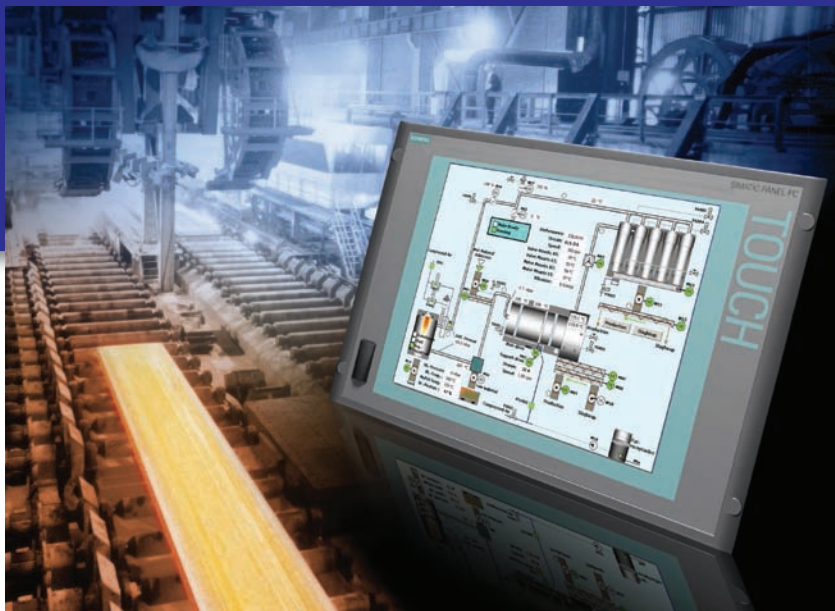


# Developing Fundamental PLC Wiring Diagrams and Ladder Logic Programs



*Courtesy of Siemens*

For ease of understanding, ladder logic programs can be compared to relay schematics. This chapter gives examples of how traditional relay schematics are converted into PLC ladder logic programs. You will learn more about the wide variety of field devices commonly used in connection with the I/O modules.

## Chapter Objectives

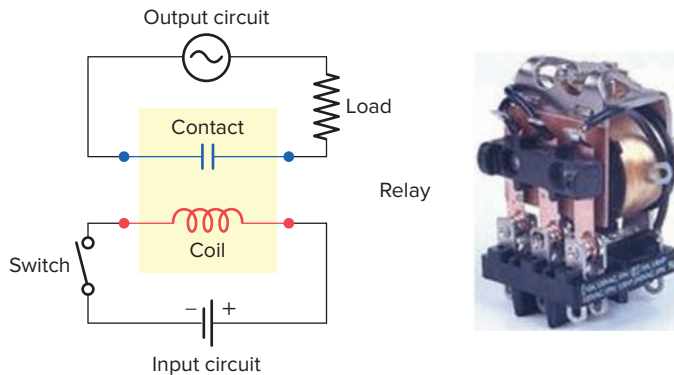
*After completing this chapter, you will be able to:*

- Identify the functions of electromagnetic control relays, contactors, and motor starters
- Identify switches commonly found in PLC installations
- Explain the operation of sensors commonly found in PLC installations
- Explain the operation of output control devices commonly found in PLC installations
- Describe the operation of an electromagnetic latching relay and the PLC-programmed LATCH/UNLATCH instruction
- Compare sequential and combination control processes
- Convert fundamental relay ladder diagrams to PLC ladder logic programs
- Write PLC programs directly from a narrative description

## 6.1 Electromagnetic Control Relays

The PLC's original purpose was the replacement of **electromagnetic relays** with a solid-state switching system that could be programmed. Although the PLC has replaced much of the relay control logic, electromagnetic relays are still used as auxiliary devices to switch I/O field devices. The programmable controller is designed to replace the physically small control relays that make logic decisions but are not designed to handle heavy current or high voltage (Figure 6-1). In addition, an understanding of electromagnetic relay operation and terminology is important for correctly converting relay schematic diagrams to ladder logic programs.

An electrical relay is a magnetic switch. It uses electromagnetism to switch contacts. A relay will usually have only one coil but may have any number of different contacts. Figure 6-2 illustrates the operation of a typical



**Figure 6-1** Electromechanical control relay.

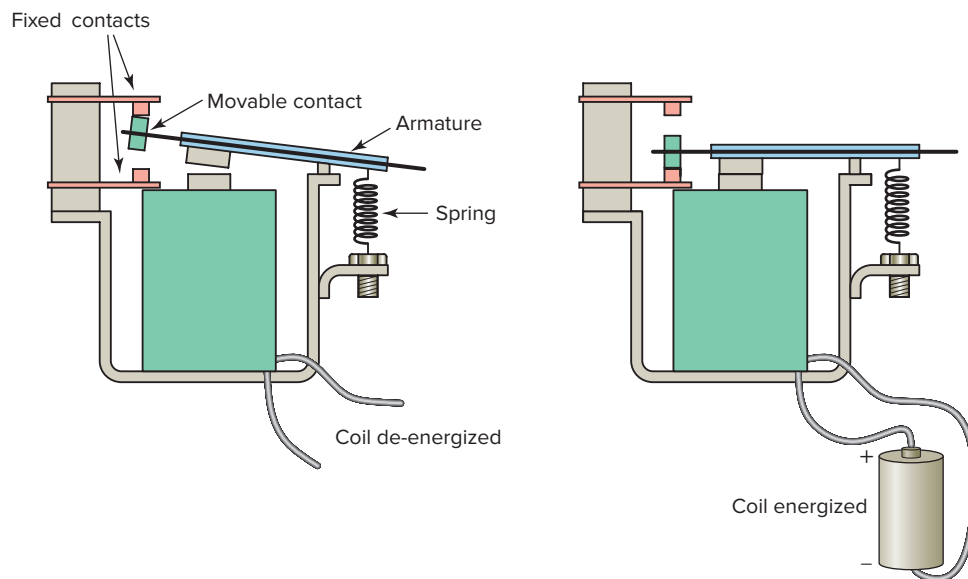
Source: Courtesy Tyco Electronics Ltd.

control relay. With no current flow through the coil (de-energized), the armature is held away from the core of the coil by spring tension. When the coil is energized, it produces an electromagnetic field. Action of this field, in turn, causes the physical movement of the armature. Movement of the armature causes the contact points of the relay to open or close. The coil and contacts are insulated from each other; therefore, under normal conditions, no electric circuit will exist between them.

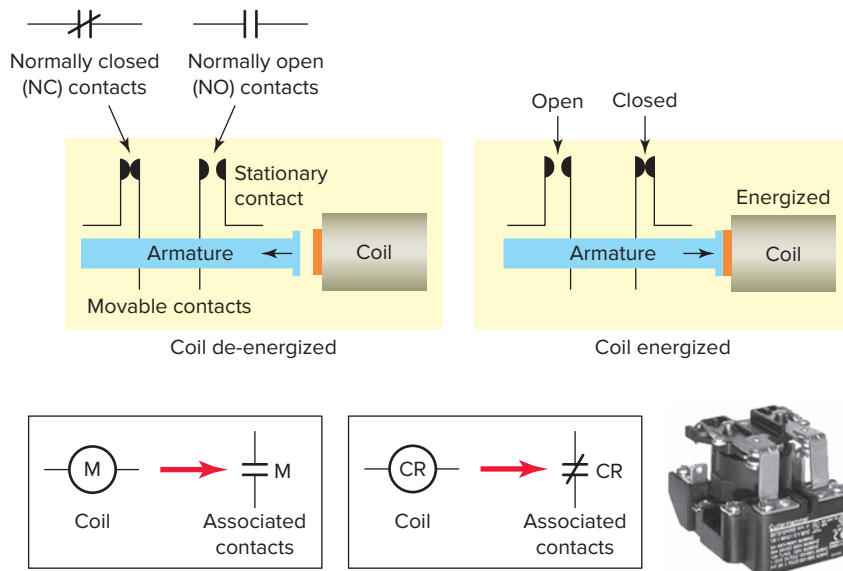
The symbol used to represent a control relay is shown in Figure 6-3. The contacts are represented by a pair of short parallel lines and are identified with the coil by means of the letters. The letter M frequently indicates a motor starter, while CR is used for control relays. **Normally open (NO) contacts** are defined as those contacts that are open when no current flows through the coil but that *close* as soon as the coil conducts a current or is energized. **Normally closed (NC) contacts are closed** when the coil is de-energized and open when the coil is energized. Each contact is usually drawn as it would appear with the coil de-energized.

A typical control relay used to control two pilot lights is shown in Figure 6-4. The operation of the circuit can be summarized as follows:

- With the switch open, coil CR is de-energized.
- The circuit to the green pilot light is completed through the normally closed contact, so this light will be on.
- At the same time, the circuit to the red pilot light is opened through the normally open contact, so this light will be off.



**Figure 6-2** Relay operation.



**Figure 6-3** Relay normally open and normally closed contacts.  
Source: Photo courtesy Eaton Corporation, [www.eaton.com](http://www.eaton.com).

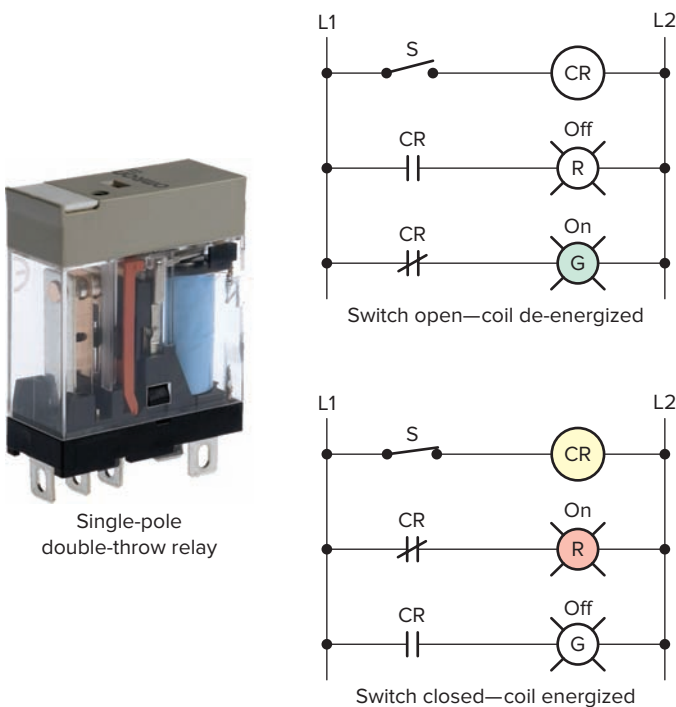
- With the switch closed, the coil is energized.
- The normally open contact closes to switch the red pilot light on.
- At the same time, the normally closed contact opens to switch the green pilot light off.

Control relay coils and contacts have separate ratings. Coils are rated for the type of operating current (DC or AC) and normal operating voltage. Contacts are rated in terms of the maximum amount of current the contacts are capable of handling at a specified voltage level and type (AC or DC). Control relay contacts generally are not designed to carry heavy currents or high voltages. The contacts are usually rated between 5 and 10 Amp, with the most common rating for the coil voltage being 120 VAC.

