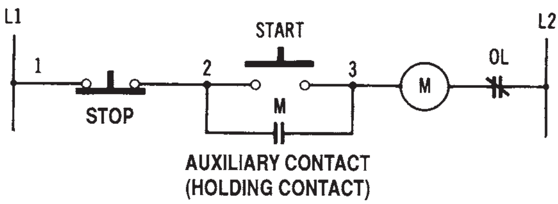

Figure 16-1. A start-stop pushbutton control circuit with overload protection (one-line diagram)

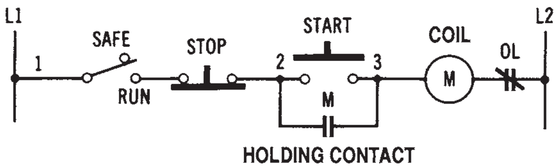

Figure 16-2. A start-stop control circuit with low-voltage protection and control from three locations

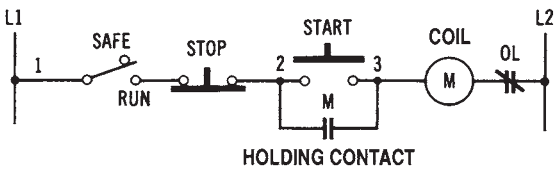

Figure 16-3. A start-stop control circuit with a safe-run selector switch

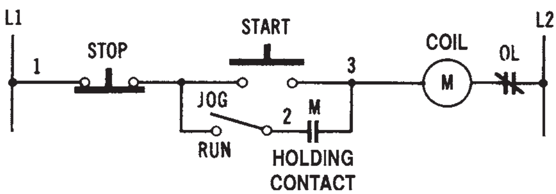

Figure 16-4. A start-stop pushbutton control circuit with a jog-run selector switch

Figure 16-5 shows a circuit that is another method of motor-jogging control. This circuit has a separate pushbutton (which relies upon an NO contact [CR] to operate) for jogging. Two control relays are used with this circuit.

The circuit in Figure 16-6 is a forward-reverse pushbutton control circuit with both forward and reverse limit switches (normally closed switches). When the "forward" pushbutton is pressed, the load will operate until the "forward" limit switch is actuated. The load will then be turned off, since the circuit from L1 to L2 will be opened. The reverse circuit operates in a similar manner. Two control relays are needed for forward-reverse operation.

The circuit of Figure 16-7 is the same as the circuit in Figure 16-6, except for the pushbutton arrangement. The forward and reverse pushbuttons are arranged in sets. Pressing the "forward" pushbutton automatically opens the reverse circuit, and pressing the "reverse" pushbutton automatically opens the forward circuit. Limit switches are also used with this circuit. Their function is the same as in the circuit shown in Figure 16-6. In the circuit in Figure 16-7, when the "forward" pushbutton is pressed, the

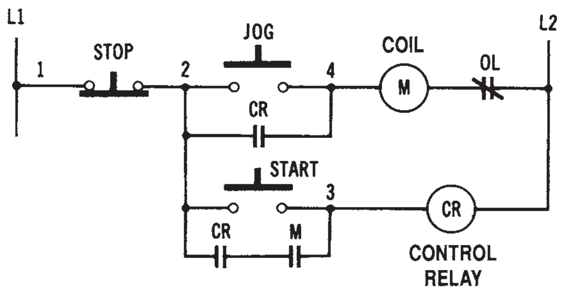

Figure 16-5. A pushbutton control circuit for start-stop-jogging

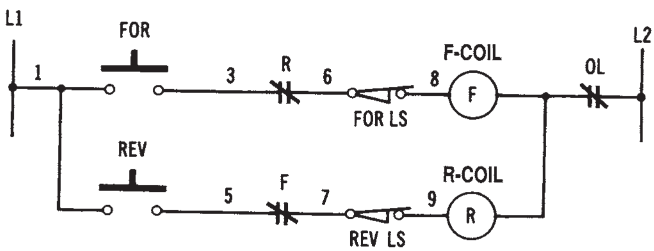

Figure 16-6. A forward-reverse pushbutton control circuit with forward and reverse limit switches

top pushbutton will momentarily close, and the lower pushbutton will momentarily open. When points 2 and 3 are connected, current will flow from L1 to L2 through coil F. When coil F is energized, NO contact F will close, and the NC contact F will open. The "forward" coil will then remain energized. The reverse pushbuttons cause similar actions of the reversing circuit. Two control relays are also required in this case.

The circuit of Figure 16-8 is similar in function to the circuit in Figure 16-7. The pushbutton arrangement of this circuit is simpler. When the NO forward pushbutton is pressed, current will flow through coil F. When the forward control relay is energized, NO contact F will close, and NC contact F will open. This action will cause a motor to operate in the forward direction. When the NC stop pushbutton is pressed, the current through coil F is interrupted. When the NO reverse pushbutton is pressed, current will flow through coil R. When the reverse coil is energized, NO contact F will close, and NC contact F will open. This action will cause a motor to operate in the reverse direction, until the stop pushbutton is pressed again.

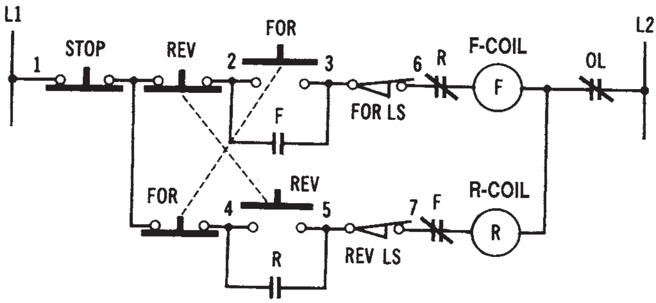

Figure 16-7. An instant forward-reverse-stop pushbutton control circuit

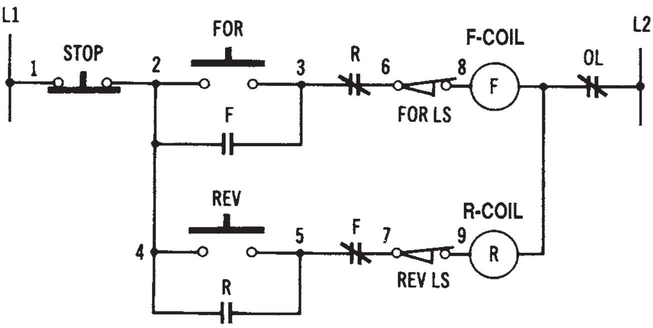

Figure 16-8. A forward-reverse-stop pushbutton control circuit

Figure 16-9 shows a circuit that is another method of forward-reverse-stop control. This control circuit has the added feature of a high- and low-speed selector switch for either the forward or reverse direction. The selector switch is placed in series with the windings of the motor. When the selector is changed from the HIGH position to the LOW position, a modification in the windings of the motor is made.

There are many other pushbutton combinations that can be used with control relays to accomplish motor control, or control of other types of loads. The circuits discussed in this section represent some basic power control functions, such as start-stop, forward-reverse-stop, jogging, and multiple-speed control.

MOTOR-STARTING SYSTEMS

The equipment used with motor-starting systems was studied in Chapter 15. Some specific systems used for starting electric motors are discussed in this section.

Function of Magnetic Contactors

Most motor-starting systems utilize one or more magnetic contactors. A schematic diagram of a magnetic contactor circuit used for control-

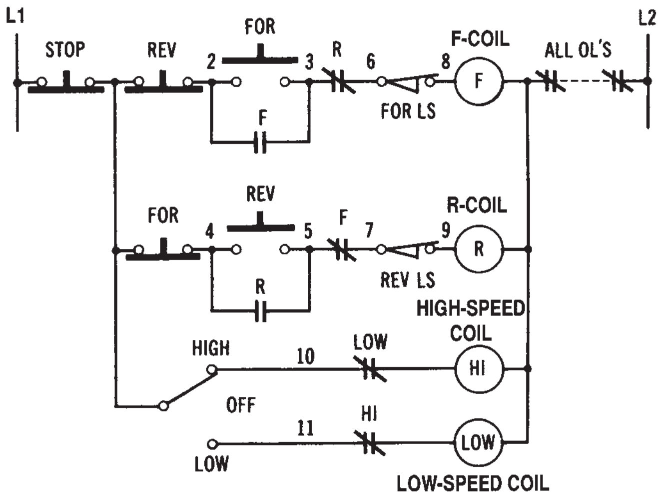

Figure 16-9. Pushbutton control circuit with a high- and low-speed selector switch

ling a single-phase motor is shown in Figure 16-10. Note that a magnetic contactor relies upon an electromagnetic coil, which energizes when current passes through it. The activated coil performs the function of closing a set of normally open contacts. These contacts are connected in series with the power input to the motor that is being controlled.

In Figure 16-10, the START pushbutton switch is an NO switch. When the start switch is pressed, current will flow through the coil of the magnetic contactor. This action energizes the coil, and the solenoid of the contactor is drawn inward to close the contacts, which are in series with the power lines. Once these contacts are closed, current will continue to flow through the electromagnetic coil through the holding contacts. Current will continue to flow until the STOP pushbutton switch is pressed. The stop switch is an NC switch. When it is pressed, the circuit to the electromagnetic coil is broken. At this time, current no longer flows through the coil. The contacts now release and cause the flow of current through the power lines to be interrupted. Thus, the motor will be turned off. Magnetic contactor circuits are sometimes referred to as *across-the-line* starters. The relay principle is utilized, since a small current through the coil controls a larger current through a motor.

Types of Starting Systems

Motor starting, particularly for large motors, can play an important role in the efficient operation of an electrical power system. There are several systems used to start electric motors. The motor-starting equipment that is used is placed between the electrical power source and the motor. Electric motors draw a larger current from the power lines during starting

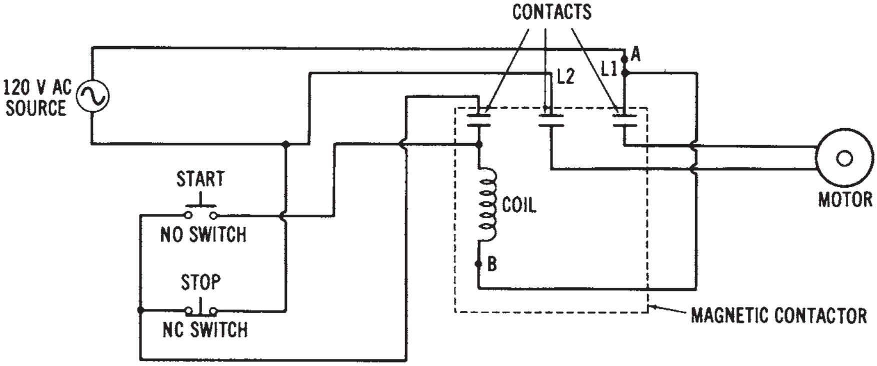

Figure 16-10. Magnetic contactor motor control circuit (Schematic diagram)

than during normal operation. Motor-starting equipment should attempt to reduce starting currents to a level that can be handled by the electrical power system where they are being used.

Full-voltage Starting—One method of starting electric motors is called *full-voltage starting*. This method is the least expensive and the simplest to install. Since full power-supply voltage is applied to the motor initially, maximum starting torque and minimum acceleration time result. However, the power system must be able to handle the starting current drawn by the motor.

