7th Edition

Industrial Motor Control

Stephen L. Herman

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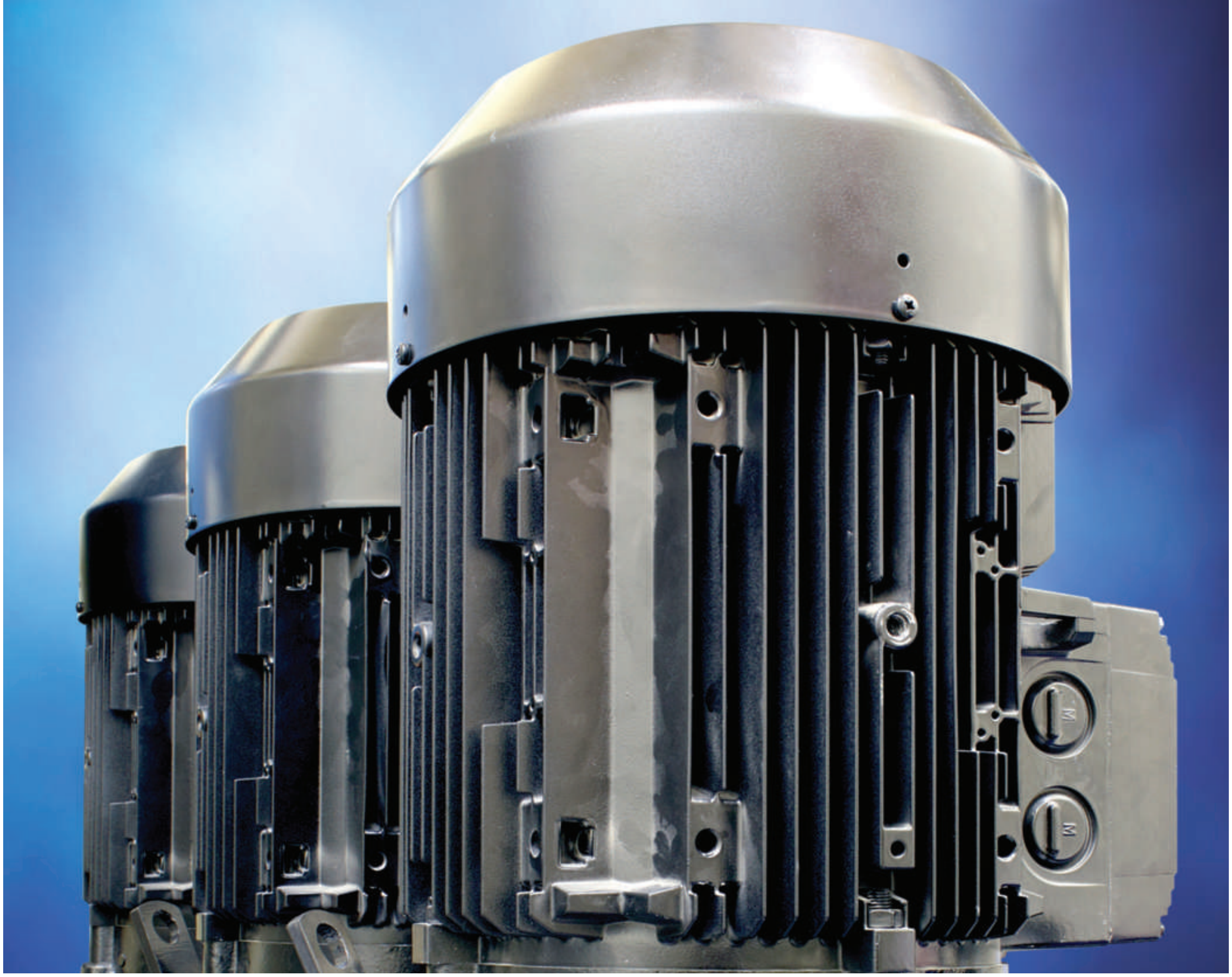

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Stephen L. Herman

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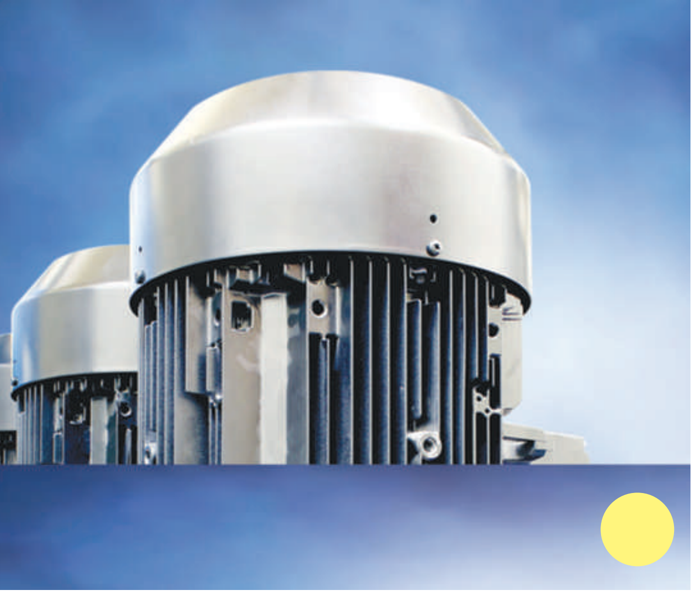