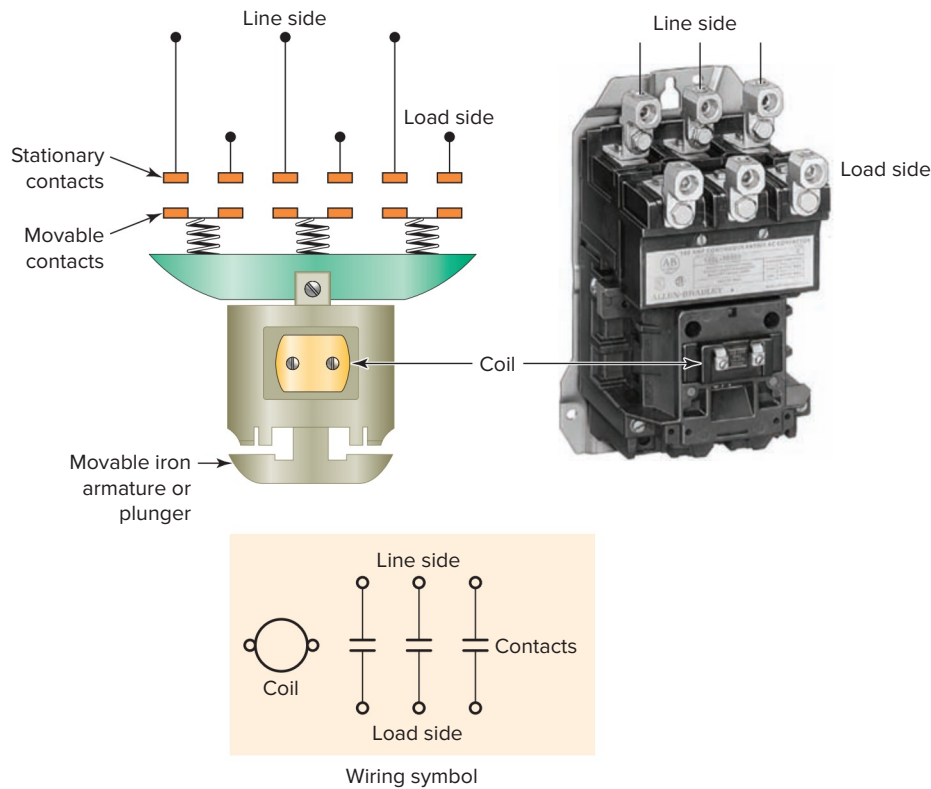
## 6.2 Contactors

A **contactor** is a special type of relay designed to handle heavy power loads that are beyond the capability of control relays. Figure 6-5 shows a three-pole magnetic contactor. Unlike relays, contactors are designed to make and break higher powered circuits without being damaged. Such loads include lights, heaters, transformers, capacitors, and electric motors for which overload protection is provided separately or not required.

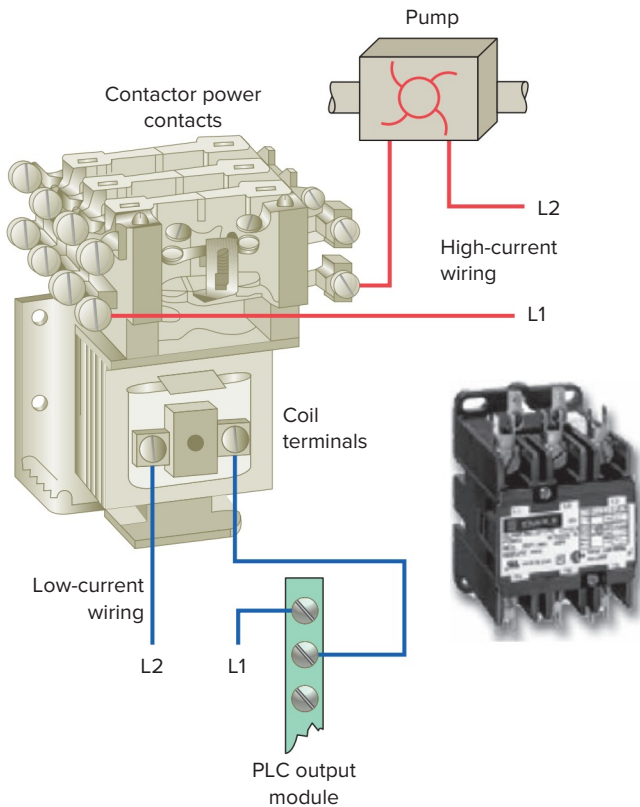
Programmable controllers normally have an output capacity capable of operating a contactor coil, but not that needed to operate heavy power loads directly. Figure 6-6 illustrates the application of a PLC used in conjunction with a contactor to switch power on and off to a pump. The output module is connected in series with the coil to form a low-current switching circuit. The contacts of the contactor are connected in series with the pump motor to form a high-current switching circuit.



**Figure 6-4** Control relay used to control two pilot lights.  
Source: Photo courtesy Digi-Key Corporation, [www.digikey.com](http://www.digikey.com).



**Figure 6-5** Three-pole magnetic contactor.  
Source: Image Courtesy of Rockwell Automation, Inc.



**Figure 6-6** Contactor used in conjunction with a PLC output.  
Source: This material and associated copyrights are proprietary to, and used with the permission of Schneider Electric.

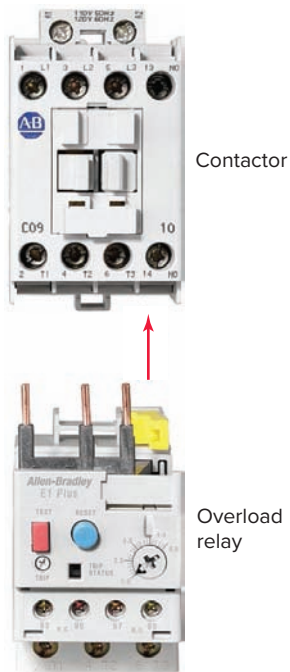
## 6.3 Motor Starters

A **motor starter** is designed to provide power to motors. The motor starter is made up of a contactor with an **overload relay** attached physically and electrically to it as illustrated in Figure 6-7. The function of the overload relay can be summarized as follows:

- Overload relays are designed to meet the special protective needs of motor control circuits.
- They allow harmless temporary overloads that occur when a motor starts.
- The overload relay will trip and disconnect power to the motor if an overload condition persists.
- Overload relays can be reset after the overload condition has been corrected.

Figure 6-8 shows the diagram for a typical three-phase, magnetic motor starter. The operation of the circuit can be summarized as follows:

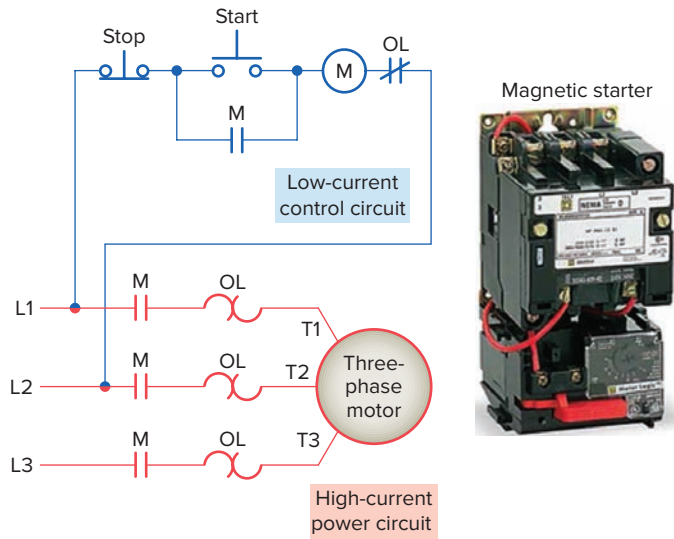
- When the START button is pressed coil M is energized closing all normally open M contacts.
- The M contacts in series with the motor close to complete the current path to the motor. These contacts are part of the **power** circuit and must be designed to handle the full load current of the motor.



**Figure 6-7** Motor starter is a contactor with an attached overload relay.

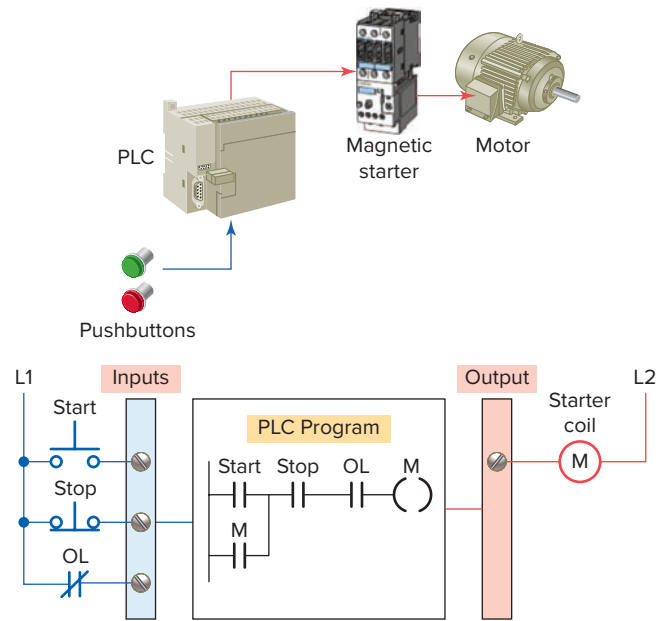
Source: Image Courtesy of Rockwell Automation, Inc.

- Control contact M (across START button) closes to seal in the coil circuit when the START button is released. This contact is part of the *control* circuit and, as such, is only required to handle the small amount of current needed to energize the coil.
- An overload (OL) relay is provided to protect the motor against current overloads. The normally closed relay contact OL opens automatically when



**Figure 6-8** Three-phase magnetic motor starter.

Source: This material and associated copyrights are proprietary to, and used with the permission of Schneider Electric.



**Figure 6-9** PLC control of a motor.

an overload current is sensed to de-energize the M coil and stop the motor.

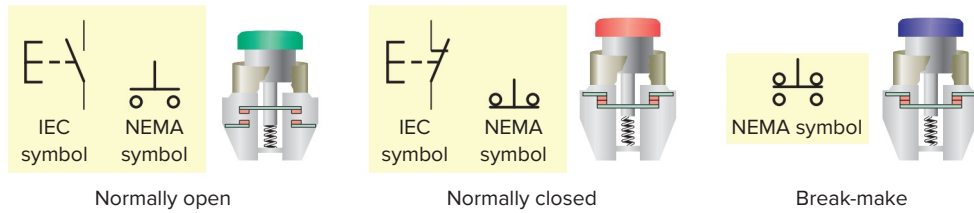
Motor starters are available in various standard National Electric Manufacturers Association (NEMA) sizes and ratings. When a PLC needs to control a large motor, it must work in conjunction with a starter as illustrated in Figure 6-9. The power requirements for the starter coil must be within the power rating of the output module of the PLC. Note that the control logic is determined and executed by the program within the PLC and not by the hardwired arrangement of the input control devices.