Full-voltage starting is illustrated by the diagram in Figure 16-11. In this power control circuit, a start-stop pushbutton station is used to control a three-phase motor. When the NO start pushbutton is pressed, current will flow through the relay coil (M), causing the NO contacts to close. The line contacts allow full voltage to be applied to the motor when they are closed. When the start pushbutton is released, the relay coil remains energized, because of the holding contact. This contact provides a current path from L1 through the NC stop pushbutton, through the holding contact, through the coil (M), through a thermal overload relay, and back to L2. When the stop pushbutton is pressed, this circuit is opened, causing the coil to be de-energized.

Primary Resistance Starting—Another motor starting method is called *primary resistance starting*. This method uses resistors in series with the power lines to reduce the motor-starting current. Ordinarily, the resistance connected into the power lines may be reduced in steps until full voltage is applied to the motor. Thus, starting current is reduced according to the value of series resistance in the power lines. Since starting torque is directly proportional to the current flow, starting torque is reduced according to the magnitude of current flow.

OPERATIONAL POWER CONTROL SYSTEMS

Figure 16-12 shows the primary resistance starting method used to control a three-phase motor. When the start pushbutton is pressed, coils Sand TR are energized. Initially, the start contacts (S) will close, applying voltage through the primary resistors to the motor. These resistors reduce the value of starting current. Once the time delay period of timing relay TR has elapsed, contact TR will close. The run contacts (R) will then close and

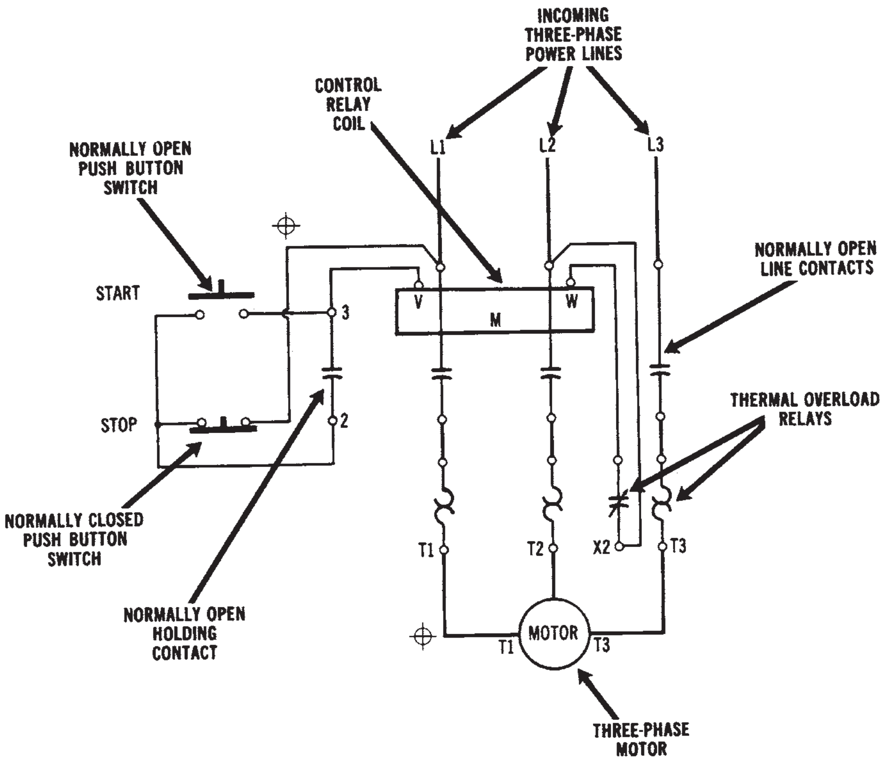

Figure 16-11. Full-voltage starting circuit for a three-phase motor (*Courtesy Furnas Electric Co.*)

apply full voltage to the motor. Notice that a step-down transformer is used for applying voltage to the control portion of the circuit. This is a commonly used technique for reducing the voltage applied to the relay coils.

Primary Reactor Starting—Another method, similar to primary resistance starting, is called the *primary reactor starting* method. Reactors (coils) are used in place of resistors, since they consume smaller amounts of power from the AC source. Usually, this method is more appropriate for large motors that are rated at 600 volts.

Autotransformer Starting—Autotransformer starting is another method used to start electric motors. This method employs one or more autotransformers to control the voltage that is applied to a motor. The autotransformers used are ordinarily tapped to provide a range of starting-cur-

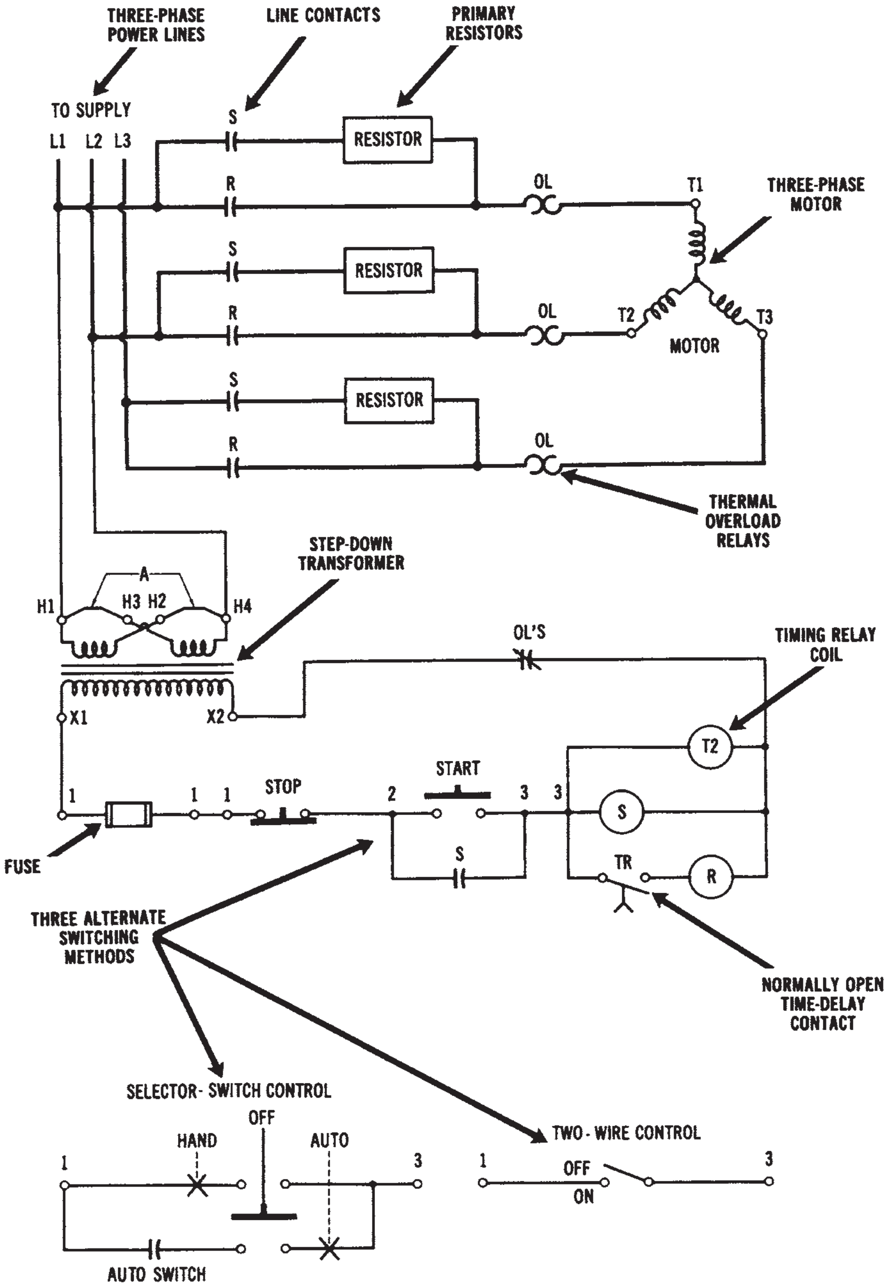

Figure 16-12. Primary resistance starter circuit (*Courtesy Furnas Electric Co.*)

rent control. When the motor has accelerated to near its normal operating speed, the autotransformer windings are removed from the circuit. A major disadvantage of this method is the expense of the autotransformers.

An autotransformer starting circuit is shown in Figure 16-13. This is an expensive type of control that uses three autotransformers and four relays. When the start pushbutton is pressed, current will flow through coils 1S, 2S, and TR. The 1S and 2S contacts will then close. Voltage will be applied through the autotransformer windings to the three-phase motor. One NC and one NO contact are controlled by timing relay TR. When the specified time period has elapsed, the NC TR contact will open, and the NO TR contact will close. Coil R will then energize, causing the NO R contacts to close and apply full voltage to the motor. NC R contacts are connected in series, with coils 1S, 2S, and TR to open their circuits when coil R is energized. When the stop pushbutton is pressed, the current to coil R will be interrupted, thus opening the power line connections to the motor.

Notice that the 65 percent taps of the autotransformer are used in Figure 16-13. There are also taps for 50 percent, 80 percent, and 100 percent, to provide more flexibility in reducing the motor-starting current.

Wye-delta Starting—It is possible to start three-phase motors more economically by using the *wye-delta-starting* method. Since, in a wye configuration, line current is equal to the phase current divided by 1.73 (or 3), it is possible to reduce the starting current by using a wye connection rather than a delta connection. This method, shown in Figure 16-14, employs a switching arrangement that places the motor windings in a wye configuration during starting, and in a delta arrangement for running. In this way, starting current is reduced. Although starting torque is reduced, running torque is still high, since full voltage appears across each winding when the motor is connected in a delta configuration.

In Figure 16-14, when the start pushbutton is pressed, coil S is energized. The normally open S contacts will close. This action connects the motor windings in a wye (or star) configuration and also activates timing relay TR and coil 1M. The NO 1M contacts then close to apply voltage to the wye-connected motor windings. After the time delay period has elapsed, the TR contacts will change state. Coil S will de-energize, and coil 2M will energize. The S contacts, which hold the motor windings in a wye arrangement, will then open. The 2M contacts will close and cause the motor windings to be connected in a delta configuration. The motor will then continue to run with the motor connected in a delta arrangement.