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Preface

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

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

The seventh edition of *Industrial Motor Control* is the most comprehensive revision since the text was first published over 20 years ago. The chapter on motor installation has been updated to reflect changes in the 2011 *National Electrical Code*®, and a unit that instructs students in basic troubleshooting techniques has been included. The chapters have been rearranged to present the information in a different order. This rearrangement was done to reflect recommendations made by instructors that use the text.

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

Industrial Motor Control is based on the results of extensive research into content, organization, and effective learning styles. Short chapters help the student to completely understand the content before progressing to the next subject, and they permit the instructor to choose the order of presentation. Each chapter contains extensive illustrations, which have been designed for maximum learning. Color is used to help the student understand exactly what is being conveyed in a particular illustration.

Industrial Motor Control, Seventh Edition, is a complete learning package that includes this comprehensive textbook, a hands-on Lab Manual, a Student Companion Web Site, an *Instructor's Guide,* and an *Instructor Companion Web Site*. The Lab Manual offers practical hands-on circuits to be wired by the student. Each of the labs uses standard components that most electrical laboratories either have on hand or can obtain without difficulty. The Lab Manual (ISBN: 1133691815) lets students learn by doing.

New for the Seventh Edition

- Updated illustrations
- Extended coverage of electronic timers.
- Additional Review Questions.
- Extended coverage concerning the installation of control systems.
- Extended coverage of motor nameplate data.
- *National Electrical Code* references updated to the 2011 *NEC*.
- New chapter on light-emitting-diodes and photodiodes.

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

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

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Content Highlights

- The most commonly used solid-state devices are thoroughly described, in terms of both operation and typical application.
- Information on analog devices that sense pressure, flow, and temperature has been added to help bridge the gap between the industrial electrician and the instrumentation technician.
- DC and AC motor theory is included so students will understand the effects of control circuits on motor characteristics.
- The text covers the operating characteristics of stepping motors when connected to either DC or AC voltage.
- Detailed instructions are given for connecting motors in the field, including the size of conductors, overload relays, and fuses or circuit breakers. All calculations are taken from the *National Electrical Code®*.
- The principles of digital logic are described in sufficient detail for students to understand programmable controllers and prepare basic programs.
- A step-by-step testing procedure for electronic components is provided in the Appendix.
- Starting methods for hermetically sealed single-phase motors include the hot-wire relay, solid-state starting relay, current relay, and potential relay.
- Extensive coverage on overload relays and methods of protecting large horsepower motors is provided.

- There is extensive coverage of variable frequency drives.
- Solid-state control devices, in addition to electromagnetic devices, are thoroughly covered.
- Basic electronics is not a prerequisite for studying this text. Sufficient solid-state theory is presented to enable the student to understand and apply the concepts discussed.

About the Author

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

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CHAPTER 1

General Principles of Motor Control

OBJECTIVES

After studying this chapter, the student will be able to

- State the purpose and general principles of motor control.
- Discuss the differences between manual and automatic motor control.
- Discuss considerations when installing motors or control equipment.
- Discuss the basic functions of a control system.
- Discuss surge protection for control systems.

The term *motor control* can have very broad meanings. It can mean anything from a simple toggle switch intended to turn a motor on or off (Figure 1–1) to an extremely complex system intended to control several motors, with literally hundreds of sensing devices that govern the operation of the circuit. The electrician working in industry should be able to install different types of motors and the controls necessary to control and protect them and also to troubleshoot systems when they fail.

Installation of Motors and Control Equipment

When installing electric motors and equipment, several factors should be considered. When a machine is installed, the motor, machine, and controls are all interrelated and must be considered as a unit. Some machines have the motor or motors and control equipment mounted on the machine itself when it is delivered from the manufacturer, and the electrician's job in this case is generally to make a simple power connection to the machine. A machine of this type is shown in Figure 1–2. Other types of machines require separately mounted motors that are connected by belts, gears, or chains. Some machines also require the connection of pilot sensing devices such as photo switches, limit switches, pressure switches, and so on. Regardless of how easy or complex the connection is, several factors must be considered.