## 6.4 Manually Operated Switches

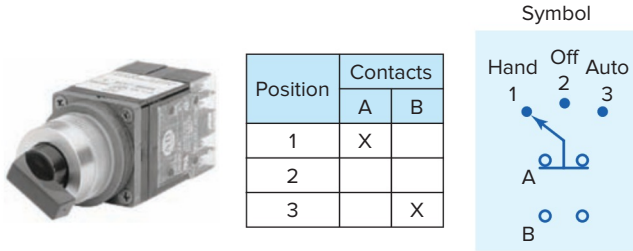
*Manually operated switches* are controlled by hand. These include toggle switches, pushbutton switches, knife switches, and selector switches.

*Pushbutton switches* are the most common form of manual control. A pushbutton operates by opening or closing contacts when pressed. Figure 6-10 shows commonly used types of pushbutton switches, which include:

- *Normally open (NO) pushbutton*, which makes a circuit when it is pressed and returns to its open position when the button is released.
- *Normally closed (NC) pushbutton*, which opens the circuit when it is pressed and returns to the closed position when the button is released.
- *Break-before-make pushbutton* in which the top section contacts are NC and the bottom section contacts are NO. When the button is pressed, the top contacts open before the bottom contacts are closed.



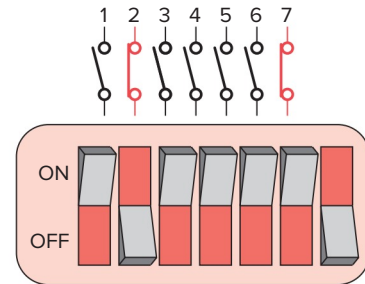
**Figure 6-10** Commonly used types of pushbutton switches.



**Figure 6-11** Three-position selector switch.  
Source: Image Courtesy of Rockwell Automation, Inc.

The **selector switch** is another common manually operated switch. The main difference between a pushbutton and selector switch is the operator mechanism. A selector switch operator is rotated (instead of pushed) to open and close contacts of the attached contact block. Figure 6-11 shows a three-position selector switch. Switch positions are established by turning the operator knob right or left. Selector switches may have two or more selector positions, with either maintained contact position or spring return to give momentary contact operation.

**Dual in-line package (DIP) switches** are small switch assemblies designed for mounting on printed circuit board modules (Figure 6-12). The pins or terminals on the bottom of the DIP switch are the same size and spacing as an integrated circuit (IC) chip. The individual switches may be of the toggle, rocker, or slide kind. DIP switches use binary (on/off) settings to set the parameters for a particular module. For example, the input voltage



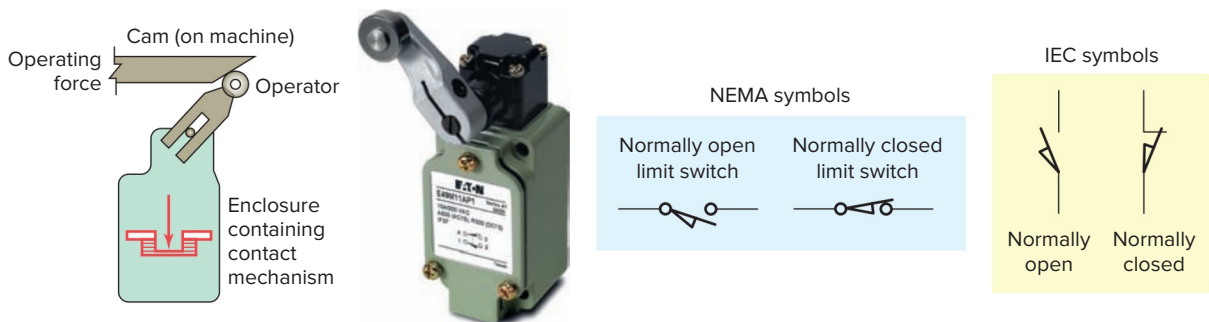
**Figure 6-12** DIP switch.

range on a particular input module may be selected by means of DIP switches located on the back of the module.

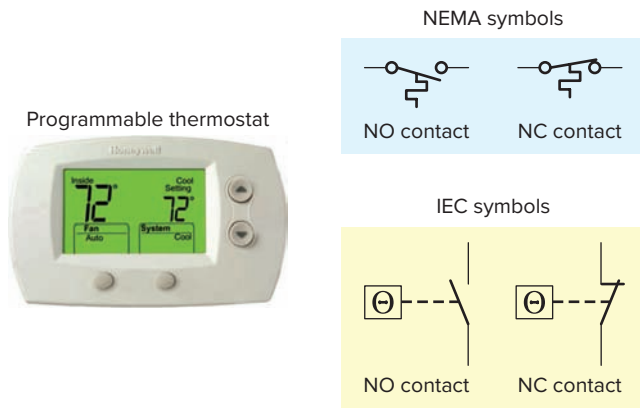
## 6.5 Mechanically Operated Switches

A **mechanically operated switch** is controlled automatically by factors such as pressure, position, or temperature. The **limit switch**, shown in Figure 6-13, is a very common industrial control device. Limit switches are designed to operate only when a predetermined limit is reached, and they are usually actuated by contact with an object such as a cam. These devices take the place of a human operator. They are often used in the control circuits of machine processes to govern the starting, stopping, or reversal of motors.

The **temperature switch**, or **thermostat**, shown in Figure 6-14 is used to sense temperature changes. Although there are many types available, they are all actuated by some specific environmental temperature change.



**Figure 6-13** Mechanically operated limit switch.  
Source: Photo courtesy Eaton Corporation.



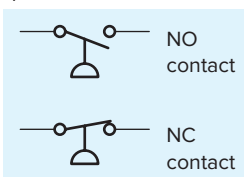
**Figure 6-14** Temperature switch.  
Source: Photo courtesy Honeywell, [www.honeywell.com](http://www.honeywell.com).

Temperature switches open or close when a designated temperature is reached. Industrial applications for these devices include maintaining the desired temperature range of air, gases, liquids, or solids.

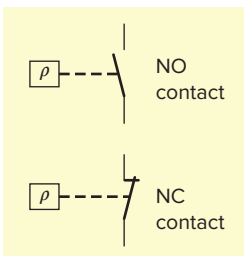
**Pressure switches**, such as that shown in Figure 6-15, are used to control the pressure of liquids and gases. Although many different types are available, they are all basically designed to actuate (open or close) their contacts when a specified pressure is reached. Pressure switches can be pneumatically (air) or hydraulically (liquid) operated switches. Generally, bellows or a diaphragm presses up against a small microswitch and causes it to open or close.

**Level switches** are used to sense liquid levels in vessels and provide automatic control for motors that transfer liquids from sumps or into tanks. They are also used to

NEMA symbols for pressure switch contacts



IEC symbols for pressure switch contacts



**Figure 6-15** Pressure switch.  
Source: Photo courtesy Honeywell, [www.honeywell.com](http://www.honeywell.com).



**Figure 6-16** Float type level switch.  
Source: Courtesy Dwyer Instruments.

open or close piping solenoid valves to control fluids. The float switch shown in Figure 6-16 is a type of level switch. This switch is weighted so that as the liquid rises the switch floats and turns upside down, actuating its internal contacts.

## 6.6 Sensors

**Sensors** are used for detecting, and often measuring, the magnitude of something. They convert mechanical, magnetic, thermal, optical, and chemical variations into electric voltages and currents. Sensors are usually categorized by what they measure, and they play an important role in modern manufacturing process control.

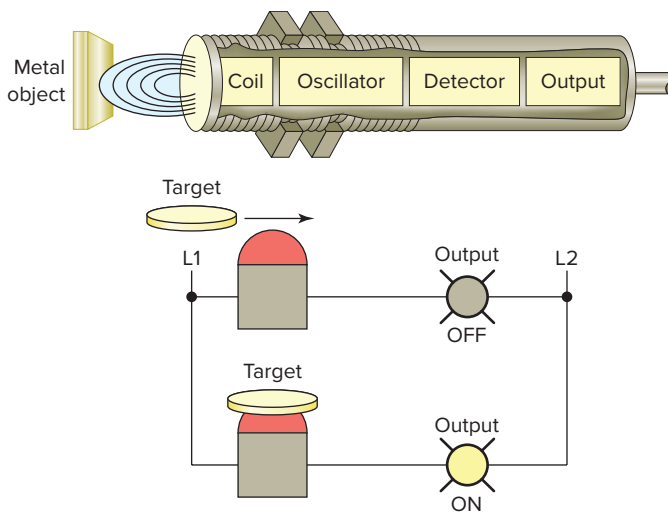
### Proximity Sensor

Pilot control devices have limited current handling capacity and are used to control current to a secondary device, such as a contactor coil, which in turn can be used to switch heavier load currents. **Proximity sensors** or switches, such as that shown in Figure 6-17, are pilot devices that detect the presence of an object (usually called the target) *without physical contact*. These solid-state electronic devices are completely encapsulated to protect against excessive vibration, liquids, chemicals, and corrosive agents found in the industrial environment. Proximity sensors are used when:

- The object being detected is too small, lightweight, or soft to operate a mechanical switch.
- Rapid response and high switching rates are required, as in counting or ejection control applications.
- An object has to be sensed through nonmetallic barriers such as glass, plastic, and paper cartons.



**Figure 6-17** Proximity sensor.  
Source: Photo courtesy Turck, Inc., [www.turck.com](http://www.turck.com).



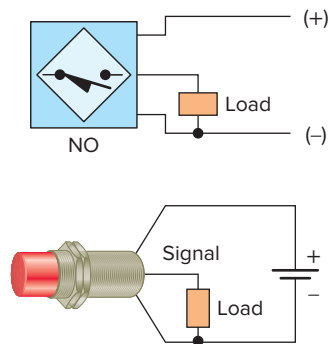
**Figure 6-18** Inductive proximity sensor.

- Hostile environments prevent proper operation of mechanical switches and demand improved sealing properties.
- Long life and reliable service are required.
- A fast electronic control system requires a bounce-free input signal.

Proximity sensors operate on different principles, depending on the type of matter being detected. When an application calls for noncontact metallic target sensing, an **inductive-type proximity sensor** is used. Inductive proximity sensors are used to detect both ferrous metals (containing iron) and nonferrous metals (such as copper, aluminum, and brass).

Inductive proximity sensors operate under the electrical principle of inductance, where a fluctuating current induces an electromotive force (emf) in a target object. The block diagram for an inductive proximity sensor is shown in Figure 6-18 and its operation can be summarized as follows:

- The oscillator circuit generates a high-frequency electromagnetic field that radiates from the end of the sensor.
- When a metal object enters the field, eddy currents are induced in the surface of the object.
- The eddy currents on the object absorb some of the radiated energy from the sensor, resulting in a loss of energy and change of strength of the oscillator.
- The sensor's detection circuit monitors the oscillator's strength and triggers a solid-state output at a specific level.
- Once the metal object leaves the sensing area, the oscillator returns to its initial value.