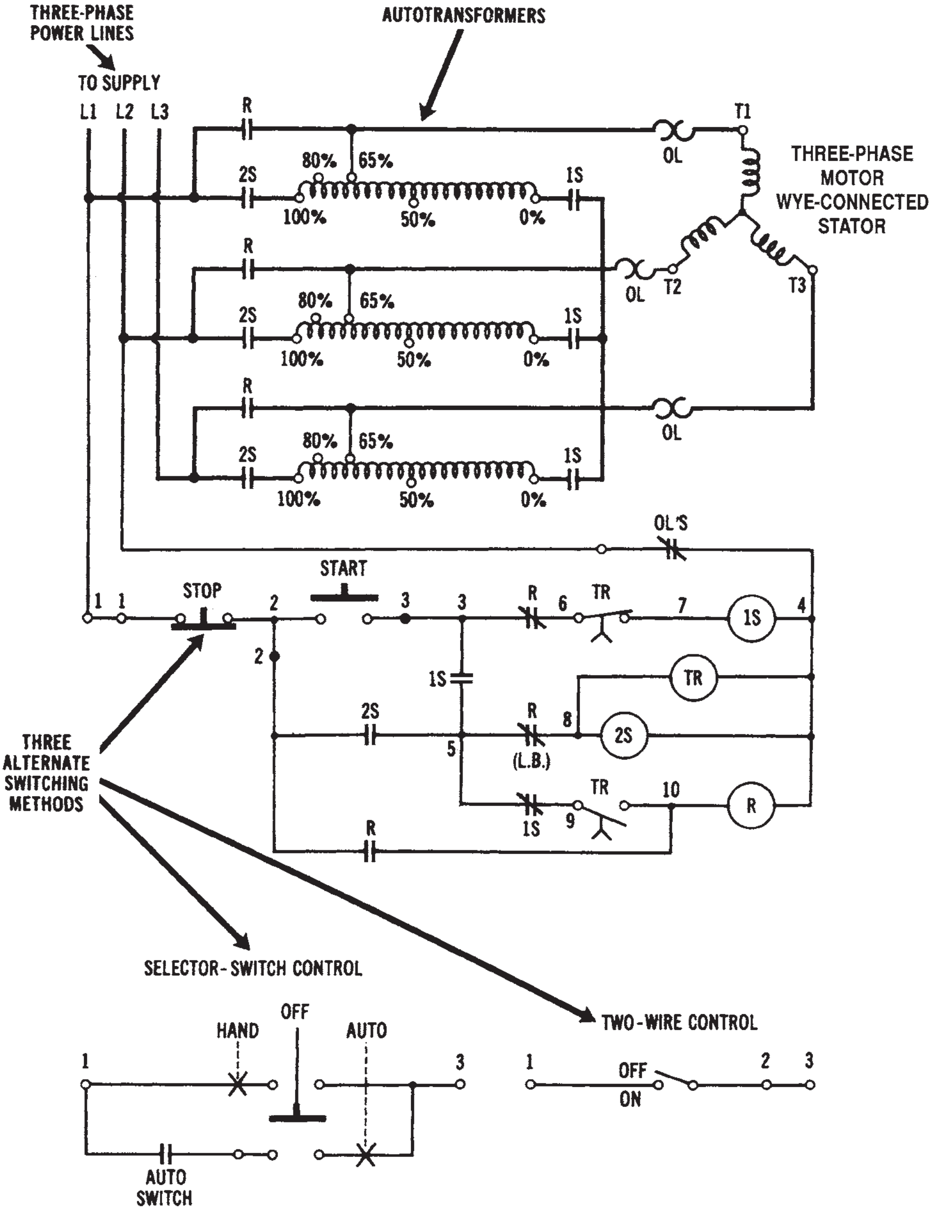

Figure 16-13. Autotransformer starter circuit used with a three-phase motor (*Courtesy Furnas Electric Co.*)

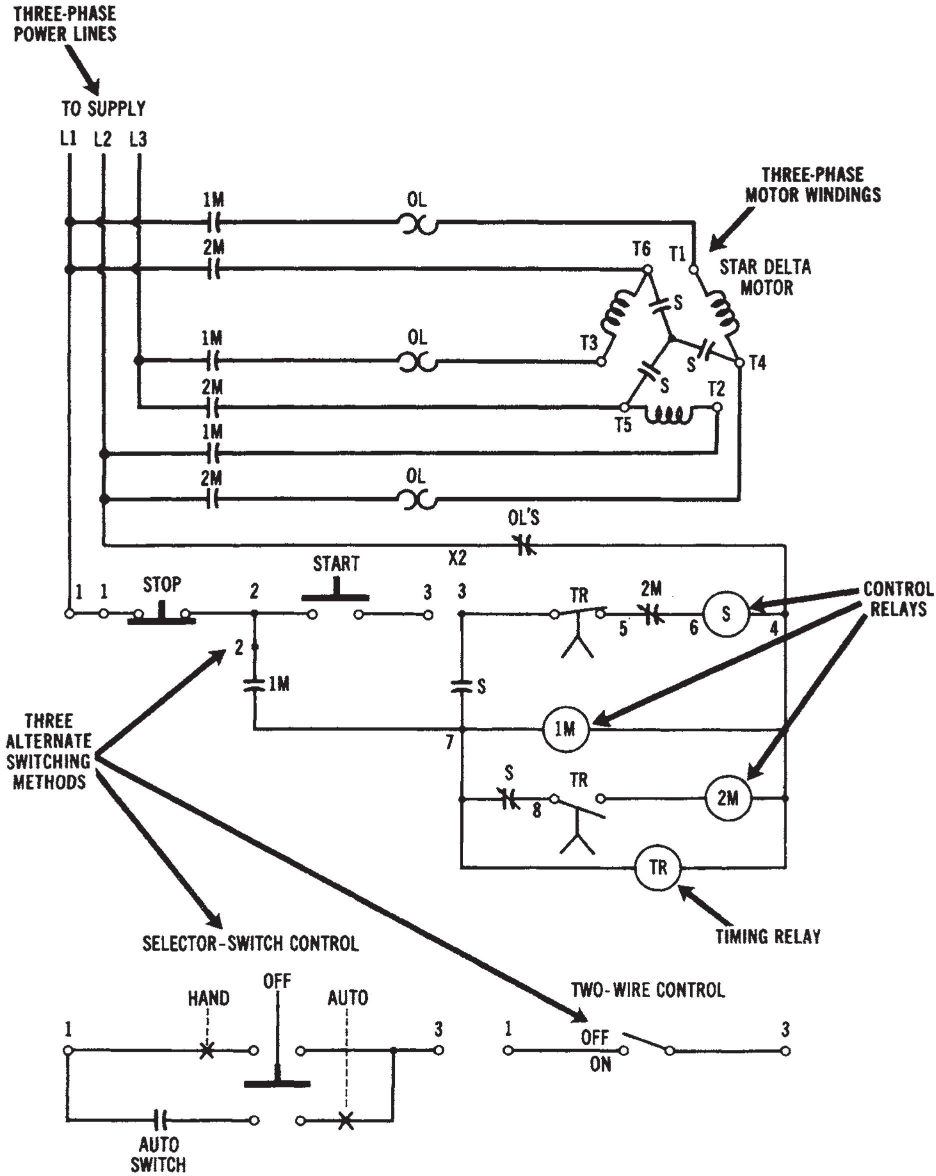

Figure 16-14. Wye-to-delta three-phase starter circuit (*Courtesy Furnas Electric Co.*)

Part-winding Starting—Figure 16-15 shows the *part-winding starting* method, which is usually simpler and less expensive than other starting methods. However, motors must be specifically designed to operate in this manner. During starting, the power-line voltage is applied across only

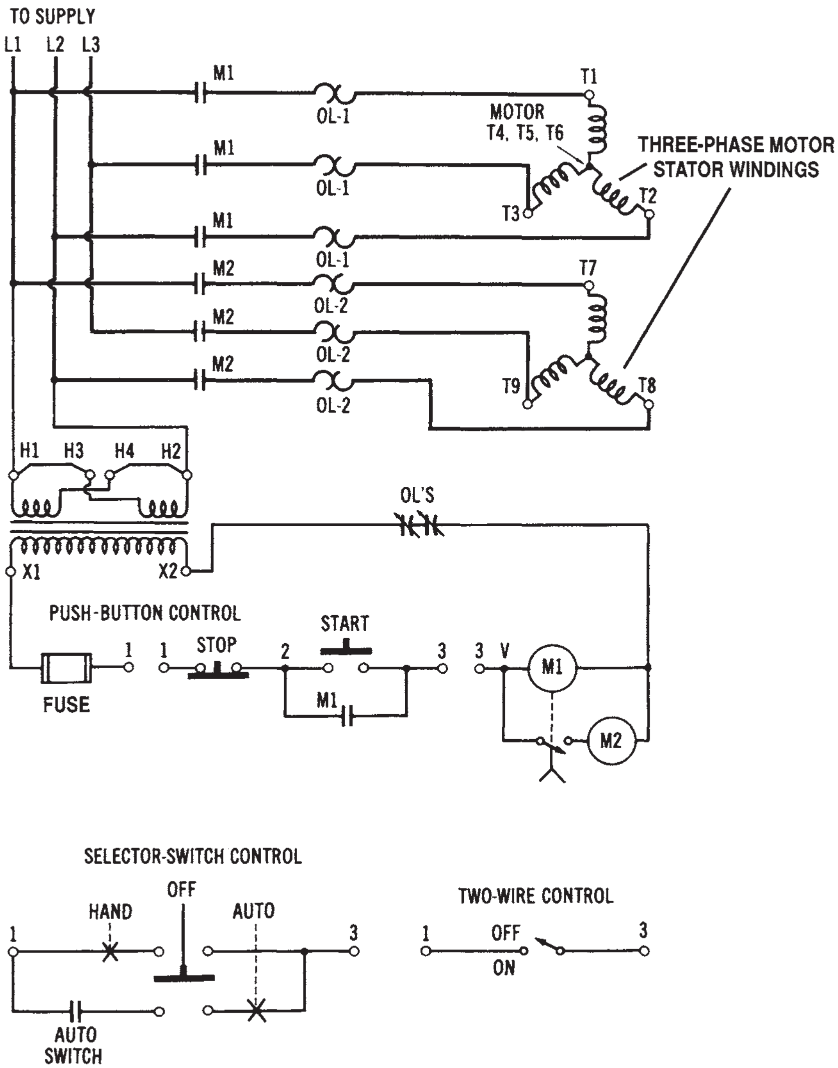

Figure 16-15. Part-winding circuit for three-phase motor starting (*Courtesy Furnas Electric Co.*)

part of the parallel-connected motor windings, thus reducing starting current. Once the motor has started, the line voltage is placed across all of the motor windings. This method is undesirable for many heavy-load applications, because of the reduction of starting torque.

In Figure 16-15, when the start pushbutton is pressed, current will flow through coil M1 of the time-delay relay. This will cause the NO contacts of M1 to close, and a three-phase voltage will be applied to windings T1, T2, and T3. After the time-delay period has elapsed, the NO contact located below coil M1 in Figure 16-15 will close. This action energizes coil M2 and causes its NO contacts to close. The M2 contacts then connect the T7, T8, and T9 windings in parallel with the T1, T2, and T3 windings. When the stop pushbutton is pressed, coils M1 and M2 will be de-energized.

Direct Current Starting Systems—Since DC motors have no counterelectromotive force (cemf) when they are not rotating (see Chapter 14), they have tremendously high starting currents. Therefore, they must use some type of control system to reduce the initial starting current. Ordinarily, a series resistance is used. This resistance can be manually or automatically reduced until a full voltage is applied. The four types of control systems commonly used with DC motors are (1) current limit, (2) definite time, (3) counter-emf, and (4) variable voltage. The *current-limit* method allows the starting current to be reduced to a specified level, and then advanced to the next resistance step. The *definite-time* method causes the motor to increase speed in timed intervals, with no regard to the amount of armature current or to the speed of the motor. The *counter-emf* method samples the amount of cemf generated by the armature of the motor to reduce the series resistance accordingly. This method can be used effectively, since cemf is proportional to both the speed and the armature current of a DC motor. The *variable-voltage* method employs a variable DC power source to apply a reduced voltage to the motor initially, and then to gradually increase the voltage. No series resistances are needed when the latter method is used.