Power Source

One of the main considerations when installing a machine is the power source. Does the machine require single-phase or three-phase power to operate? What is the horsepower of the motor or

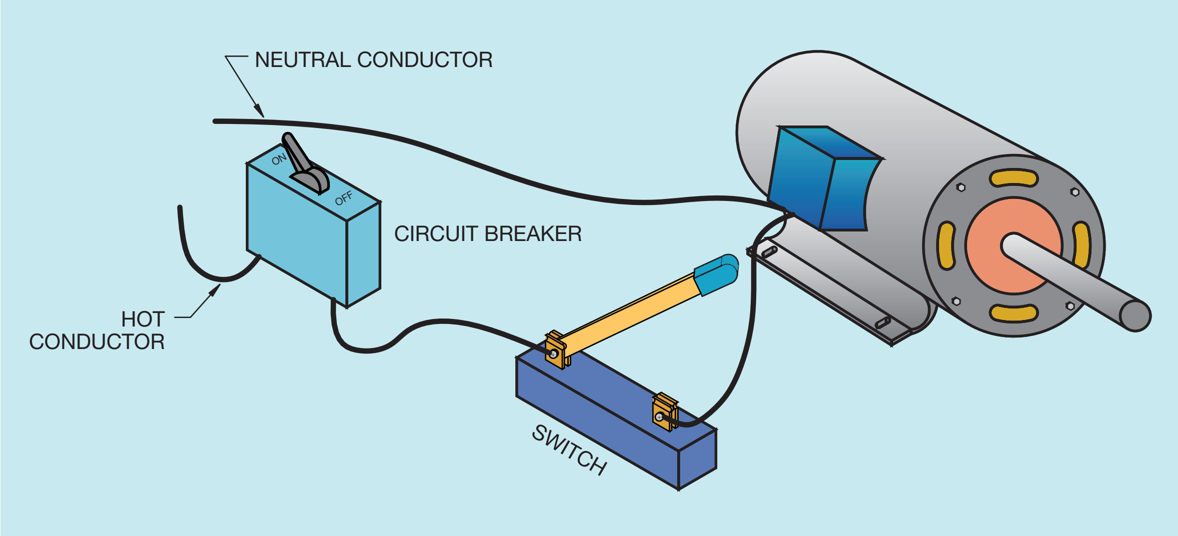

FIGURE 1–1
Motor controlled by a simple toggle switch.

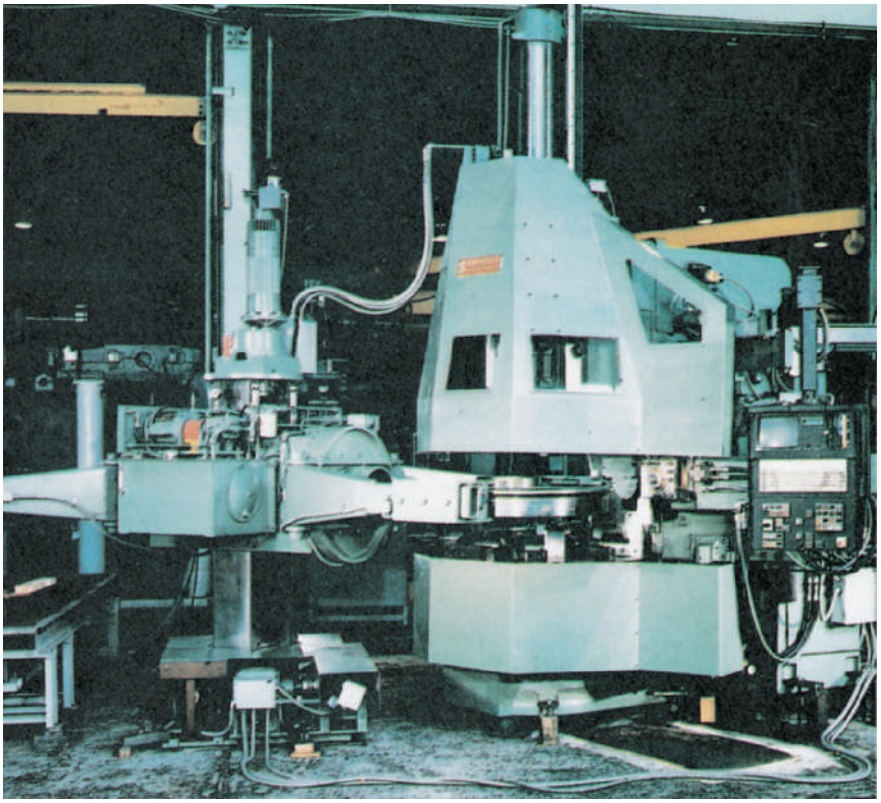

FIGURE 1–2
This machine was delivered with self-contained motors and controls.

motors to be connected? What is the amount of inrush current that can be expected when the motor starts? Does the motor require some type of reduced voltage starter to limit inrush current? Is the existing power supply capable of handling the power requirement of the machine, or is it necessary to install a new power system?

The availability of power can vary greatly from one area of the country to another. Power companies that supply power to heavily industrialized areas can generally permit larger motors to be started across-the-line than companies that supply power to areas that have light industrial needs. In some areas, the power company may permit a motor of several thousand horsepower to be started across-the-line, but in other areas the power company may require a reduced voltage starter for motors rated no more than 100 horsepower.