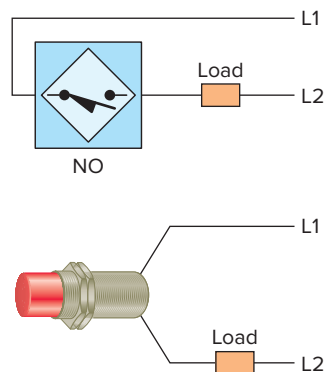


**Figure 6-19** Typical three-wire DC sensor connection.

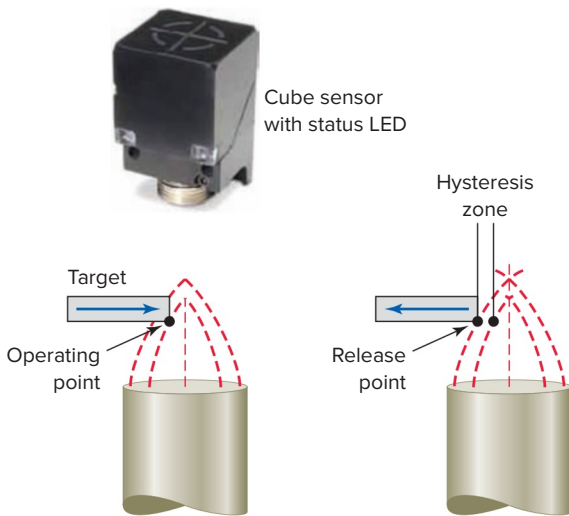
Most sensor applications operate either at 24V DC or at 120V AC. The method of connecting a proximity sensor varies with the type of sensor and its application. Figure 6-19 shows a typical three-wire DC sensor connection. The three-wire DC proximity sensor has the positive and negative line leads connected directly to it. When the sensor is actuated, the circuit will connect the signal wire to the positive side of the line if operating normally open. If operating normally closed, the circuit will disconnect the signal wire from the positive side of the line.

Figure 6-20 shows a typical two-wire proximity sensor connection intended to be connected in series with the load. They are manufactured for either AC or DC supply voltages. In the off state, enough current must flow through the circuit to keep the sensor active. This off state current is called leakage current and typically may range from 1 to 2 mA. When the switch is actuated, it will conduct the normal load circuit current.

Figure 6-21 shows the proximity sensor sensing range. Hysteresis is the distance between the operating point when the target approaches the proximity sensor face and the release point when the target is moving away from the sensor face. The object must be closer to turn the sensor on rather than to turn it off. If the target is moving toward the sensor, it will have to move to a closer point. Once the sensor turns on, it will remain on until the target moves to



**Figure 6-20** Typical two-wire proximity sensor connection.

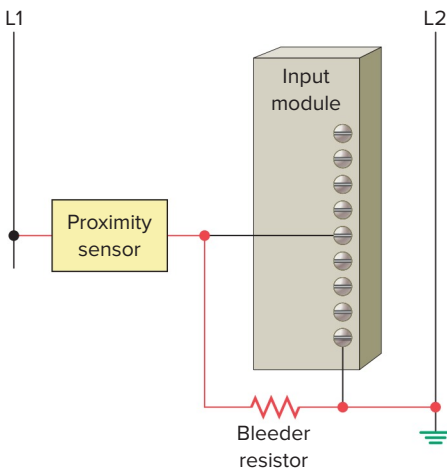


**Figure 6-21** Proximity sensor sensing range.  
Source: Photo courtesy Eaton Corporation, [www.eaton.com](http://www.eaton.com).

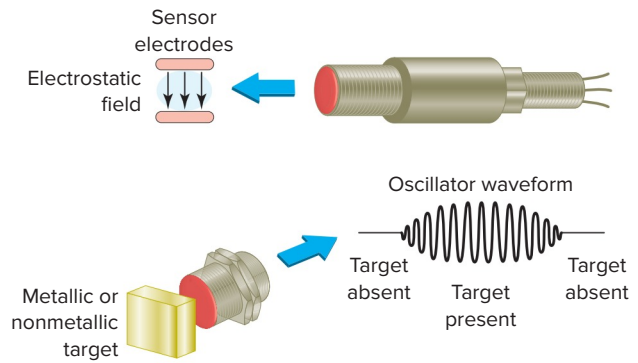
the release point. Hysteresis is needed to keep proximity sensors from chattering when subjected to shock and vibration, slow-moving targets, or minor disturbances such as electrical noise and temperature drift. Most proximity sensors come equipped with an LED status indicator to verify the output switching action.

As a result of solid-state switching of the output, a small leakage current flows through the sensor even when the output is turned off. Similarly, when the sensor is on, a small voltage drop is lost across its output terminals. To operate properly, a proximity sensor should be powered continuously. Figure 6-22 illustrates the use of a bleeder resistor connected to allow enough current for the sensor to operate but not enough to turn on the input of the PLC.

**Capacitive proximity sensors** are similar to inductive proximity sensors. The main differences between the two types are that capacitive proximity sensors produce an



**Figure 6-22** Bleeder resistor connected to continuously power a proximity sensor.



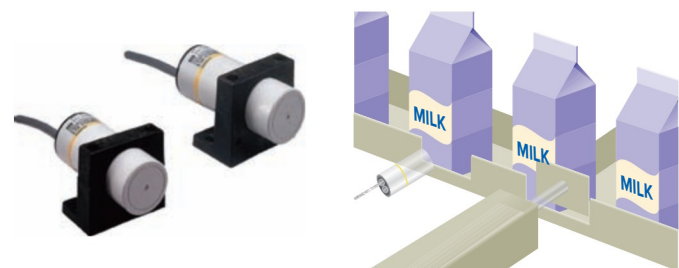
**Figure 6-23** Capacitive proximity sensor.

electrostatic field instead of an electromagnetic field and are actuated by both conductive and nonconductive materials.

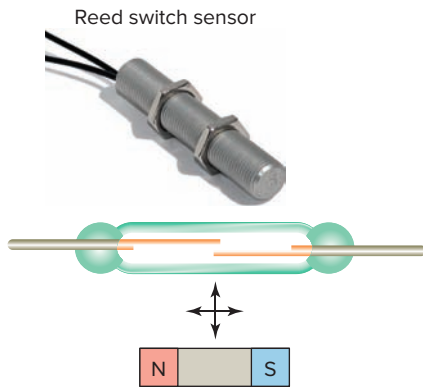
Figure 6-23 illustrates the operation of a capacitive sensor. A capacitive sensor contains a high-frequency oscillator along with a sensing surface formed by two metal electrodes. When the target nears the sensing surface, it enters the electrostatic field of the electrodes and changes the capacitance of the oscillator. As a result, the oscillator circuit begins oscillating and changes the output state of the sensor when it reaches a certain amplitude. As the target moves away from the sensor, the oscillator's amplitude decreases, switching the sensor back to its original state.

Capacitive proximity sensors will sense metal objects as well as nonmetallic materials such as paper, glass, liquids, and cloth. They typically have a short sensing range of about 1 inch, regardless of the type of material being sensed. The larger the dielectric constant of a target, the easier it is for the capacitive sensor to detect. This makes possible the detection of materials inside nonmetallic containers as illustrated in Figure 6-24. In this example, the liquid has a much higher dielectric constant than the cardboard container, which gives the sensor the ability to see through the container and detect the liquid. In the process shown, detected empty containers are automatically diverted via the push rod.

Inductive proximity switches may be actuated only by a metal and are insensitive to humidity, dust, dirt, and the like. Capacitive proximity switches, however, can be actuated



**Figure 6-24** Capacitive proximity sensor liquid detection.  
Source: Photo courtesy Omron Industrial Automation, [www.ia.omron.com](http://www.ia.omron.com).

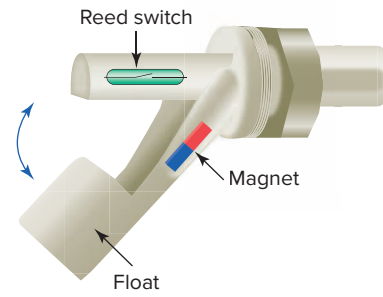


**Figure 6-25** Magnetic reed switch.  
Source: Courtesy of Reed Switch Developments Corp., used with permission.

by any dirt in their environment. For general applications, the capacitive proximity switches are not really an alternative but a supplement to the inductive proximity switches. They are a supplement when there is no metal available for the actuation (e.g., for woodworking machines and for determining the exact level of liquids or powders).

### Magnetic Reed Switch

A **magnetic reed switch** is composed of two flat contact tabs that are hermetically sealed (airtight) in a glass tube filled with protective gas, as illustrated in Figure 6-25. When a magnetic force is generated parallel to the reed switch, the reeds become flux carriers in the magnetic circuit. The overlapping ends of the reeds become opposite magnetic poles, which attract each other. If the magnetic force between the poles is strong enough to overcome the restoring force of the reeds, the reeds will be drawn together to actuate the switch. Because the contacts are sealed, they are unaffected by dust, humidity, and fumes; thus, their life expectancy is quite high.



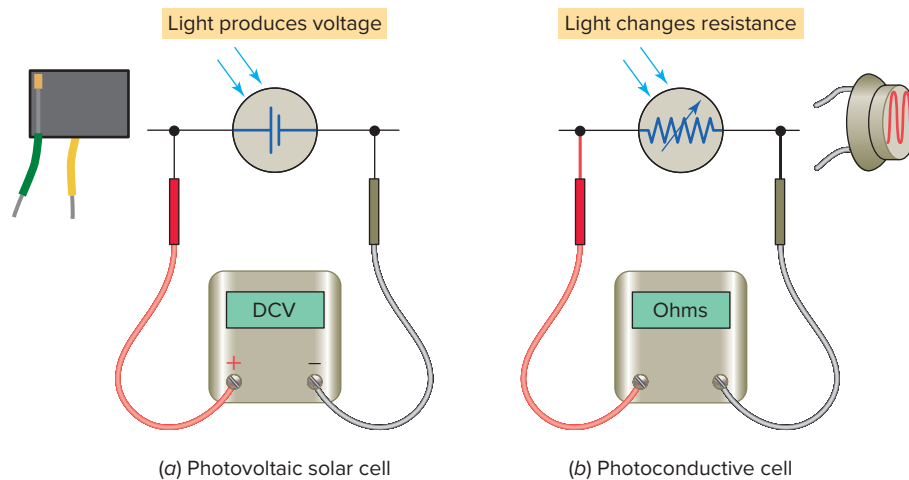
**Figure 6-26** Magnetic reed float switch.