SPECIALIZED CONTROL SYSTEMS

Electrical power control is usually desired for some specific application. In this section, we will discuss some common types of specialized, electrical power control systems that are used today.

Forward and Reverse Operation of Motors

Most types of electrical motors can be made to rotate in either forward or reverse direction by some simple modifications of their connections. Ordinarily, motors require two magnetic contactors to accomplish forward and reverse operation. These contactors are used in conjunction with a set of three pushbutton switches—FORWARD, REVERSE, and STOP. When the FORWARD pushbutton switch is depressed, the forward contactor will be energized. It is deactivated when the STOP pushbutton switch is depressed. A similar procedure takes place during reverse operation.

DC Motor Reversing

DC motors can have their direction of rotation reversed by changing either the armature connections, or the field connections to the power source. In Figure 16-16, a DC shunt-motor-control circuit is shown. When the forward pushbutton is pressed, the F coil will be energized, causing the F contacts to close. The armature circuit is then completed from L1 through the lower F contact, up through the armature, through the upper F contact, and back to L2. Pressing the stop pushbutton will de-energize the F coil.

The direction of rotation of the motor is reversed when the reverse pushbutton is pressed. This is due to the change of the current direction through the armature. Pressing the reverse pushbutton energizes the R coil and closes the R contacts. The armature current path is then from L1 through the lower R contact, down through the armature, through the upper R contact, and back to L2. Pressing the stop button will de-energize the R coil.

Single-phase Induction Motor Reversing

Single-phase AC induction motors that have start and run windings can have their direction of rotation reversed by the circuit in Figure 16-18. If we modify the diagram by replacing the shunt field coils with the run windings, and the armature with the start windings, directional reversal of a single-phase AC motor can be accomplished. Single-phase induction motors are reversed by changing the connections of either the start windings or the run windings, but not of both at the same time.

Three-phase Induction-Motor Reversing

Three-phase motors can have their direction of rotation reversed by simply changing the connections of any two power input lines. This

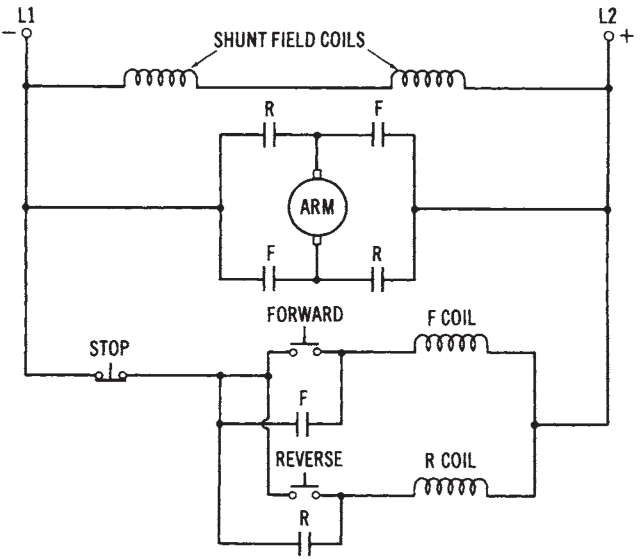

Figure 16-16. Control circuit for the forward and reverse operation of a DC shunt motor

changes the phase sequence applied to the motor. A control circuit for three-phase induction-motor reversing is shown in Figure 16-17.

When the forward pushbutton is pressed, the forward coil will energize and close the F contacts. The three-phase voltage is applied from L1 to T1, L2 to T2, and L3 to T3, to cause the motor to operate. The stop pushbutton de-energizes the forward coil. When the reverse pushbutton is pressed, the reverse coil is energized, and the R contacts will close. The voltage is then applied from L1 to T3, L2 to T2, and L3 to T1. This action reverses the L1 and L3 connections to the motor, and causes the motor to rotate in the reverse direction.

Starting Protection

Overload protection was discussed previously. Protection of expensive electric motors is necessary to extend the lifetime of these machines. The cost of overload protection is small compared to the cost of replacing large electric motors. Motors present unique problems for protection since their starting currents are much higher than their running currents during normal operation. Solid-state overload protection and microprocessor-based monitoring systems are now available to provide motor protection.

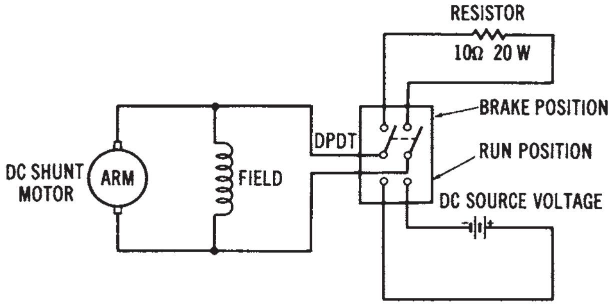

Figure 16-17. Control circuit for the forward and reverse operation of a three-phase AC induction motor

Dynamic Braking

When a motor is turned off, its shaft will continue to rotate for a short period of time. This continued rotation is undesirable for many applications. Dynamic braking is a method used to bring a motor to a quick stop whenever power is turned off. Motors with wound armatures utilize a resistance connected across the armature as a dynamic braking method. When power is turned off, the resistance is connected across the armature. This causes the armature to act as a loaded generator, making the motor slow down immediately. This dynamic braking method is shown in Figure 16-18.

AC induction motors can be slowed down rapidly by placing a DC voltage across the winding of the motor. This DC voltage sets up a constant magnetic field, which causes the rotor to slow down rapidly. A circuit for the dynamic braking of a single-phase AC induction motor is shown in Figure 16-19.

Universal Motor Speed Control

An important advantage of a universal AC/DC motor is the ease of speed control. The universal motor has a brush/commutator assembly, with the armature circuit connected in series with the field windings. By varying may be varied from zero to maximum.

The circuit used for this purpose, shown in Figure 16-20 uses a gate-controlled triac. The triac is a semiconductor device whose conduction may be varied by a trigger voltage applied to its gate. A silicon-controlled rectifier (SCR) could also be used as a speed-control device for a universal motor. Speed-control circuits like this one are used for many applications,

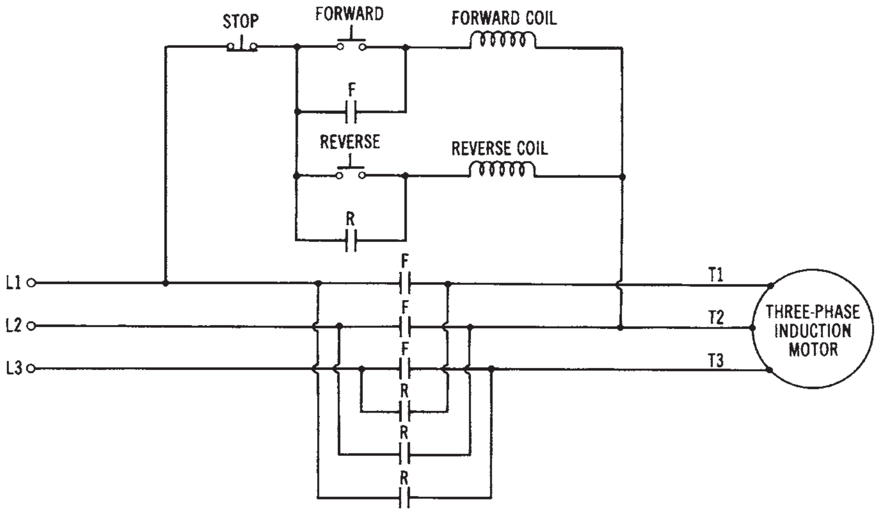

Figure 16-18. Dynamic braking circuit for a DC shunt motor

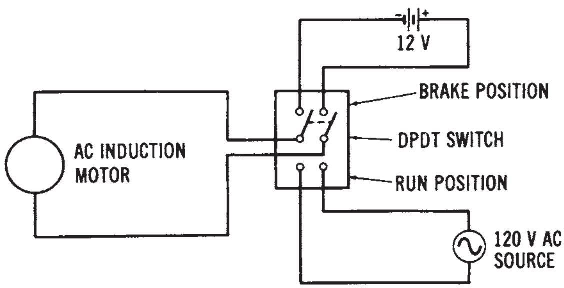

Figure 16-19. Dynamic braking circuit for a single-phase AC induction motor

such as electric drills, sewing machines, electric mixers, and industrial applications.

FREQUENCY-CONVERSION SYSTEMS

The power system frequency used in the United State is 60 hertz, or 60 cycles per second. However, there are specific applications that require other frequencies in order to operate properly. Mechanical frequency converters may be used to change an incoming frequency into some other fre-

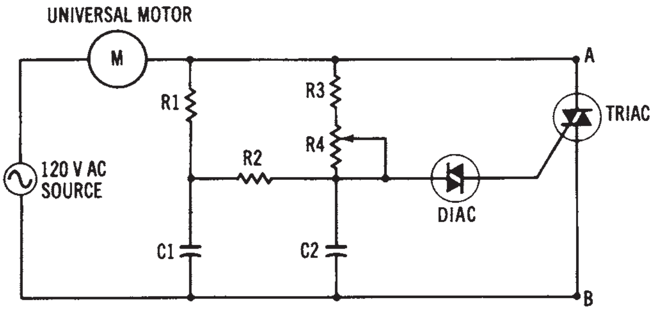

Figure 16-20. Speed control circuit for a universal motor

quency. Frequency converters are motor/generator sets that are connected together, or solid-state variable frequency drives.

For example, a frequency of 60 Hz could be applied to a synchronous motor that rotates at a specific speed. A generator connected to its shaft could have the necessary number of poles to cause it to produce a frequency of 25 Hz. Recall that frequency is determined by the following relationship:

$$\text{Freq. (Hz)} = \frac{\text{Speed of Rotation (rpm)} \times \text{No. of poles}}{120}$$

A frequency-conversion system is shown in Figure 16-21. Synchronous units, such as the one shown, are used wherever precise frequency control is required. It is also possible to design units that are driven by induction motors, if some frequency variation can be tolerated. Variable frequency drives are now being used to control many types of industrial machinery. They are used because they are not as expensive as variable speed controllers have been in the past. Solid-state variable frequency drives are used to control overhead cranes, hoists, and many other types of industrial equipment that operate from AC power lines. Variable speed can be accomplished less expensively, in most cases, with solid-state drives than with DC motors or electromechanical variable-frequency drives. Solid-state drives can be used with AC induction motors to change their speed by varying the input frequency to the motor. There are fewer maintenance problems with AC induction motors than with DC motors. In addition, fewer electromechanical parts are involved in the control operation; thus, equipment has a longer life expectancy.