Motor Connections

When connecting motors, several factors should be considered, such as horsepower, service factor (SF), marked temperature rise, voltage, full-load current rating, and National Electrical Manufacturers Association (NEMA) Code letter. This information is found on the motor nameplate. The information found on the nameplate will be discussed in more detail in a later chapter. The conductor size, fuse or circuit breaker size, and overload size are generally determined using the *National Electrical Code®* *(NEC®)* and/or local codes. It should be noted that local codes generally supersede the *National Electrical Code* and should be followed when they apply. Motor installation based on the *NEC* is covered in this text.

Motor Type

The type of motor best suited to operate a particular piece of equipment can be different for different types of machines. Machines that employ gears generally require a motor that can start at reduced speed and increase speed gradually. Wound rotor induction motors or squirrel-cage motors controlled by variable frequency drives are generally excellent choices for this requirement. Machines that require a long starting period, such as machines that operate large inertia loads such as flywheels or centrifuges, require a motor with high starting torque and relatively low starting current. Squirrel-cage motors with a type A rotor or synchronous motors are a good choice for these types of loads. Synchronous motors have an advantage in that they can provide power factor correction for themselves or other inductive loads connected to the same power line.

Squirrel-cage motors controlled by variable frequency drives or direct-current motors can be employed to power machines that require variable speed. Squirrel-cage induction motors are used to power most of the machines throughout industry. These motors are rugged and have a proven record of service unsurpassed by any other type of power source.

Controller Type

The type of controller can vary depending on the requirements of the motor. Motor starters can be divided into two major classifications: NEMA (National Electrical Manufacturers Association) and IEC (International Electrotechnical Commission). NEMA is an American organization that rates electrical components. NEMA starter sizes range from 00 through 8. A NEMA size 00 starter is rated to control a 2-horsepower motor connected to a 460-volt, three-phase power supply. A size 8 starter will control a 900-horsepower motor connected to a 460-volt, three-phase power source. IEC starter sizes range from size A through size Z. Size A starters are rated to control a 3-horsepower motor connected to a 460-volt, three-phase source. Size Z starters are rated to control a 900-horsepower motor connected to a 460-volt source. It should be noted that the contact size for an IEC starter is smaller than for a NEMA starter of the same rating. It is common practice when using IEC starters to increase the listed size by one or two sizes to compensate for the difference in contact size.

Environment

Another consideration is the type of environment in which the motor and control system operates. Can the controls be housed in a general-purpose enclosure similar to the one shown in Figure 1–3,

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FIGURE 1–3
General-purpose enclosure (NEMA 1).

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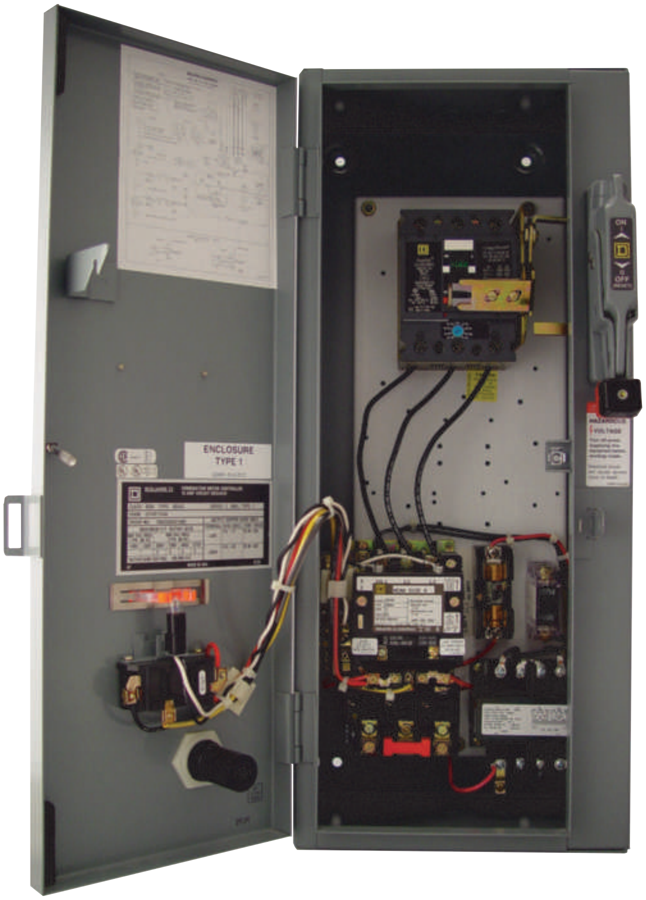
FIGURE 1–4
Explosion-proof enclosure (NEMA 7).

or is the system subject to moisture or dust? Are the motor and controls to be operated in a hazardous area that requires explosion-proof enclosures similar to that shown in Figure 1–4? Some locations may contain corrosive vapor or liquid or extremes of temperature. All of these conditions should be considered when selecting motors and control components. Another type of starter commonly found in industry is the combination starter (Figure 1–5). The combination starter contains the disconnecting means, fuses or circuit breaker, starter, and control transformer. It may also have a set of push buttons or switches mounted on the front panel to control the motor.