One practical application for a magnetic reed switch is its use in a float switch, illustrated in Figure 6-26. The reed switch opens or closes a circuit as the level of a liquid rises or falls. The switch assembly is made up of a permanent magnet installed within the movable float arm and a magnetic reed switch installed within the fixed housing. The movement of the float, due to the changing liquid level, will cause the reed switch to open or close a circuit at a particular level.

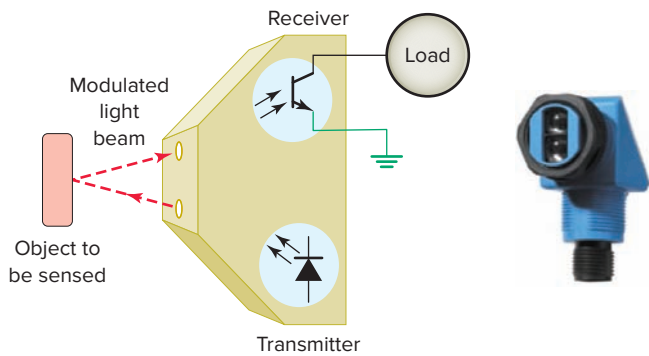
### Light Sensors

The photovoltaic cell and the photoconductive cell, illustrated in Figure 6-27, are two examples of light sensors. The **photovoltaic or solar cell** reacts to light by converting the light energy directly into electric energy. The **photoconductive cell** (also called a **photoresistive cell**) reacts to light by change in the resistance of the cell.

A **photoelectric sensor** is an optical control device that operates by detecting a visible or invisible beam of light and responding to a change in the received light intensity. Photoelectric sensors are composed of two basic components: a transmitter (light source) and a receiver (sensor), as shown in Figure 6-28. These two components may or may not be housed in separate units. The



**Figure 6-27** Photovoltaic and photoconductive light cells.



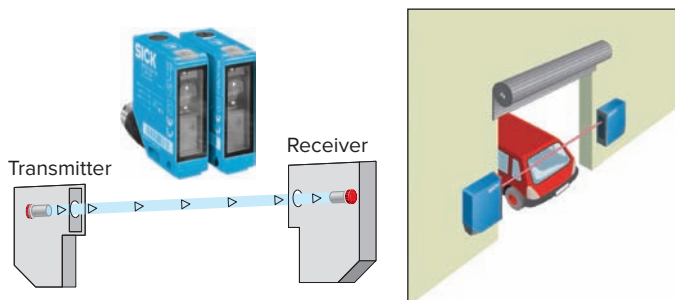
**Figure 6-28** Photoelectric sensor.

Source: Photo courtesy SICK, Inc., [www.sick.com](http://www.sick.com).

basic operation of a photoelectric sensor can be summarized as follows:

- The transmitter contains a light source, usually an LED along with an oscillator.
- The oscillator modulates or turns the LED on and off at a high rate of speed.
- The transmitter sends this modulated light beam to the receiver.
- The receiver decodes the light beam and switches the output device, which interfaces with the load.
- The receiver is tuned to its emitter's modulation frequency and will amplify only the light signal that pulses at the specific frequency.
- Most sensors allow adjustment of how much light will cause the output of the sensor to change state.
- Response time is related to the frequency of the light pulses. Response times may become important when an application calls for the detection of very small objects, objects moving at a high rate of speed, or both.

The **scan technique** refers to the method used by photoelectric sensors to detect an object. The *through-beam* scan technique (also called direct scan) places the transmitter and receiver in direct line with each other, as illustrated in Figure 6-29. Because the light beam travels



**Figure 6-29** Through-beam scan.

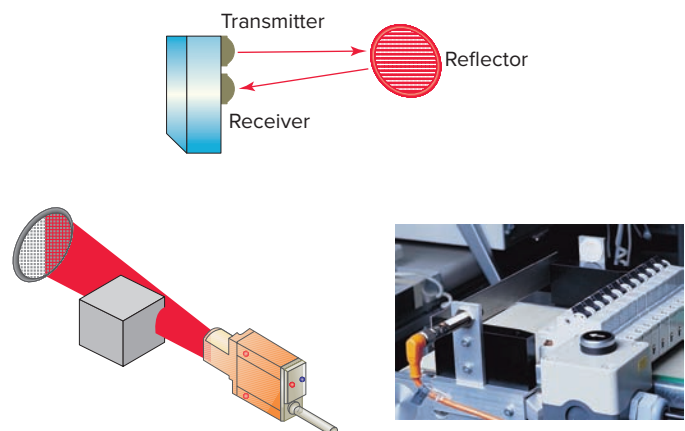
Source: Photo courtesy SICK, Inc., [www.sick.com](http://www.sick.com).

in only one direction, through-beam scanning provides long-range sensing. Quite often, a garage door opener has a through-beam photoelectric sensor mounted near the floor, across the width of the door. For this application the sensor senses that nothing is in the path of the door when it is closing.

In a *retroreflective scan*, the transmitter and receiver are housed in the same enclosure. This arrangement requires the use of a separate reflector or reflective tape mounted across from the sensor to return light back to the receiver. The retroreflective scan is designed to respond to objects that interrupt the beam normally maintained between the transmitter and receiver, as illustrated in Figure 6-30. In contrast to a through-beam application, retroreflective sensors are used for medium-range applications.

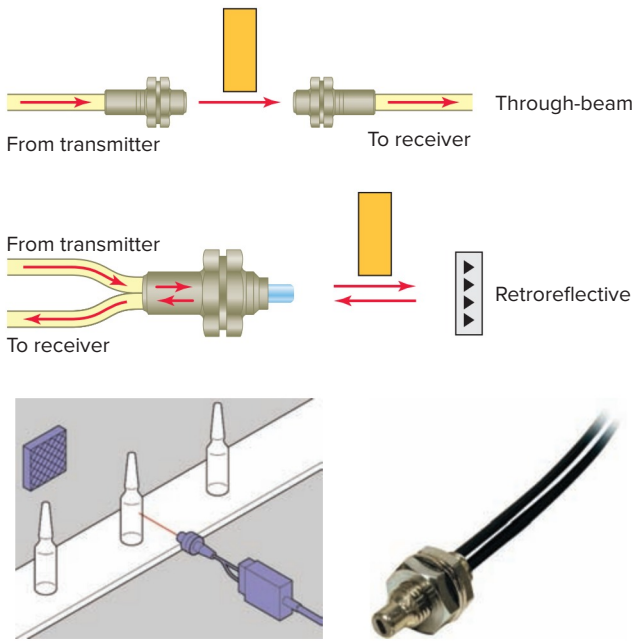
Fiber optics is not a scan technique, but another method for transmitting light. **Fiber optic sensors** use a flexible cable containing tiny fibers that channel light from emitter to receiver, as illustrated in Figure 6-31. Fiber optic sensor systems are completely immune to all forms of electrical interference. The fact that an optical fiber does not contain any moving parts and carries only light means that there is no possibility of a spark. This means that it can be safely used even in the most hazardous sensing environments such as a refinery for producing gases, grain bins, mining, pharmaceutical manufacturing, and chemical processing.

**Bar code** technology is widely implemented in industry to enter data quickly and accurately. **Bar code scanners** are the eyes of the data collection system. A light source within the scanner illuminates the bar code symbol; those bars absorb light, and spaces reflect light. A photodetector collects this light in the form of an electronic-signal pattern representing the printed symbol. The decoder receives the signal from the scanner and converts these data into the character data representation



**Figure 6-30** Retroreflective scan.

Source: Photo courtesy ifm efector, [www.ifm.com/us](http://www.ifm.com/us).



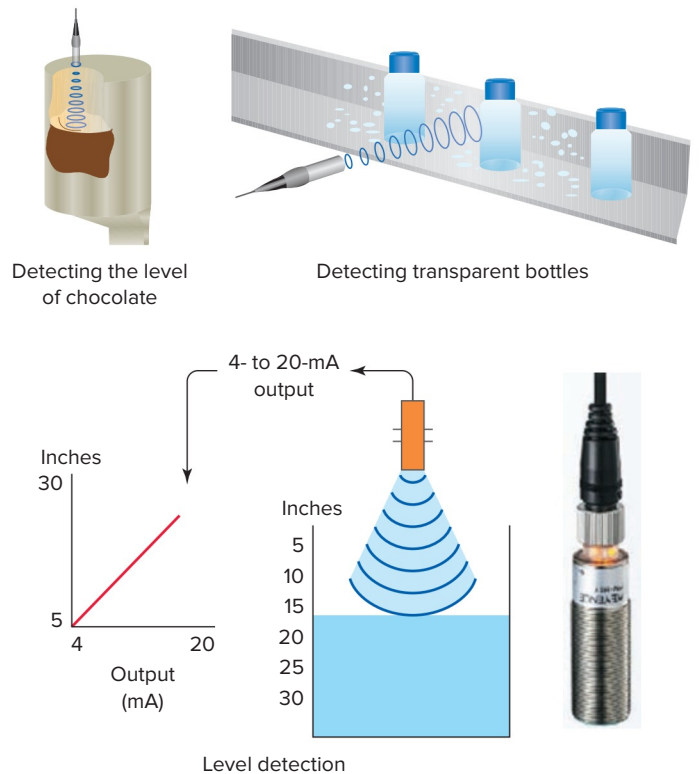
**Figure 6-31** Fiber optic sensors.  
Source: Photo courtesy Omron Industrial Automation, [www.ia.omron.com](http://www.ia.omron.com).

of the symbol's code. Figure 6-32 illustrates a typical PLC application which involves a bar code module reading the bar code on boxes as they move along a conveyor line. The PLC is then used to divert the boxes to the appropriate product lines according to the data read from the bar code.

### Ultrasonic Sensors

An *ultrasonic sensor* operates by sending high-frequency sound waves toward the target and measuring the time it takes for the pulses to bounce back. The time taken for this echo to return to the sensor is directly proportional to the distance or height of the object because sound has a constant velocity.

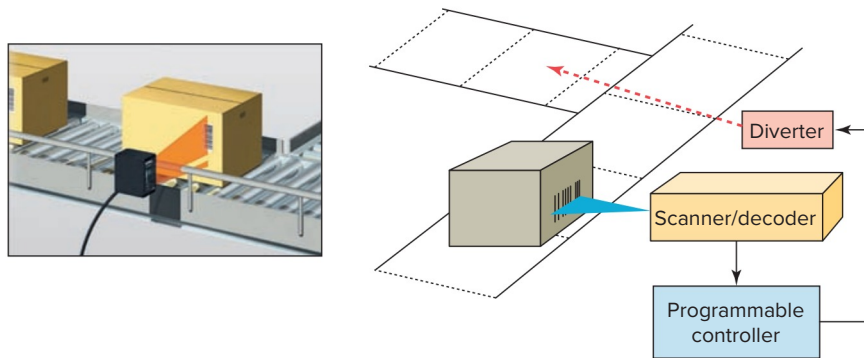
Figure 6-33 illustrates a practical application in which the returning echo signal is electronically converted to a 4- to 20-mA output, which supplies a monitored flow rate



**Figure 6-33** Ultrasonic sensor.  
Source: Courtesy Keyence Canada, Inc.

to external control devices. The operation of this process can be summarized as follows:

- The 4- to 20-mA mA represents the sensor's measurement span.
- The 4-mA set point is typically placed near the bottom of the empty tank, or the greatest measurement distance from the sensor.
- The 20-mA set point is typically placed near the top of the full tank, or the shortest measurement distance from the sensor.
- The sensor will proportionately generate a 4-mA signal when the tank is empty and a 20-mA signal when the tank is full.