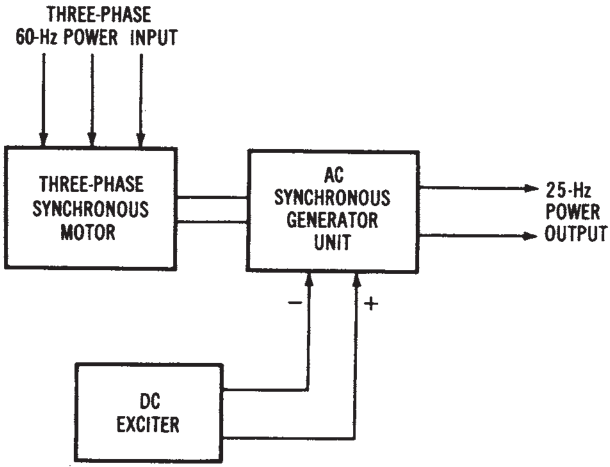

Figure 16-21. A 60 hertz to 25 hertz frequency conversion system

PROGRAMMABLE LOGIC CONTROLLERS (PLCS)

For a number of years, industrial control was achieved by electromechanical devices, such as relays, solenoid valves, motors, linear actuators, and timers. These devices were used to control large production machines where only switching operations were necessary. Most controllers were used simply to turn the load device on or off. In addition, some basic logic functions could also be achieved. Production line sequencing operations were achieved by motor-driven drum controllers with timers. As a rule, nearly all electromagnetic controllers were hardwired into the system, and responded as permanent fixtures. Modification of the system was rather difficult to accomplish and somewhat expensive. In industries where production changes were frequent, this type of control was rather costly. It was, however, the best way-and in many cases the only way-that control could be effectively achieved with any degree of success.

In the late 1960s, solid-state devices and digital electronics began to appear in controllers. These innovations were primarily aimed at replacing the older electromechanical control devices. The transition to solid-state electronics has, however, been much more significant than expected. The use of solid-state electronic devices, digital logic integrated circuits (ICs), and microprocessors has led to the development of programmable logic controllers (PLCs). These devices have capabilities that far exceed the older relay controllers. Programmable logic controllers are extremely flexible, have reduced downtime when making changeovers, occupy very little space, and have improved operational efficiency.

A programmable logic controller is very similar to a small computer. In fact, most programmable logic controllers are classified as dedicated computers. This type of unit is usually designed to perform a number of specific control functions in the operation of a machine or industrial process. The degree of sophistication or "power" of a programmable logic controller is dependent on its application. Many PLCs respond like a computer terminal and interface with a mainframe computer. Other units are completely independent and respond only to those things that are needed to control a specific machine's operation.

Programmable Logic Controller Components

A programmable logic controller is basically a software-based equivalent of the older electromagnetic relay control panel. Essentially, the PLC is a flexible system that can be easily modified and still be used as a general-purpose control device. Most PLCs can be programmed to control a variety of machine functions at one time. When a production change is necessitated, the program can be altered by a keyboard to make the system conform to the needed changes. The new control procedure may be entirely different from the original.

Mini-Programmable Logic Controller Systems

Recent improvements in large-scale IC and power transistor manufacturing technology are responsible for the development of mini-PLCs. These systems can be used economically to control simple machine operations and numerous manufacturing processes. A number of companies are now producing mini-PLCs.

Mini-PLCs are classified as systems that can economically replace as few as four relays in a control application. They are capable of providing timer and counter functions, as well as relay logic, and are small enough to fit into a standard rack assembly. Most systems of this type have fewer than 32 I/O ports or modules. Some units can be expanded to drive up to 400 I/O devices. Typically, the I/O of this type of system responds to digital signals. Some units are capable of responding to analog information. This makes it possible for the system to respond to temperature, pressure, flow, level, light, weight, and practically any analog control application.

Mini-PLCs, in general, can achieve the same control functions as the larger programmable controllers, only on a smaller basis. Mini-PLCs are usually smaller, less expensive, simpler to use, and rather efficient, compared with mainframe programmable controllers. Mini-units are now beginning to make their way into the PLC field. In the future, these systems will obviously playa greater role in the control of industrial systems.

PROGRAMMING THE PLC

Instructions for the operation of a programmable logic controller are given to the PLC through pushbuttons, a keyboard programmer, magnetic disks, or cassette tape. Each PLC has a special set of instructions and procedures that makes it functional. How the PLC performs is based on the design of its programming procedure. In general, PLCs can be programmed by relay ladder diagrams or logic diagrams. These procedures can be expressed as language words or as symbolic expressions on a CRT display. One manufacturer describes these methods of programming as *assembly language* and *relay language.* Assembly language is generally used by the microprocessor of the system. Relay language is a symbolic logic system that employs the relay ladder diagram as a method of programming. This method of programming relies heavily on relay symbols instead of words and letter designations.

Assembly Language

Assembly language is a basic instructional set that is specific to the type of the microprocessor used in the construction of the PLC. For one type of microprocessor, the assembly language program is a combination of mnemonics and labels that the programmer uses to solve a control problem. If the system is programmed directly with binary numbers, the programmer will probably use a lookup table to write the program in assembly language. It is usually easier to keep track of loops and variables in an assembly language. It is also easier for others to look at the program when they are trying to see how it works. Ultimately, the programmer must type the coded information into the computer in binary form. This generally means that an assembly language program needs to be translated into binary data before it can be entered. This can be done by laboriously writing down each mnemonic and label, line by line, and then entering the translation into memory. A convenient alternative to this procedure is to have a program that takes lines of assembly language as its input and does the translation for the programmer automatically. A program called "assembler" functionally performs this operation. It actually puts together the operational codes and the addresses that take the place of mnemonics and labels. When the procedure is complete, the assembler has a duplicate of the assembly language in the machine language of the microprocessor. These data can then be entered by the programmer manually, but they are generally applied directly to the input, since it is in memory when the translation is completed.

Relay Language or Logic

The processor of a programmable logic controller dictates the language and programming procedure to be followed by the system. Essentially, it is capable of doing arithmetic and logic functions. It can also store and handle data, and continuously monitor the status of its input and output signals. The resulting output being controlled is based on the response of the signal information being handled by the system. The processor is generally programmed by a keyboard panel program panel, or CRT terminal.

In a relay language system, the basic element of programming is the relay contact. This contact may be NO or NC. Typically, each contact has a four-digit reference number. This number is used to identify specific contacts being used in the system. The contact is then connected in either series or parallel to form a horizontal rung of a relay ladder diagram.

Once a relay program has been entered into the PLC, it may be monitored on the CRT and modified by a keystroke. Monitoring the operation of a program is achieved by illuminating the current path by making it brighter than the remainder of the circuit components. Modification of the diagram can be achieved by simply placing the cursor of the CRT on the device to be altered, and making the change with a keystroke. Cursor control is achieved by manipulation of the four arrow keys on the right of the keyboard. Contact status can be changed or bypassed, and different outputs can be turned on or off, by this procedure. Each input or output has a four-digit number that can be altered by the numerical data entry part of the keyboard.

All the control components of a PLC are identified by a numbering system. As a rule, each manufacturer has a unique set of component numbers for its system. One manufacturer has a four-digit numbering system for referencing components. The numbers are divided into discrete component references and register references. A discrete component is used to achieve on and off control operations. Limit switches, pushbuttons, relay contacts, motor starters, relay coils, solenoid valves, and solid-state devices are examples of discrete component references. Registers are used to store some form of numerical data or information. Timing counts, number counts, and arithmetic data may be stored in register devices. All component references and register references are identified by a numbering system. Each manufacturer has a particular way of identifying system components.

Programming Basics

Programmable logic controllers are provided with the capability to program or simulate the function of relays, timers, and counters. Programming is achieved on a format of up to 10 elements in each horizontal row or rung of a relay diagram, and up to seven of these rungs may be connected to form a network. A network can be as simple as a single rung, or can be a combination of several rungs, as long as there is some interconnection between the elements of each rung. The left rail of the ladder can be the common connecting element. Each network can have up to seven coils connected in any order to the right rail of the ladder. These coils can be assigned any valid number for identification. The coil number can only by used once in the operational sequence. The quantity of discrete devices and registers available for use depends on the power or capacity of the system.

When programming a relay ladder diagram into a PLC, the discrete devices and registers are placed in component format. Each component in this case is assigned a four-digit identification number. The specific reference number depends on the memory size of the system. In a low-capacity system, number assignments could be 0001 to 0064 for output coils, and 0258 to 0320 for internal coils. A system with a larger capacity might use number assignments of 0001 to 0256 for output coils, and 0258 to 0512 for internal coils. Any coil output or internal coil can only be used once in the system. References to contacts controlled by a specific coil can be used as many times as needed to complete the control operation. Output coils that are not used to drive a specific load can be used internally in the programming procedure.

When the response of a particular input module is programmed, it may be identified as a relay contact. In this regard, the symbol may be a NC contact or a NO contact. The coil or actuating member of the contact takes on the same numbering assignment as the coil. The coil, however, is identified as a circle on the diagram, and the contacts are identified by the standard contact symbol. The contacts can be programmed to achieve either the NO or NC condition, according to their intended functions.

Chapter 17

Control Devices

One of the most efficient methods of electrical power control that is circuit switching. When a switch is turned on, power is consumed by the load device. When a switch in any circuit is turned off, no power is consumed. This switching method of power control is shown in Figure 17-1 using a lamp as the load device. Since the switch is low resistant, it consumes little power. When the switch is open, it consumes no power. By switching the circuit on and off rapidly, the average current flow can be reduced. The brightness of the lamp will also be reduced. In effect, lamp brightness is controlled by the switching speed. Power in this method of control is not consumed by the control device. This type of power control is both efficient and effective.

The switching method of electrical power control cannot be achieved effectively with a manual switch. The mechanical action of the switch will not permit it to be turned on and off quickly. A switch would soon wear out if used in this manner. Electronic switching can be used to achieve the same result. Switching action of this type can be accomplished in a circuit without a noticeable flicker of a lamp. Electronic control devices such as silicon controlled rectifiers and triacs are used with the switching method for controlling power. The operation of these devices is described in this chapter.

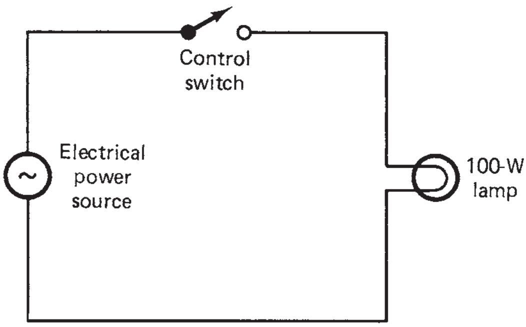

Figure 17-1. Switch-controlled lamp circuit.

IMPORTANT TERMS

Chapter 17 describes control devices that are commonly used in electrical power control systems. After studying this chapter, you should have an understanding of the following terms:

Silicon Controlled Rectifier (SCR)
Circuit Switching
I – V Characteristics
DC Power Control
AC Power Control
Triac
Static Switching
Start-Stop Control
Diac

SILICON-CONTROLLED RECTIFIERS

A silicon-controlled rectifier or SCR is probably the most popular electronic power control device today. The SCR is used primarily as a switching device. Power control is achieved by switching the SCR on and off during one alter-nation of the ac source voltage. For 60 Hz ac the SCR would be switched on and off 60 times per second. Control of electrical power is achieved by altering or delaying the turn-on time of an alternation.

An SCR, as the name implies, is a solid-state rectifier device. It conducts current in only one direction. It is similar in size to a comparable silicon power diode. SCRs are usually small, rather inexpensive, waste little power, and require practically no maintenance. The SCR is available today in a full range of types and sizes to meet nearly any power control application. Presently, they are available in current ratings from less than 1 A to over 1400 A. Voltage values range from 15 to 2600 V.