Codes and Standards

Another important consideration is the safety of the operator or persons that work around the machine. In 1970, the Occupational Safety and Health Act (OSHA) was established. In general, OSHA requires employers to provide an environment free of recognized hazards that are likely to cause serious injury.

Another organization that exhibits much influence on the electrical field is Underwriters Laboratories (UL). Underwriters Laboratories was established by insurance companies in an effort to reduce the number of fires caused by electrical equipment. They test equipment to determine whether it is safe under different conditions. Approved equipment is listed in an annual publication that is kept current with bimonthly supplements.



Courtesy of Schneider Electric USA, Inc.

FIGURE 1–5
Combination motor starter with circuit breaker, disconnect switch, starter, and control transformer.

Another previously mentioned organization is the *National Electrical Code*. The *NEC* is actually part of the National Fire Protection Association. They establish rules and specifications for the installation of electrical equipment. The *National Electrical Code* is not a law unless it is made law by a local authority.

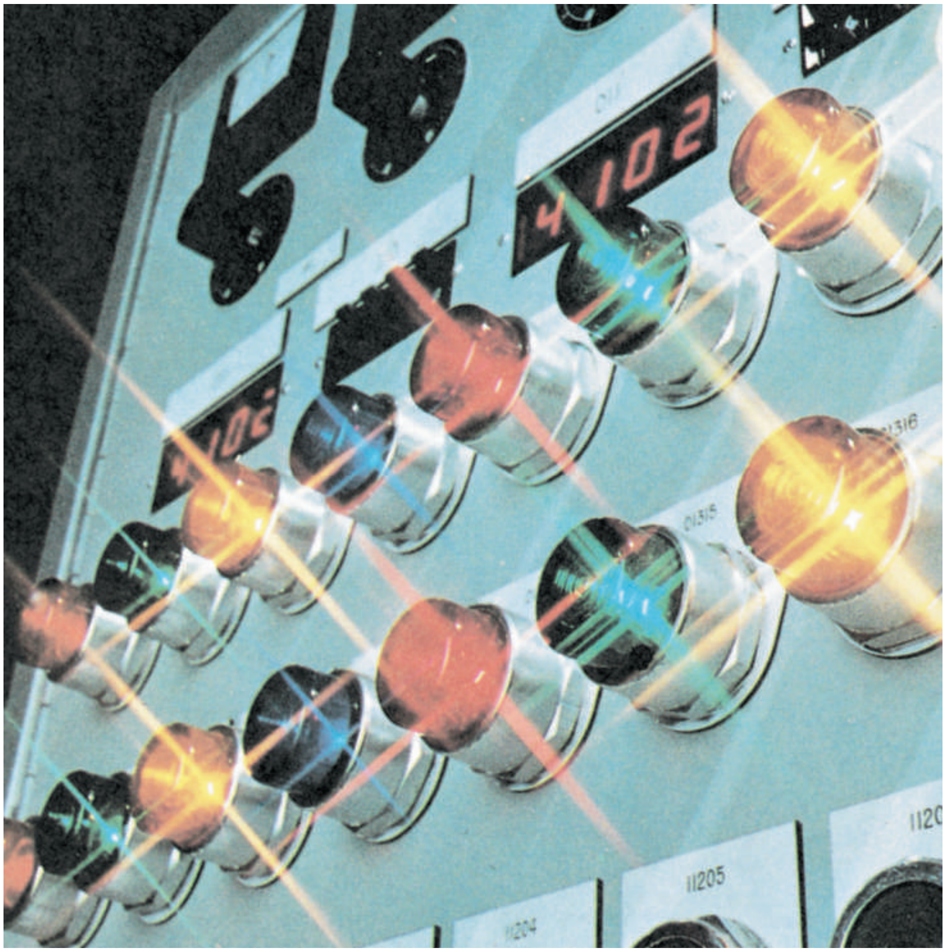
Two other organizations that have great influence on control equipment are NEMA and IEC. Both of these organizations are discussed later in the text.

Types of Control Systems

Motor control systems can be divided into three major types: manual, semiautomatic, and automatic. Manual controls are characterized by the fact that the operator must go to the location of the controller to initiate any change in the state of the control system. Manual controllers are generally very simple devices that connect the motor directly to the line. They may or may not provide overload protection or low-voltage release. Manual control may be accomplished by simply connecting a switch in series with a motor (Figure 1–1).

Semiautomatic control is characterized by the use of push buttons, limit switches, pressure switches, and other sensing devices to control the operation of a magnetic contactor or starter. The starter actually connects the motor to the line, and the push buttons and other pilot devices control the coil of the starter. This permits the actual control panel to be located away from the motor or starter. The operator must still initiate certain actions, such as starting and stopping, but does not have to go to the location of the motor or starter to perform the action. A typical control panel is shown in Figure 1–6. A schematic and wiring diagram of a start–stop push button station is shown in Figure 1–7. A schematic diagram shows components in their electrical sequence without regard for physical location. A wiring diagram is basically a pictorial representation of the control components with connecting wires. Although the two circuits shown in Figure 1–7 look different, electrically they are the same.