**Figure 6-32** PLC bar code application.  
Source: Courtesy Keyence Canada, Inc.

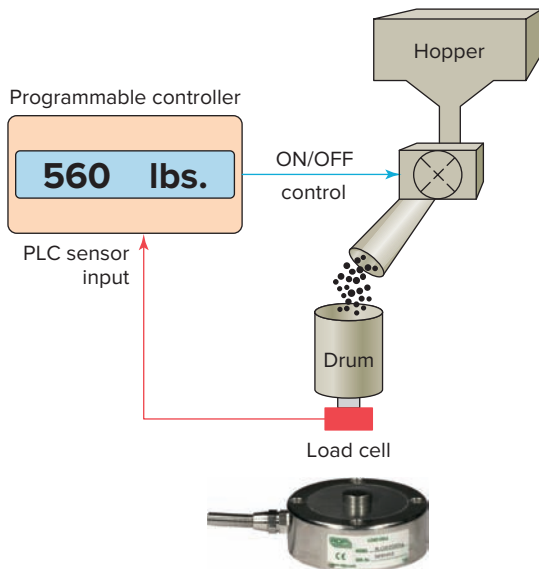
- Ultrasonic sensors can detect solids, fluids, granular objects, and textiles. In addition, they enable the detection of different objects irrespective of color and transparency and therefore are ideal for monitoring transparent objects.

## Strain/Weight Sensors

A *strain gauge* converts a mechanical strain into an electric signal. Strain gauges are based on the principle that the resistance of a conductor varies with length and cross-sectional area. The force applied to the gauge causes the gauge to bend. This bending action also distorts the physical size of the gauge, which in turn changes its *resistance*. This resistance change is fed to a bridge circuit that detects small changes in the gauge's resistance. *Strain gauge load cells* are usually made with steel and sensitive strain gauges. As the load cell is loaded, the metal elongates or compresses very slightly. The strain gauge detects this movement and translates it to a varying voltage signal. Many sizes and shapes of load cells are available, and they range in sensitivity from grams to millions of pounds. Strain gauge-based load cells are used extensively for industrial weighing applications similar to the one illustrated in Figure 6-34.

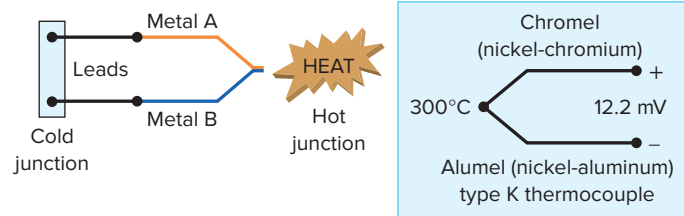
## Temperature Sensors

The thermocouple is the most widely used temperature sensor. Thermocouples operate on the principle that when two dissimilar metals are joined, a predictable DC voltage will be generated that relates to the difference in temperature between the hot junction and the cold junction (Figure 6-35). The hot junction (measuring junction) is the joined end of a thermocouple that is exposed to the process where the temperature measurement is desired. The cold junction (reference



**Figure 6-34** Strain gauge load cell.

Source: Courtesy RDP Group.



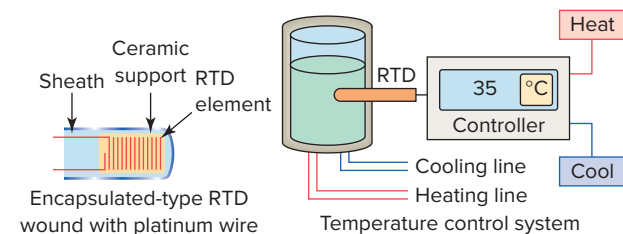
**Figure 6-35** Thermocouple temperature sensor.

Source: Photo courtesy Omron Industrial Automation, [www.ia.omron.com](http://www.ia.omron.com).

junction) is the end of a thermocouple that is kept at a constant temperature to provide a reference point. For example, a K-type thermocouple, when heated to a temperature of 300°C at the hot junction, will produce 12.2 mV at the cold junction. Because of their ruggedness and wide temperature range, thermocouples are used in industry to monitor and control oven and furnace temperatures. Thermocouples produce a relative low output signal that is nonlinear. As a result, accurate thermocouple measurements need signal conditioning modules with outputs, which are linearly scaled to temperature.

**Resistance temperature detectors (RTDs)** are wire-wound temperature-sensing devices that operate on the principle of the positive temperature coefficient (PTC) of metals. That means the electrical resistance of metals is directly proportional to temperature. The hotter they become, the larger or higher the value of their electrical resistance. This proportional variation is precise and repeatable, and therefore allows the consistent measurement of temperature through electrical resistance detection. Platinum is the material most often used in RTDs because of its superiority regarding temperature limit, linearity, and stability.

RTDs are among the most precise temperature sensors available and are normally found encapsulated in probes for external temperature sensing and measurement or enclosed inside devices where they measure temperature as a part of the device's function. Figure 6-36 illustrates how



**Figure 6-36** Resistance temperature detector (RTD).

an RTD is used as part of a temperature control system. A controller uses the signal from the RTD sensor to monitor the temperature of the liquid in the tank and thereby control heating and cooling lines.

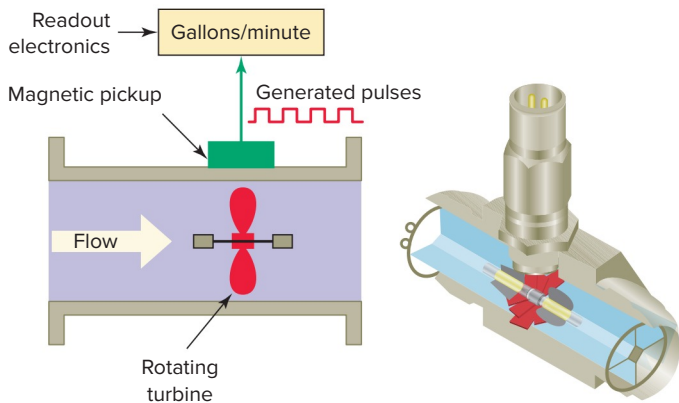
## Flow Measurement

Many industrial processes depend on accurate measurement of fluid flow. Although there are several ways to measure fluid flow, the usual approach is to convert the kinetic energy that the fluid has into some other measurable form.

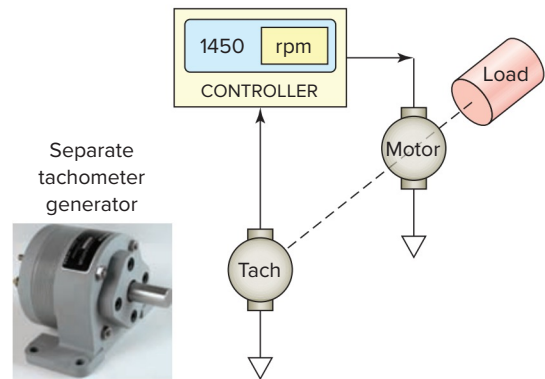
*Turbine-type flowmeters* are a popular means of measurement and control of liquid products in industrial, chemical, and petroleum operations. Turbine flowmeters, like windmills, utilize their angular velocity (rotation speed) to indicate the flow velocity. The operation of a turbine flowmeter is illustrated in Figure 6-37. Its basic construction consists of a bladed turbine rotor installed in a flow tube. The bladed rotor rotates on its axis in proportion to the rate of the liquid flow through the tube. A magnetic pickup sensor is positioned as close to the rotor as practical. Fluid passing through the flow tube causes the rotor to rotate, which generates pulses in the pickup coil. The frequency of the pulses is then transmitted to readout electronics and displayed as gallons per minute.

## Velocity and Position Sensors

*Tachometer generators* provide a convenient means of converting rotational speed into an analog voltage signal that can be used for motor speed indication and control applications. A tachometer generator is a small AC or DC generator that develops an output voltage (proportional to its rpm) whose phase or polarity depends on the rotor's direction of rotation. The DC tachometer generator usually has permanent magnetic field excitation. The AC tachometer generator field is excited by



**Figure 6-37** Turbine type flowmeter.



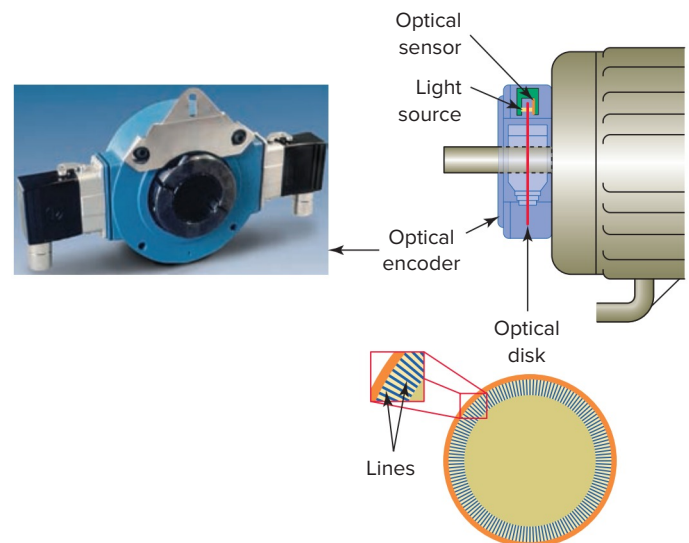
**Figure 6-38** Tachometer generator feedback.

Source: Courtesy ATC Digitec.

a constant AC supply. In either case, the rotor of the tachometer is mechanically connected, directly or indirectly, to the load.

Figure 6-38 illustrates motor speed control applications in which a tachometer generator is used to provide a feedback voltage to the motor controller that is proportional to motor speed. The control motor and tachometer generator may be contained in the same or separate housings.

An *encoder* is used to convert linear or rotary motion into a binary digital signal. Encoders are used in applications where positions have to be precisely determined. The optical encoder illustrated in Figure 6-39 uses a light source shining on an optical disk with lines or slots that interrupt the beam of light to an optical sensor. An electronic circuit counts the interruptions of the beam and generates the encoder's digital output pulses.