SCR Construction

An SCR is a solid-state device made of four alternate layers of *P*- and *N*-type silicon. Three *P-N* junctions are formed by the structure. Each SCR has three leads or terminals. The anode and cathode terminals are similar to those of a regular silicon diode. The third lead is called the *gate.* This lead determines when the device switches from its off to on state. An SCR will usually not go into conduction by simply for-ward biasing the anode and cathode. The gate must be forward biased at the same time. When these conditions occur, the SCR becomes conductive. The internal resistance of a conductive SCR is less than 1 Ω. Its reverse or off-state resistance is generally in excess of 1 MΩ. This allows the device to be similar to a mechanical switch.

A schematic symbol and the crystal structure of an SCR are shown in Figure 17-2. Note that the device has a *PNPN* structure from anode to cathode. Three distinct *P-N* junctions are formed. When the anode is made positive and the cathode negative, junctions 1 and 3 are forward biased. J_2 is reverse biased. Reversing the polarity of the source alters this condition. J_1 and J_3 would be reverse biased and J_2 would be forward biased and would not permit conduction. Conduction will occur only when the anode, cathode, and gate are all forward biased at the same time.

Some representative SCRs are shown in Figure 17-3. A few of the more popular packages are shown here. As a general rule, the anode is connected to the largest electrode if there is a difference in their physical size. The gate is usually smaller than the other electrodes. Only a small gate current is needed to achieve control. In some packages, the SCR symbol is used for lead identification.

To turn off a conductive SCR, it is necessary to momentarily remove or reduce the anode-cathode voltage. The device will then remain in this state until the anode, cathode, and gate are forward biased again. With

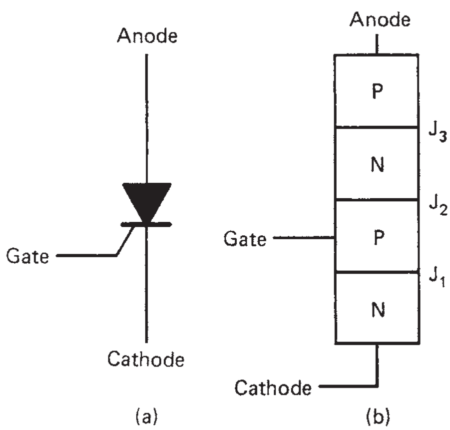

Figure 17-2. SCR crystal: (a) symbol; (b) structure

ac applied to an SCR, it will automatically turn off during one alternation of the input. Control is achieved by altering the turn-on time during the conductive or "on" alternation.

SCR *I-V* Characteristics

The current-voltage characteristics of an SCR tell much about its operation. The *I-V* characteristic curve of Figure 17-4 shows that an SCR has two conduction states. Quadrant I shows conduction in the forward direction, which shows how conduction occurs when the forward breakover voltage (V_{BO}) is exceeded. Note that the curve returns to approximately zero after the V_{BO} has been exceeded. When conduction occurs, the internal resistance of the SCR drops to a minute value similar to that of a forward-biased silicon diode. The conduction current (I_{AK}) must be limited by an external resistor. This current, however, must be great enough to maintain conduction when it starts. The holding current or I_H level must

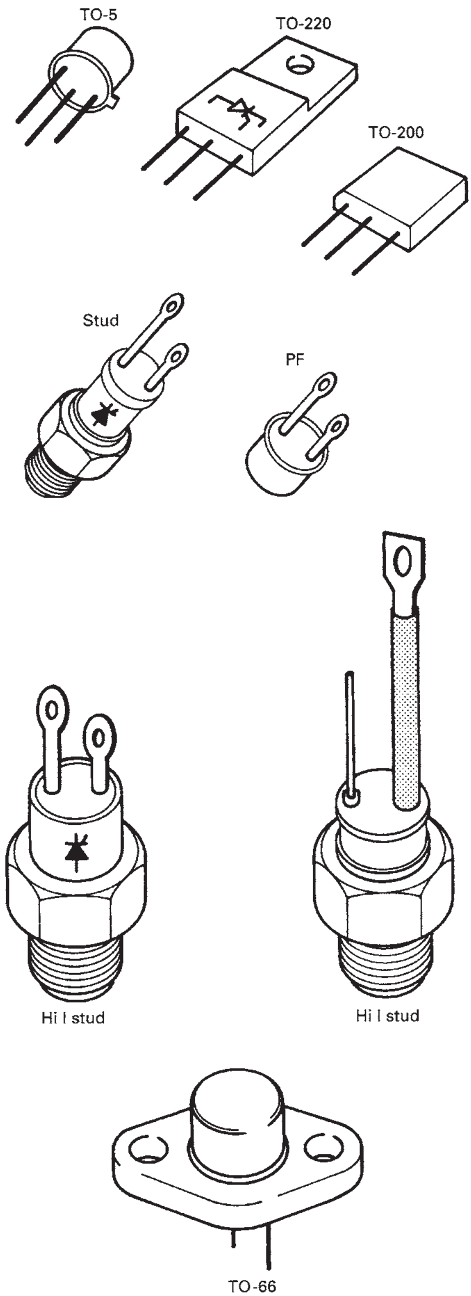

Figure 17-3. Representative SCR packages

be exceeded for this to take place. Note that the I_H level is just above the knee of the I_{AK} curve after it returns to the center.

Quadrant III of the *I-V* characteristic curve shows the reverse breakdown condition of operation. This characteristic of an SCR is similar to that of a silicon diode. Conduction occurs when the peak reverse voltage (PRV) value is reached. Normally, an SCR would be permanently damaged if the PRV is exceeded. Today, SCRs have PRV ratings of 25 to 2000 V.

For an SCR to be used as a power control device, the forward V_{BO} must be altered. Changes in gate current will cause a decrease in the V_{BO}. This occurs when the gate is for-ward biased. An increase in I_G will cause a large reduction in the forward V_{BO}. An enlargement of quadrant I of the *I-V* characteristics is shown in Figure 8-9, which also shows how different values of I_G change the V_{BO}. With 0 I_G it takes a V_{BO} *o* of 400 V to produce conduction. An increase in I_G reduces this quite significantly. With 7 mA of I_G the SCR conducts as a forward-biased silicon diode. Lesser values of

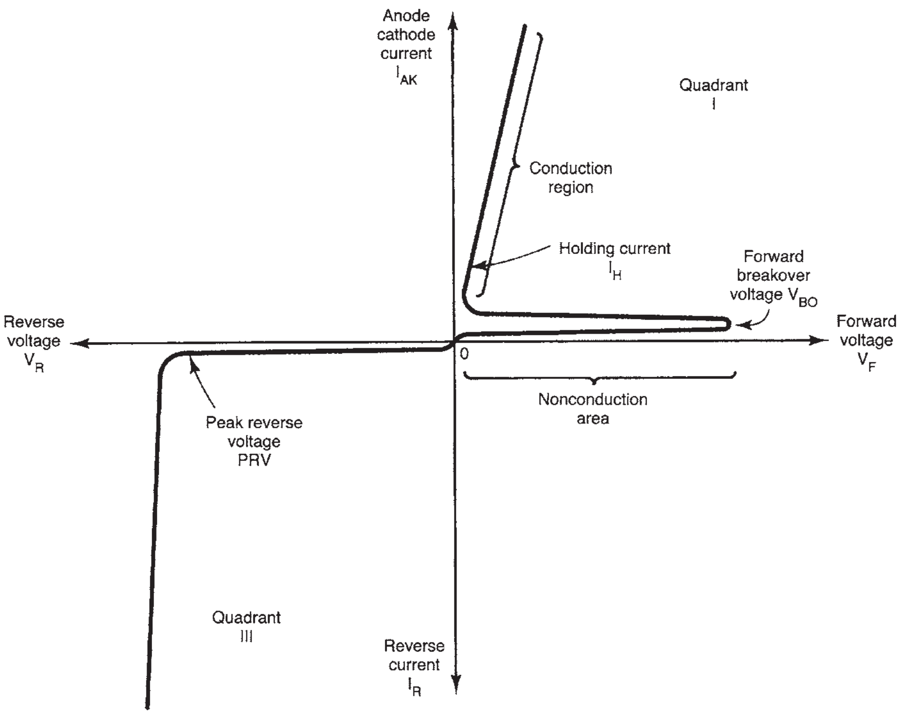

Figure 17-4. *I-V* characteristics of an SCR

I_G will cause an increase in the V_{BO} needed to produce conduction.

The gate current characteristic of an SCR shows an important electrical operating condition. For any value of I_G there is a specific V_{BO} that must be reached before conduction can occur, which means that an SCR can be turned on when a proper combination of I_G and V_{BO} is achieved. This characteristic is used to control conduction when the SCR is used as a power control device.

DC Power Control with SCRs

When an SCR is used as a power control device, it responds primarily as a switch. When the applied source voltage is be-low the forward breakdown voltage, control is achieved by increasing the gate current. Gate current is usually made large enough to ensure that the SCR will turn on at the proper time. Gate current is generally applied for only a short time. In many applications this may be in the form of a short-duration pulse. Continuous I_G is not needed to trigger an SCR into conduction. After conduction occurs, the SCR will not turn off until the I_{AK} drops to zero.

Figure 17-5 shows an SCR used as a dc power control switch. In this type of circuit, a rather high load current is controlled by a small gate current. Note that the electrical power source (V_S) is controlled by the SCR. The polarity of V_S must forward bias the SCR, which is achieved by mak-

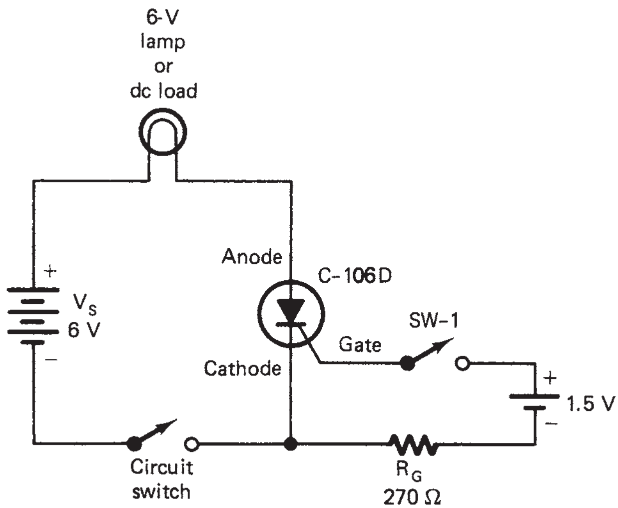

Figure 17-5. Dc power control switch

ing the anode positive and the cathode negative.

When the circuit switch is turned on initially, the load is not energized. In this situation the $V_{B}o$ is in excess of the V_S voltage. Power control is achieved by turning on SW-1 which forward biases the gate. If a suitable value of I_G occurs, it will lower the V_{BO} and turn on the SCR. The I_G can be removed and the SCR will remain in conduction. To turn the circuit off, momentarily open the circuit switch. With the circuit switch on again, the SCR will remain in the off state. It will go into conduction again by closing SW-1.