Automatic control is very similar to semiautomatic control in that pilot sensing devices are employed to operate a magnetic contactor or starter that actually controls the motor. With automatic control, however, an operator does not have to initiate certain actions. Once the control conditions have been set, the system will continue to operate on its own. A good example of an automatic control



Courtesy of Rockwell Automation, Inc.

FIGURE 1–6
Typical push button control center.

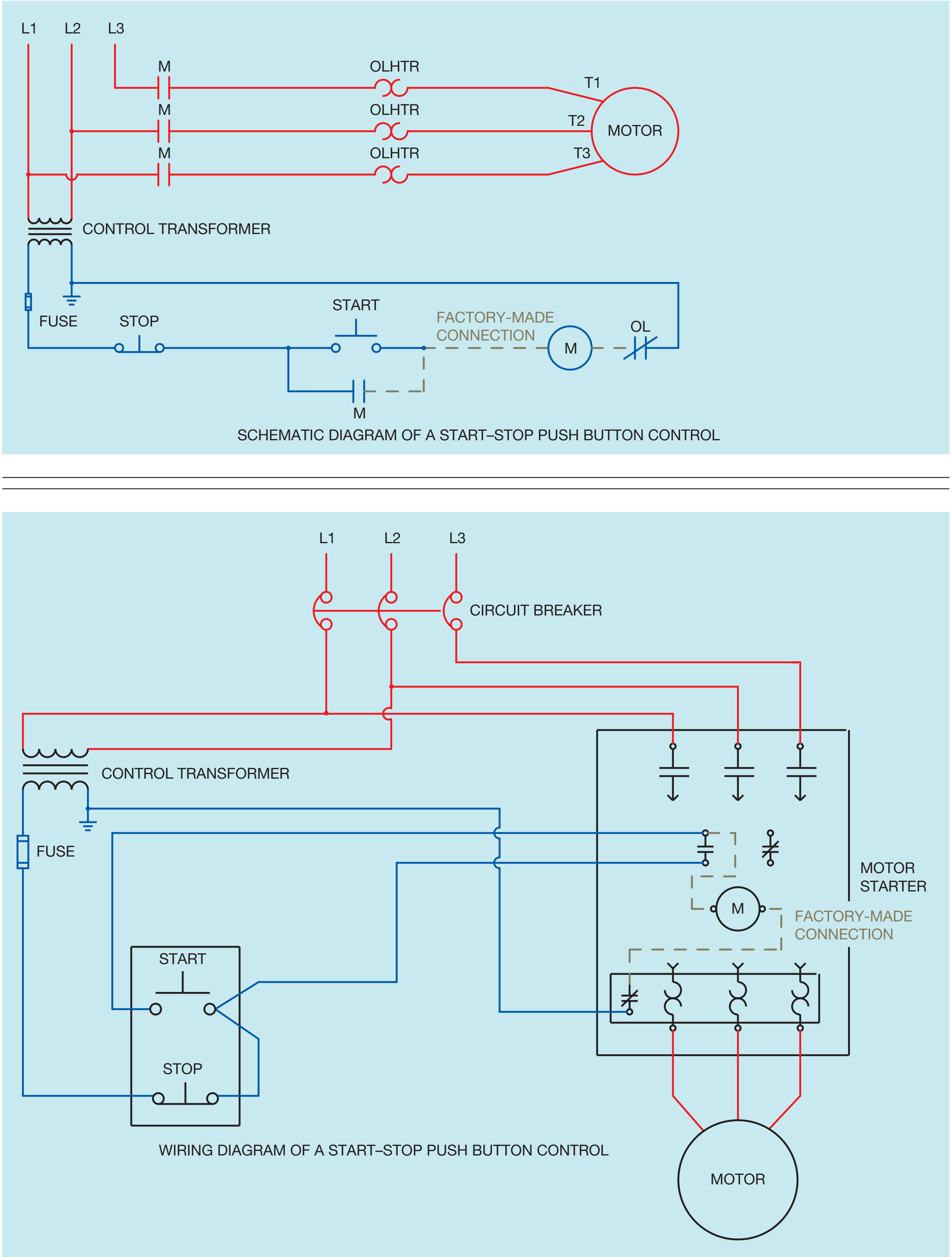


FIGURE 1–7
Schematic and wiring diagram of a start-stop push button control.

system is the heating and cooling system found in many homes. Once the thermostat has been set to the desired temperature, the heating or cooling system operates without further attention from the home owner. The control circuit contains sensing devices that automatically shut the system down in the event of an unsafe condition such as motor overload, excessive current, no pilot light or ignition in gas heating systems, and so on.

Functions of Motor Control

There are some basic functions that motor control systems perform. The ones listed below are by no means the only ones but are very common. These basic functions are discussed in greater detail in this text. It is important not only to understand these basic functions of a control system but also to know how control components are employed to achieve the desired circuit logic.