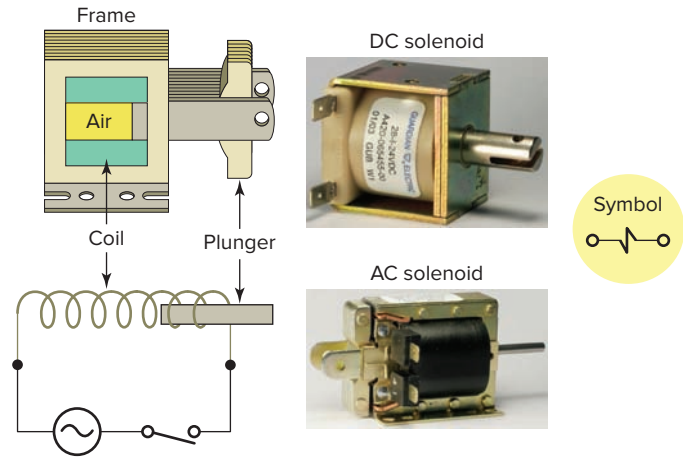
**Figure 6-39** Optical encoder.

Source: Photo courtesy Avtron, [www.avtron.com](http://www.avtron.com).

## 6.7 Output Control Devices

A variety of output control devices can be operated by the PLC output to control traditional industrial processes. These devices include pilot lights, control relays, motor starters, alarms, heaters, solenoids, solenoid valves, small motors, and horns. Similar electrical symbols are used to represent these devices both on relay schematics and PLC output connection diagrams. Figure 6-40 shows common electrical symbols used for various output devices. Although these symbols are generally acceptable, some differences among manufacturers do exist.

An *actuator*, in the electrical sense, is any device that converts an electrical signal into mechanical movement. An electromechanical solenoid is an actuator that uses electrical energy to magnetically cause mechanical control action. A **solenoid** consists of a coil, frame, and plunger (or armature, as it is sometimes called). Figure 6-41 shows the basic construction



**Figure 6-41** Solenoid construction and operation.

Source: Photos courtesy Guardian Electric, [www.guardian-electric.com](http://www.guardian-electric.com).

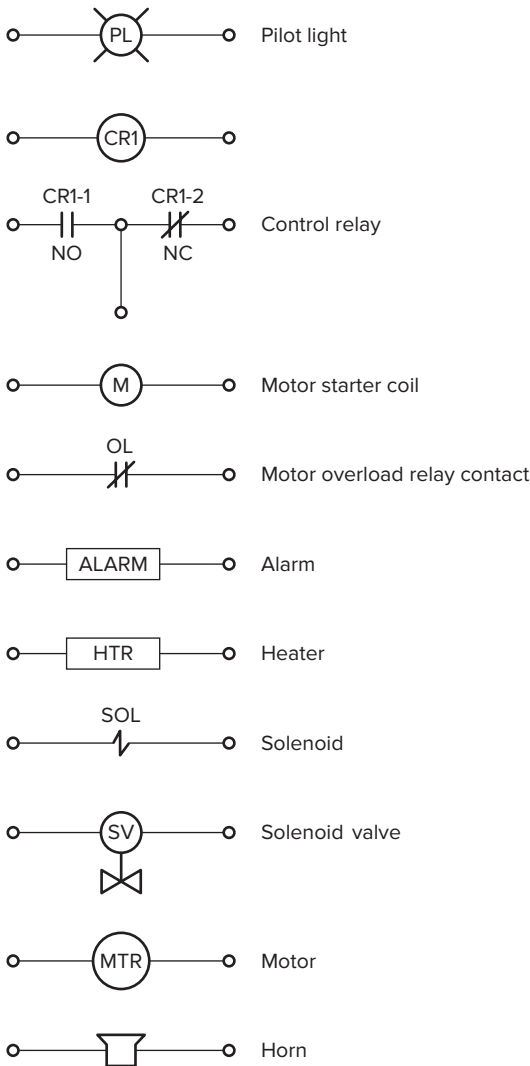
and operation of a solenoid. Its operation can be summarized as follows:

- The coil and frame form the fixed part.
- When the coil is energized, it produces a magnetic field that attracts the plunger, pulling it into the frame and thus creating mechanical motion.
- When the coil is de-energized the plunger returns to its normal position through gravity or assistance from spring assemblies within the solenoid.
- The frame and plunger of an AC-operated solenoid are constructed with laminated pieces instead of a solid piece of iron to limit eddy currents induced by the magnetic field.

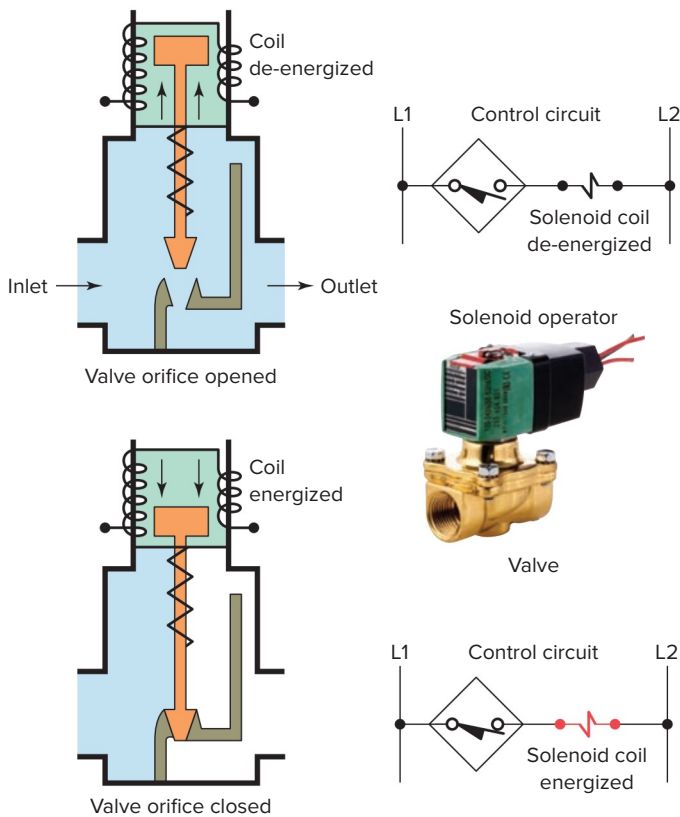
Solenoid valves are electromechanical devices that work by passing an electrical current through a solenoid, thereby changing the state of the valve. Normally, there is a mechanical element, which is often a spring, that holds the valve in its default position. A solenoid valve is a combination of a solenoid coil operator and valve, which controls the flow of liquids, gases, steam, and other media. When electrically energized, they open, shut off, or direct the flow of media.

Figure 6-42 illustrates the construction and principle of operation of a typical fluid solenoid valve. Its operation can be summarized as follows:

- The valve body contains an orifice in which a disk or plug is positioned to restrict or allow flow.
- Flow through the orifice is either restricted or allowed depending on whether the solenoid coil is energized or de-energized.
- When the coil is energized, the core is drawn into the solenoid coil to open the valve.
- The spring returns the valve to its original closed position when the coil is de-energized.



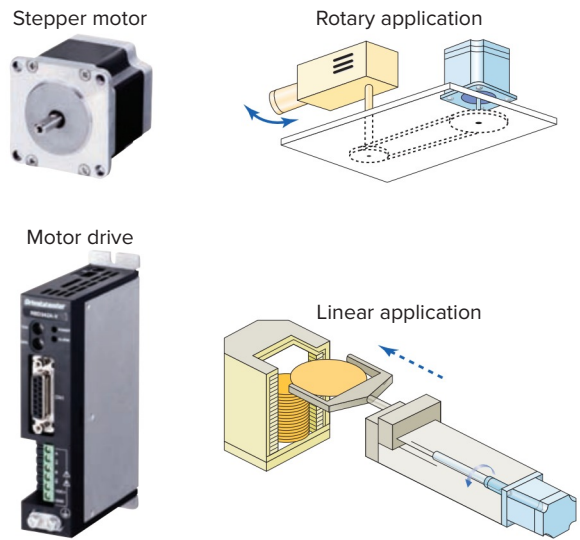
**Figure 6-40** Symbols for output control devices.



**Figure 6-42** Solenoid valve construction and operation.  
Source: Photo courtesy ASCO Valve Inc., [www.ascovalve.com](http://www.ascovalve.com).

- A valve must be installed with direction of flow in accordance with the arrow cast on the side of the valve body.

**Stepper motors** operate differently than standard types, which rotate continuously when voltage is applied to their terminals. The shaft of a stepper motor rotates in discrete increments when electrical command pulses are applied to it in the proper sequence. Every revolution is divided into a number of steps, and the motor must be sent a voltage pulse for each step. The amount of rotation is directly proportional to the number of pulses, and the speed of rotation is relative to the frequency of those pulses. A 1-degree-per-step

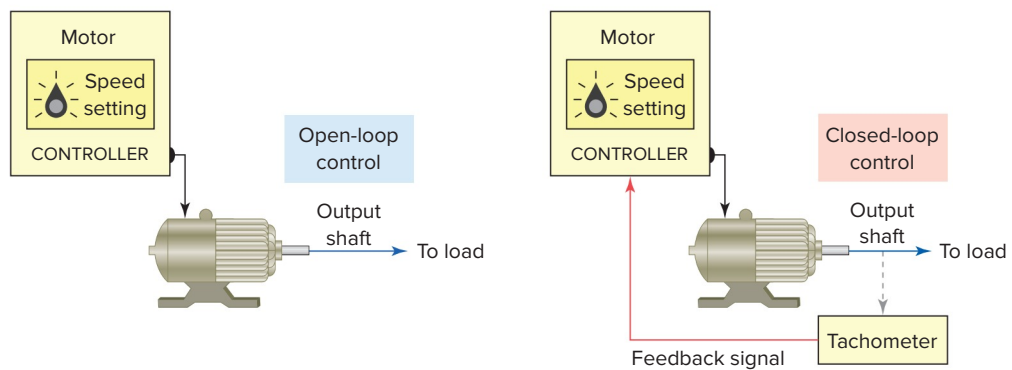


**Figure 6-43** Stepper motor/drive unit.  
Source: Photos courtesy Oriental Motor, [www.orientalmotor.com](http://www.orientalmotor.com).

motor will require 360 pulses to move through one revolution; the degrees per step are known as the **resolution**. When stopped, a stepper motor inherently holds its position. Stepper systems are used most often in “open-loop” control systems, where the controller tells the motor only how many steps to move and how fast to move, but does not have any way of knowing what position the motor is at.

The movement created by each pulse is precise and repeatable, which is why stepper motors are so effective for load-positioning applications. Conversion of rotary to linear motion inside a linear actuator is accomplished through a threaded nut and lead screw. Generally, stepper motors produce less than 1 hp and are therefore frequently used in low-power position control applications. Figure 6-43 shows a stepper motor/drive unit along with typical rotary and linear applications.

All **servo motors** operate in closed-loop mode, whereas most stepper motors operate in open-loop mode. Closed-loop and open-loop control schemes are illustrated in Figure 6-44. **Open loop** is control



**Figure 6-44** Open- and closed-loop motor control systems.

without feedback, for example, when the controller tells the stepper motor how many steps to move and how fast to move, but does not verify where the motor is. **Closed-loop** control compares speed or position feedback with the commanded speed or position and generates a modified command to make the error smaller. The error is the difference between the required speed or position and the actual speed or position.