Dc power control applications of the SCR require two switches to achieve control, but this application of the SCR is not practical. The circuit switch would need to be capable of handling the load current. The gate switch could be rated at an extremely small value. If several switches were needed to control the load from different locations, this circuit would be more practical. More practical dc power circuits can be achieved by adding a number of additional components. Figure 17-6 shows a dc power control circuit with one SCR being controlled by a second SCR. SCR_1 would control the dc load current. SCR_2 controls the conduction of SCR_1. In this circuit, switching of a high-current load is achieved with two small, low-current switches. SCR_1 would be rated to handle the load current. SCR_2 could have a rather small current-handling capacity. Control of this type could probably be achieved for less than a circuit employing a large electrical contactor switch.

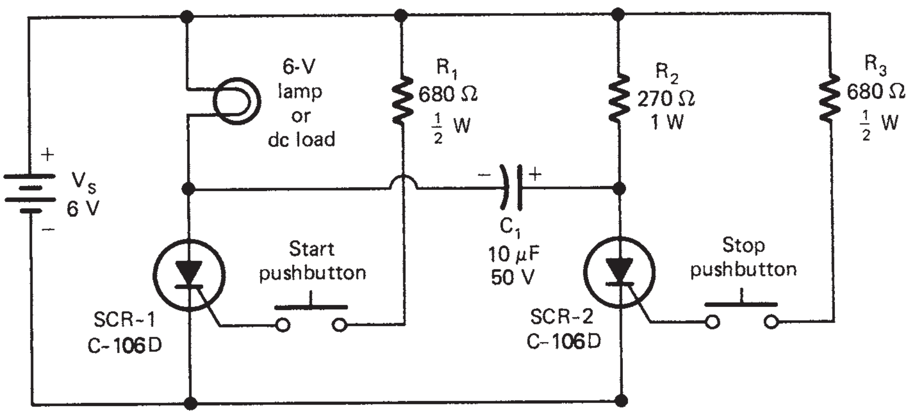

Figure 17-6. Dc power control circuit

Operation of the dc control circuit of Figure 17-6 is based on the conduction of SCR_1 and SCR_2. To turn on the load, the "start" pushbutton is momentarily closed, and thus forward biases the gate of SCR_1. The V_{BO} is reduced and SCR1 goes into conduction. The load current latches SCR_1 in its conduction state. This action also causes C_1 to charge to the indicated polarity. The load will remain energized as long as power is supplied to the circuit.

Turn-off of SCR_1 is achieved by pushing the stop button, which momentarily applies I_G to SCR_2 and causes it to be conductive. The charge on C_1 is momentarily applied to the anode and cathode of SCR_1, which reduces the I_{AK} of SCR_1 and causes it to turn off. The circuit will remain in the off state until it is energized by the start button. An SCR power circuit of this type can be controlled with two small pushbuttons. As a rule, control of this type would be more reliable and less expensive than a dc electrical contactor circuit.

Ac Power Control with SCRs

Ac electrical power control applications of an SCR are common. As a general rule, control is easy to achieve. The SCR automatically turns off during one alternation of the ac input and thus eliminates the turn-off problem with the dc circuit. The load of an ac circuit will see current only for one alternation of the input cycle. In effect, an SCR power control circuit has half-wave output. The conduction time of an alternation can be varied with an SCR circuit. We can have variable output through this method of control.

A simple SCR power control switch is shown in Figure 17-7. Connected in this manner, conduction of ac will only occur when the anode is positive and the cathode negative. Conduction will not occur until SW-1 is closed. When this takes place, there is gate current. The value of I_G lowers the V_{BO} to where the SCR becomes conductive. R_G of the gate circuit limits the peak value of I_G. Diode *(D_1)* prevents reverse voltage from being applied between the gate and cathode of the SCR. With SW-1 closed, the gate will be forward biased for only one alternation, which is the same alternation that forward biases the anode and cathode. With a suitable value of I_G and correct anode-cathode voltage *(V_{AK})*, the SCR will become conductive.

The ac power control switch of Figure 17-7 is designed primarily to take the place of a mechanical switch. With a circuit of this type, it is possible to control a rather large amount of electrical power with a rather small switch. Control of this type is reliable. The switch does not have contacts

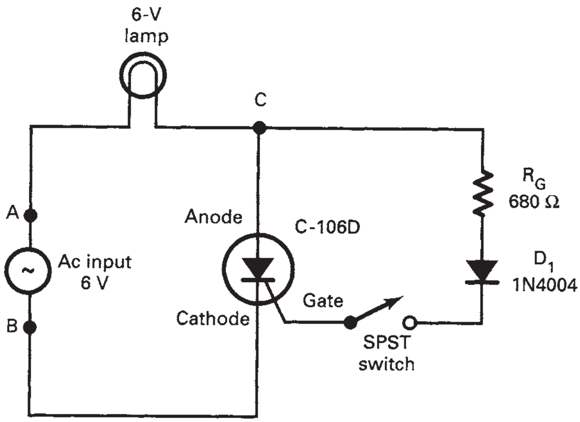

Figure 17-7. SCR power control switch

that spark and arc when changes in load current occur. Control of this type, however, is only an on-off function. SCRs are widely used to control the amount of electrical power supplied to a load device. Circuits of this type respond well to 60 Hz ac.

TRIAC POWER CONTROL

Ac power control can be achieved with a device that switches on and off during each alternation. Control of this type is accomplished with a special solid-state device known as a *triac.* This device is described as a three-terminal ac switch. Gate current is used to control the conduction time of either alternation of the ac waveform. In a sense, the triac is the equivalent of two reverse-connected SCRs feeding a common load device.

A triac is classified as a gate-controlled ac switch. For the positive alternation it responds as *a PNPN* device. An alternate crystal structure of the *NPNP* type is used for the negative alternation. Each crystal structure is triggered into conduction by the same gate connection. The gate has a dual-polarity triggering capability.

Triac Construction

A triac is a solid-state device made of two different four-layer crystal structures connected between two terminals. We do not generally use the terms *anode* and *cathode* to describe these terminals. For one alternation they would be the anode and cathode. For the other alternation they would respond as the cathode and anode. It is common practice therefore to use the terms *main 1* and *main 2* or *terminal 1* and *terminal 2* to describe these leads. The third connection is the gate. This lead determines when the device switches from its off to its on state. The gate *G* will normally go into conduction when it is forward biased, and is usually based on the polarity of terminal 1. If T_1 is negative, G must be positive. When T_1 is positive, the gate must be negative. This means that ac volt-age must be applied to the gate to cause conduction during each alternation of the T_1-T_2 voltage. The schematic symbol and the crystal structure of a triac are shown in Figure 17-8. Notice the junction of the crystal structure simplification. Looking from T_1 to T_2, the structure involves crystals N_1, P_1, N_2, and P_2. The gate is used to bias P_1. This is primarily the same as an SCR with T_1 serving as the cathode and T_2 the anode.

Looking at the crystal structure from T_2 to T_1, it is N_3, P_2, N_2, and P_1. The gate is used to bias N_4 for control in this direction, which is similar to the structure of an SCR in this direction. Notice that T_1, T_2, and G

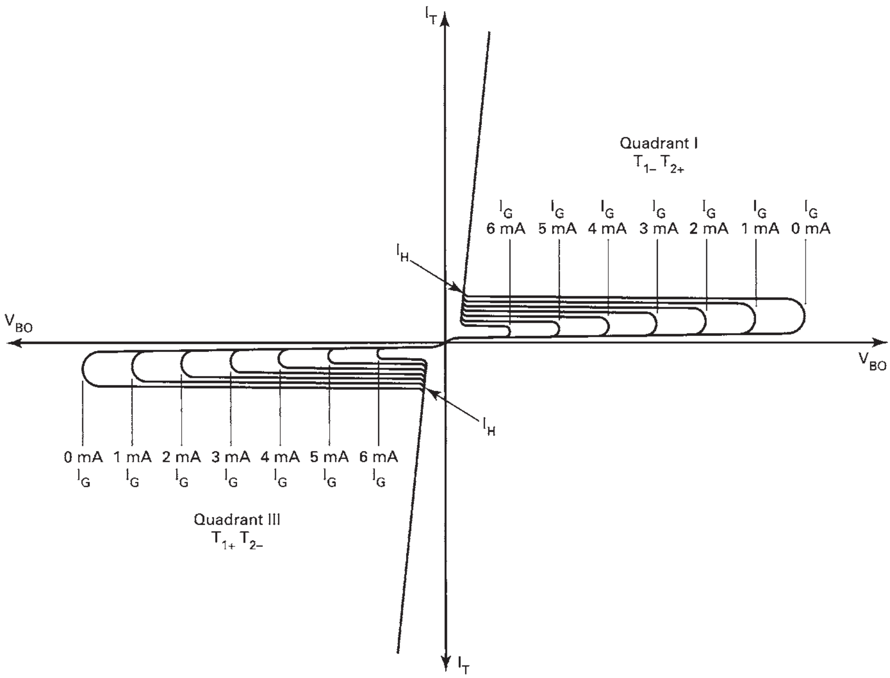

Figure 17-8. *I-V* characteristics of a triac

are all connected to two pieces of crystal. Conduction will take place only through the crystal polarity that is forward biased. When T_1 is negative, for example, N_1 is forward biased and P_1 is reverse biased. Terminal selection by bias polarity is the same for all three terminals.

The schematic symbol of the triac is representative of reverse-connected diodes. The gate is connected to the same end as T_1, which is an important consideration when connecting the triac into a circuit. The gate is normally forward biased with respect to T_1.

When ac is applied to a triac, conduction can occur for each alternation, but T_1 and T_2 must be properly biased with respect to the gate. Forward conduction occurs when T_1 is negative, the gate (*G*) is positive, and T_2 is positive. Reverse conduction occurs when T_1 is positive, *G* is negative, and T_2 is negative. Conduction in either direction is similar to that of the SCR.

Triac *I-V* Characteristics

The *I-V* characteristic of a triac shows how it responds to forward and reverse voltages. Figure 17-8 is a typical triac *I-V* characteristic. Note that conduction occurs in quadrants I and III. The conduction in each quadrant is primarily the same. With 0 IG, the breakover voltage is usually quite high. When breakover occurs, the curve quickly returns to the center. This shows a drop in the internal resistance of the device when conduction occurs. Conduction current must be limited by an external resistor. The holding current or I_H of a triac occurs just above the knee of the I_T curve. I_H must be attained or the device will not latch during a specific alternation.

Quadrant III is normally the same as quadrant I and thus ensures that operation will be the same for each alter-nation. Because the triac is conductive during quadrant III, it does not have a peak reverse voltage rating. It does, however, have a maximum reverse conduction current value the same as the maximum forward conduction value. The conduction characteristics of quadrant III are mirror images of quadrant I.

Triac Applications

Triacs are used primarily to achieve ac power control. In this application the triac responds primarily as a switch. Through normal switching action, it is possible to control the ac energy source for a portion of each alternation. If conduction occurs for both alternations of a complete sine wave, 100% of the power is delivered to the load device. Conduction for half of each alternation permits 50% control. If conduction is for one-fourth of each alternation, the load receives less than 25% of its normal power. It is possible through this device to control conduction for the entire sine wave, which means that a triac is capable of controlling from 0% to 100% of the electrical power supplied to a load device. Control of this type is efficient as practically no power is consumed by the triac while performing its control function.