Starting

Starting the motor is one of the main purposes of a motor control circuit. There are several methods that can be employed, depending on the requirements of the circuit. The simplest method is *across-the-line* starting. This is accomplished by connecting the motor directly to the power line. There may be situations, however, that require the motor to start at a low speed and accelerate to full speed over some period of time. This is often referred to as *ramping*. In other situations, it may be necessary to limit the amount of current or torque during starting. Some of these methods are discussed later in the text.

Stopping

Another function of the control system is to stop the motor. The simplest method is to disconnect the motor from the power line and permit it to coast to a stop. Some conditions, however, may require that the motor be stopped more quickly or that a brake hold a load when the motor is stopped.

Jogging or Inching

Jogging and inching are methods employed to move a motor with short jabs of power. This is generally done to move a motor or load into some desired position. The difference between jogging and inching is that jogging is accomplished by momentarily connecting the motor to full line voltage, and inching is accomplished by momentarily connecting the motor to reduced voltage.

Speed Control

Some control systems require variable speed. There are several ways to accomplish this. One of the most common ways is with variable frequency control for alternating-current motors or by controlling the voltage applied to the armature and fields of a direct-current motor. Another method may involve the use of a direct-current clutch. These methods are discussed in more detail later in this text.

Motor and Circuit Protection

One of the major functions of most control systems is to provide protection for both the circuit components and the motor. Fuses and circuit breakers are generally employed for circuit protection, and overload relays are used to protect the motor. The different types of overload relays are discussed later.

Surge Protection

Another concern in many control circuits is the voltage spikes or surges produced by collapsing magnetic fields when power to the coil of a relay or contactor is turned off. These collapsing magnetic fields can induce voltage spikes that are hundreds of volts (Figure 1–8). These high voltage surges can damage electronic components connected to the power line. Voltage spikes are of greatest concern in control systems that employ computer-controlled devices such as programmable logic controllers and measuring instruments used to sense temperature, pressure, and so on. Coils connected to alternating current often have a metal oxide varistor (MOV) connected across the coil (Figure 1–9). Metal oxide varistors are voltage-sensitive resistors. They have the ability to change their resistance value in accord with the amount of voltage applied to them. The MOV has a voltage rating greater than that of the coil it is connected across. An MOV connected across a coil intended to operate on 120 volts, for example, has a rating of about 140 volts. As long as the voltage applied to the MOV is below its voltage rating, it exhibits an extremely high amount of

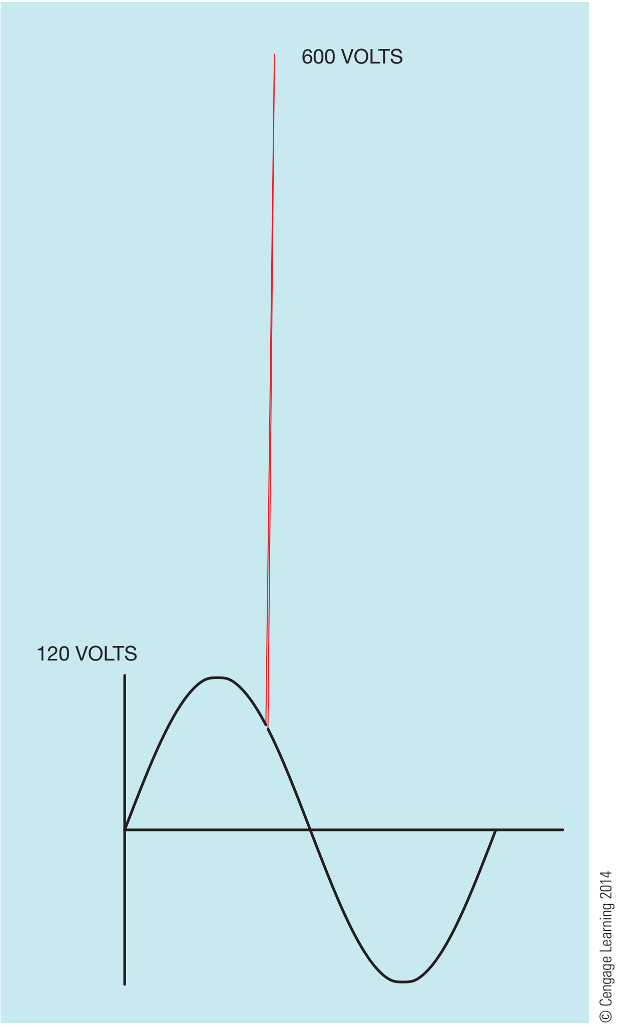


FIGURE 1–8
Spike voltages produced by collapsing magnetic fields can be hundreds of volts.

resistance, generally several million ohms. The current flow through the MOV is called *leakage current* and is so small that it does not affect the operation of the circuit.

If the voltage across the coil should become greater than the voltage rating of the MOV, the resistance of the MOV suddenly changes to a very low value, generally in the range of 2 or 3 ohms. This effectively short-circuits the coil and prevents the voltage from becoming any higher than the voltage rating of the MOV (Figure 1–10). Metal oxide varistors change resistance value very quickly, generally in the range of 3 to 10 nanoseconds. When the circuit voltage drops below the voltage rating of the MOV, it returns to its high resistance value. The energy of the voltage spike is dissipated as heat by the MOV.

Diodes are used to suppress the voltage spikes produced by coils that operate on direct current. The diode is connected reverse bias to the voltage connected to the coil (see Figure 1–11). During normal operation, the diode blocks the flow of current, permitting all the circuit current to flow through the coil. When the power is disconnected, the magnetic field around the coil collapses and induces a voltage into the coil. Because the induced voltage is opposite in polarity to the applied voltage (Lenz's Law), the induced voltage causes the diode to become forward biased. A silicon diode exhibits a forward voltage drop of approximately 0.7 volt. This limits the induced voltage to a value

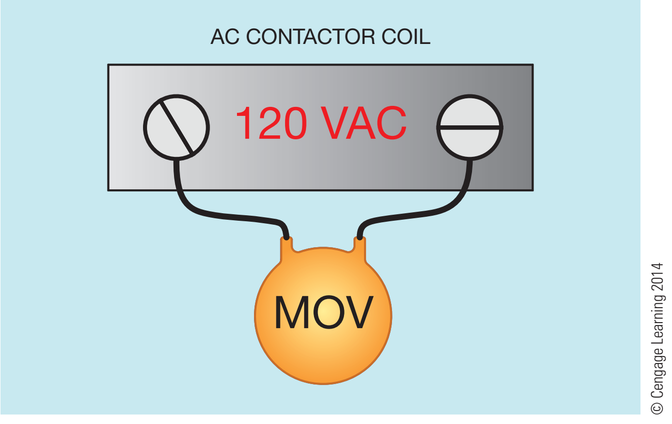


FIGURE 1–9
A metal oxide varistor (MOV) is used to eliminate voltage spikes on coils connected to alternating current.

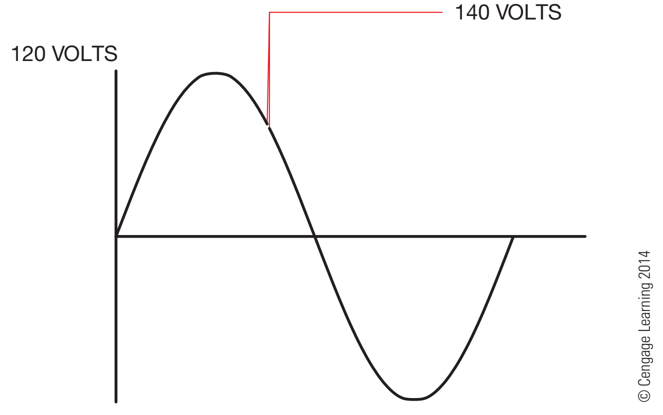


FIGURE 1–10
The metal oxide varistor limits the voltage spike to 140 volts.

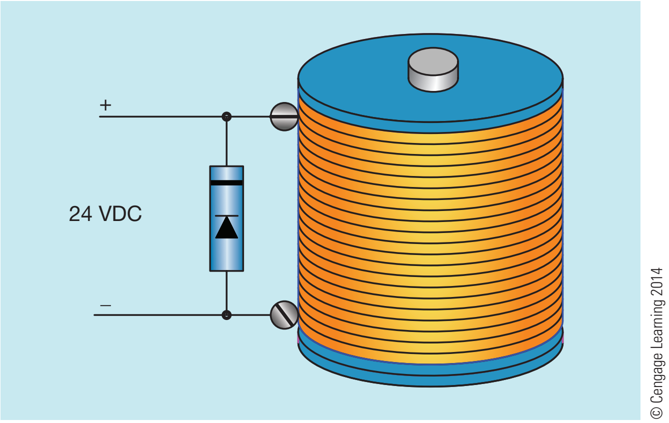


FIGURE 1–11
A diode is used to prevent voltage spikes on coils connected to direct current.

of about 0.7 volt. The energy of the voltage spike is dissipated as heat by the diode.

Safety

Probably the most important function of any control system is to provide protection for the operator or persons that may be in the vicinity of the machine. These protections vary from one type of machine to another, depending on the specific function of the machine. Many machines are provided with both mechanical and electrical safeguards.

REVIEW QUESTIONS

1. When installing a motor control system, list four major factors to consider concerning the power system.
2. Where is the best place to look to find specific information about a motor, such as horsepower, voltage, full-load current, service factor, and full-load speed?
3. Is the *National Electrical Code* a law?
4. Explain the difference between manual control, semiautomatic control, and automatic control.
5. What is the simplest of all starting methods for a motor?
6. Explain the difference between jogging and inching.
7. What is the most common method of controlling the speed of an alternating-current motor?
8. What agency requires employers to provide a workplace free of recognized hazards for its employees?
9. What is meant by the term *ramping*?
10. What is the most important function of any control system?