Static Switching. The use of a triac as a static switch is primarily an on-off function. Control of this type has a number of advantages over mechanical load switching. A high-current energy source can be controlled with a very small switch. No contact bounce occurs with solid-state switching which generally reduces arcing and switch contact destruction. Control of this type is rather easy to achieve. Only a small number of parts are needed for a triac switch.

Two rather simple triac switching applications are shown in Figure 17-9. The circuit in Figure 17-9(a) shows the load being controlled by an SPST switch. When the switch is closed, ac is applied to the gate. Resistor R_1 limits the gate current to a reasonable operating value. With ac applied to the gate, conduction occurs for the entire sine wave. The gate of this circuit requires only a few milliamperes of current to turn on the triac. Practically any small switch could be used to control a rather large load current.

The circuit of Figure 17-9(b) is considered to be a three-position switch. In position 1, the gate is open and the power is off. In position 2, gate current flows for only one alternation. The load receives power during one alternation, which is the half-power operating position. In position 3, gate cur-rent flows for both alternations. The load receives full ac power in this position.

Start-stop Triac Control

Some electrical power circuits are controlled by two push-buttons or start-stop switches. Control of this type begins by momentarily pushing the start button. Operation then continues after releasing the depressed button. To turn off the circuit, a stop button is momentarily pushed. The circuit then resets itself in preparation for the next starting operation. Control of this type is widely used in motor control applications and for lighting circuits. A triac can be adapted for this type of power control.

A start-stop triac control circuit is shown in Figure 17-10. When electrical power is first applied to this circuit, the triac is in its nonconductive

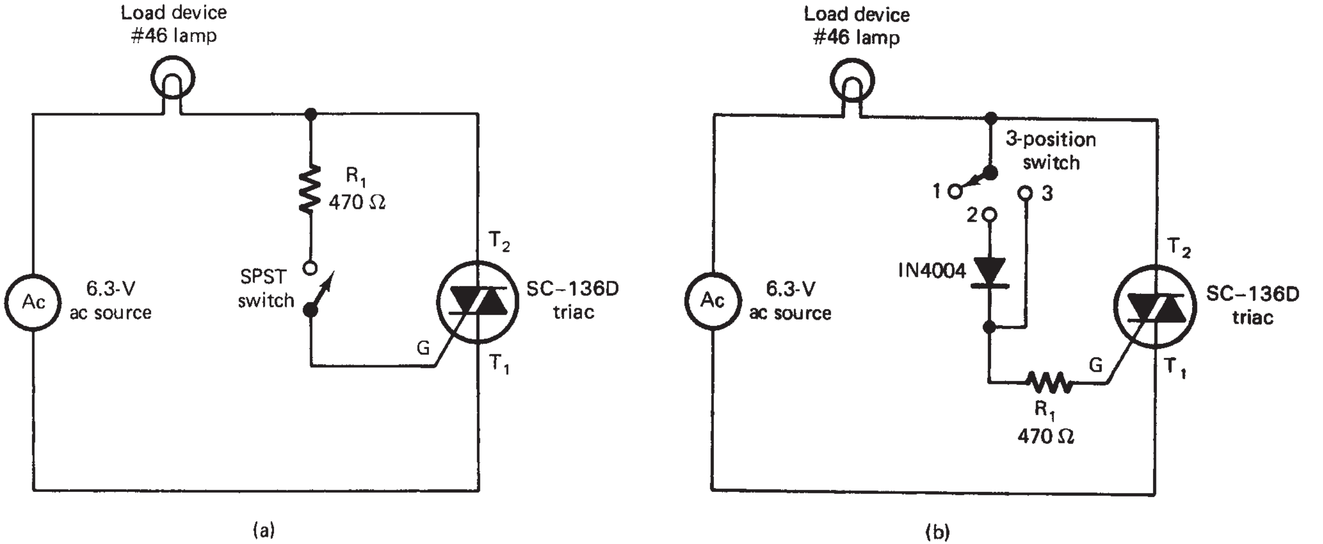

Figure 17-9. Triac switching circuits: (a) static triac switch; (b) three-position static switch

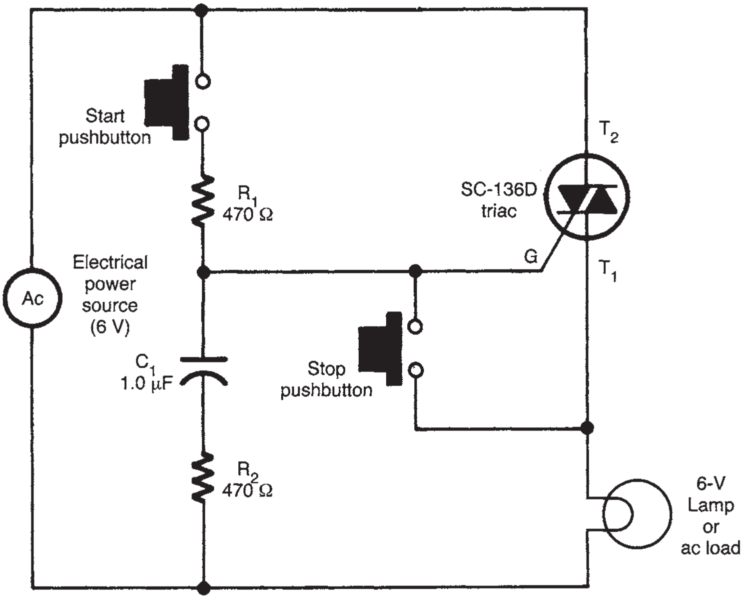

Figure 17-10. Start-stop control

state. The load does not receive any power for operation. All the supply voltage appears across the triac because of its high resistance. No voltage appears across the *RC* circuit, the gate, or the load device initially.

To energize the load device, the start pushbutton is momentarily pressed. C_1 charges immediately through R_1 and R_2, which in turn causes I_G to flow into the gate. The V_{BO} of the triac is lowered and it goes into conduction. Voltage now appears across the load, R_2-C_1, and the gate. The charging current of *R2*-C_1 and the gate continue and are at peak value when the source voltage alternation changes. The gate then retriggers the triac for the next alternation. C_1 is recharged through the gate and R_2. The next alternation change causes I_G to again flow for retriggering of the triac. The load receives full power from the source. The process will continue into conduction as long as power is supplied by the source. To turn off the circuit, the stop button is momentarily depressed. This action immediately bypasses the gate current around the triac. With no gate current, the triac will not latch during the alternation change. As a result, *C*1 cannot be recharged. The triac will then remain off for each succeeding alternation change. Conduction can be restored only by pressing the start button. This circuit is a triac equivalent of the ac motor electrical contactor.

Triac Variable Power Control

The triac is widely used as a variable ac power control device. Control of this type is generally called *full-wave control*. Full wave refers to the fact that both alternations of a sine wave are being controlled. Variable control of this type is achieved by delaying the start of each alternation. This process is similar to that of the SCR. The primary difference is that triac conduction applies to the entire sine wave. For this to be accomplished, ac must be applied to both the gate and the conduction terminals.

Variable ac power control can be achieved rather easily when the source is low voltage. Figure 17-11 shows a simple low-voltage variable lamp control circuit. Note that the gate current of this circuit is controlled by a potentiometer. Connected in this manner, adjustment of R_1 determines the value of gate current for each alternation.

Conduction of a triac is controlled by the polarity of T_I and T_2 with respect to the gate voltage. For the positive alternation, assume that point A is positive and B is negative, thus causing a $+T_2$, a $-T_1$, and a $+I_G$.. The value of the circuit gate current is determined by the resistance of R_1 and R_2. For a high-resistance setting of R_1, the triac may not go into conduction at all. For a smaller resistance value, conduction can be delayed in varying amounts. Generally, conduction delay will occur only during the first 90°

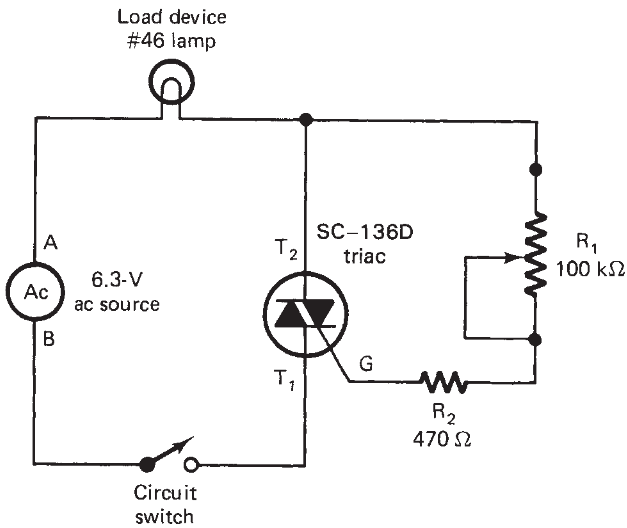

Figure 17-11. Variable lamp control

of the alternation. If conduction does not occur by this time, it will be off for the last 90° of the alternation.

Variable control of the same type also occurs during the negative alternation. For this alternation, point A is negative and point B is positive, thus causing a $-T_2$, a $+T_1$, and a $-I_G$. Gate current will flow and cause conduction during this alternation. The resistance setting of R_1 influences I_G in the same manner as it did for the positive alternation. Both alternations will therefore be controlled equally. Variable control of this type applies to only 50% of the source volt-age. If conduction does not occur in the first 90% of an alternation, no control will be achieved.

DIAC POWER CONTROL

A diac is a special diode that can be triggered into conduction by voltage. This device is classified as a bidirectional trigger diode, meaning that it can be triggered into conduction in either direction. The word *diac* is derived from "*di*ode for *ac*." This device is used primarily to control the gate current of a triac. It will go into conduction during either the positive or the negative alternation. Conduction is achieved by simply exceeding the breakover voltage.

Figure 17-12 shows the crystal structure, schematic symbol, and *I-V* characteristics of a diac. Note that the crystal is similar to that of a transistor without a base. The *N*1 and N_2 crystals are primarily the same in all respects. A diac will therefore go into conduction at precisely the same negative or positive voltage value. Conduction occurs only when in-put voltage exceeds the breakover voltage. A rather limited number of diacs are available today. The one shown here has a minimum V_{BO} of 28 V. This particular device is a standard trigger for triac control. Note that the voltage across the diac decreases in value after it has been triggered.

ELECTRONIC CONTROL CONSIDERATIONS

Electronic power control with an SCR or a triac is efficient when used properly. These devices are, however, attached directly to the ac power line. Severe damage to a load device and a potential electrical hazard may occur if this method of control is connected improperly. As a general rule, SCR and triac control should not be attempted for ac-only equipment such as fluorescent lamps, TV receivers, induction motors, and other transformer-operated devices.

SCR and triac control can be used effectively to control resistive loads such as incandescent lamps, soldering irons or pencils, heating devices and electric blankets. It is also safe to use this type of control for universal motors. This type of motor is commonly used in portable power tools and some small appliances such as portable drills, saws, sanders, electric knives, and mixers. When in doubt about a particular device, check the manufacturer's instruction manual. It is also important that the wattage rating of the load not exceed the wattage of the control device. Wattage ratings are nearly always marked on the device.

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