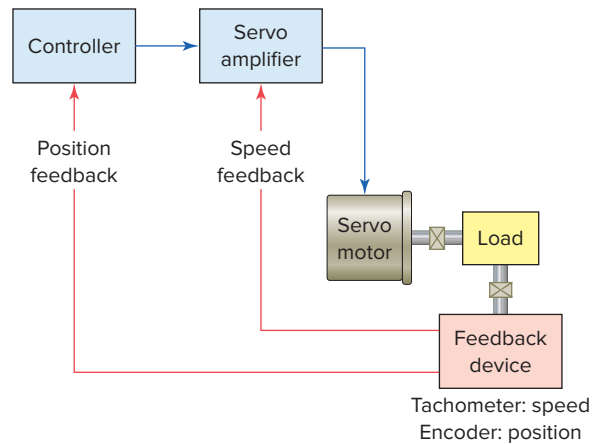
Figure 6-45 illustrates a closed-loop servo motor system. The motor controller directs operation of the servo motor by sending speed or position command signals to the amplifier, which drives the servo motor. A feedback device such as an encoder for position and a tachometer for speed are either incorporated within the servo motor or are remotely mounted, often on the load itself. These provide the servo motor's position and speed feedback information that the controller compares to its programmed motion profile and uses to alter its position or speed.

## 6.8 Seal-In Circuits

**Seal-in**, or **holding**, circuits are very common in both relay logic and PLC logic. Essentially, a seal-in circuit is a method of maintaining current flow after a momentary switch has been pressed and released. In these types of circuits, the seal-in contact is usually in parallel with the momentary device.



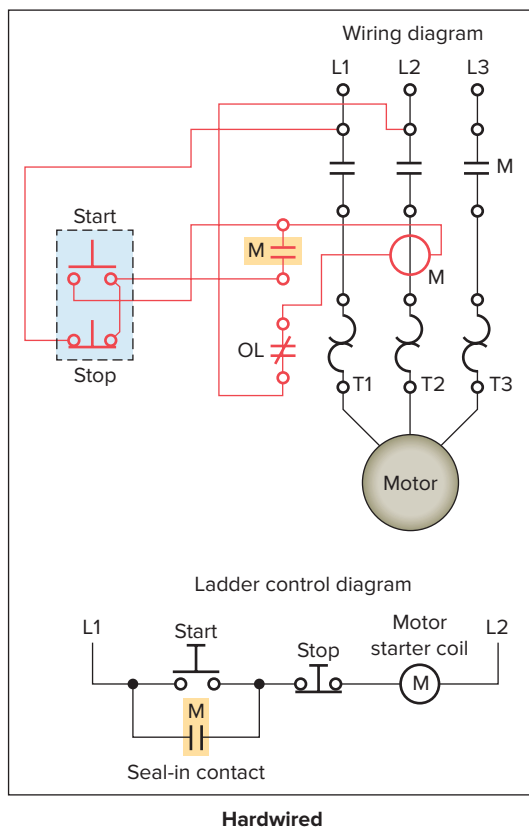
Motor/controller



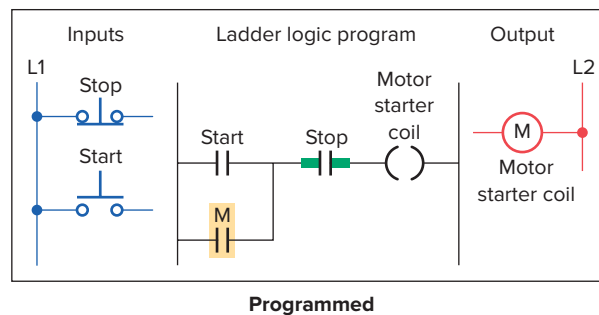
**Figure 6-45** Closed-loop servo motor system.

Source: Photos courtesy Omron Industrial Automation, [www.ia.omron.com](http://www.ia.omron.com).

The motor stop/start circuit shown in Figure 6-46 is a typical example of a seal-in circuit. The hardwired circuit consists of a normally closed stop button in series with a normally open start button. The seal-in auxiliary contact of the starter is connected in parallel with the start button to keep the starter coil energized when the start button is

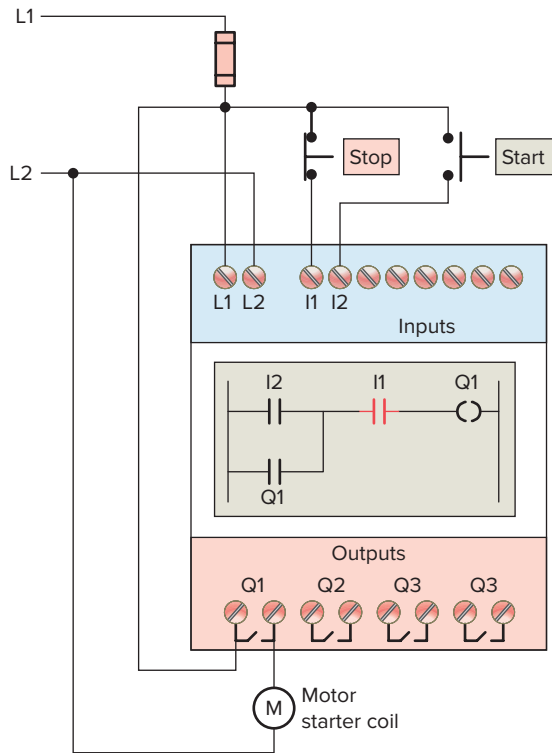


Hardwired



Programmed

**Figure 6-46** Hardwired and programmed seal-in circuit.



**Figure 6-47** Motor seal-in circuit implemented using an Allen-Bradley Pico controller.

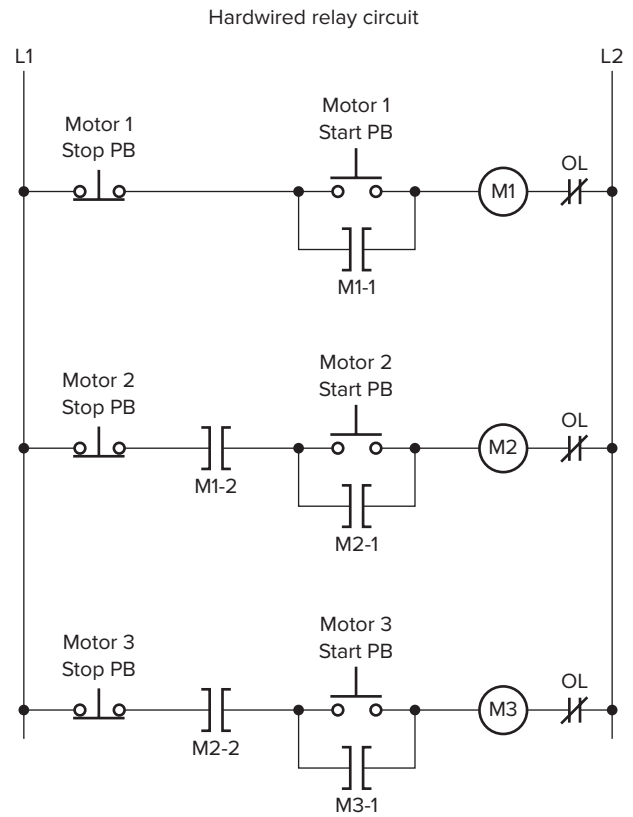
released. When this circuit is programmed into a PLC, both the start and stop buttons are examined for a closed condition because both buttons must be closed to cause the motor starter to operate.

Figure 6-47 shows a PLC wiring diagram of the motor seal-in circuit implemented using an Allen-Bradley Pico controller. The controller is programmed using ladder logic. Each programming element can be entered directly via the Pico display. This controller also lets you program the circuit from a personal computer using PicoSoft programming software.

## 6.9 Electrical Interlocking Circuits

An electrical interlocking circuit is used to prevent a piece of equipment from operating under certain potentially hazardous or undesirable conditions. Figure 6-48 shows a three motor hardwired relay control circuit electrically interlocked to prevent the motors from accidentally operating in an order other than their proper sequence. The interlocking feature of the circuit can be summarized as follows:

- Motor 1 has to be operating before Motor 2 can be started.
- The NO auxiliary interlocking contact M1-2 is used for this purpose.



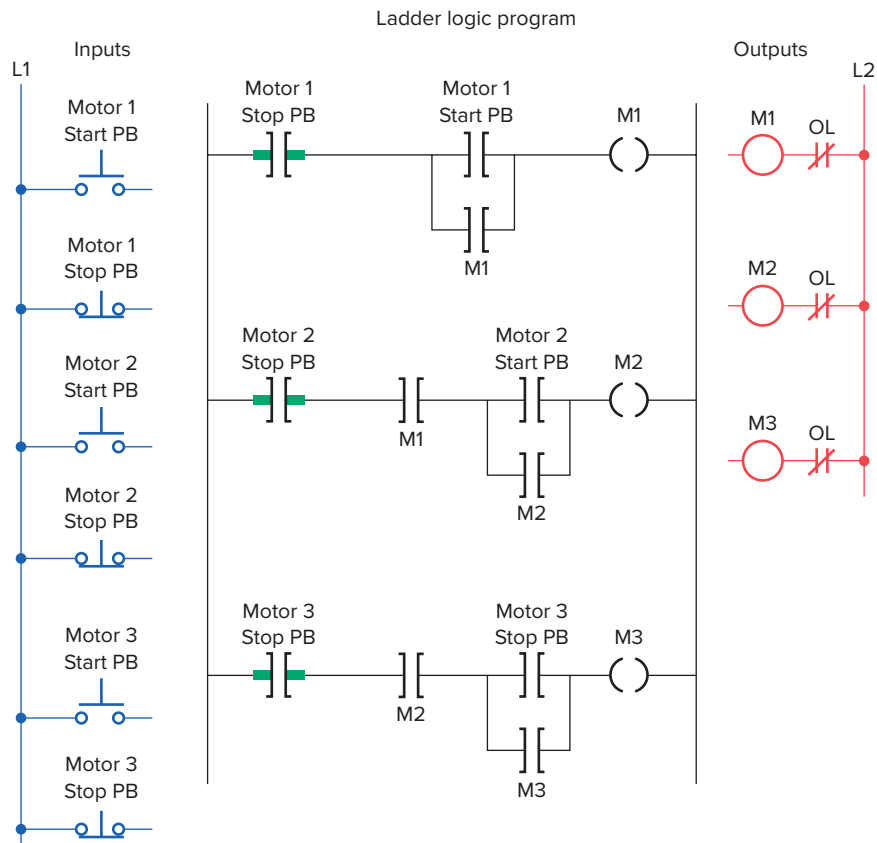
**Figure 6-48** Sequential hardwired three motor relay control circuit.

- Motor 2 has to be operating before Motor 3 can be started.
- The NO auxiliary interlocking contact M2-2 is used for this purpose.

Figure 6-49 shows a PLC program equivalent of the hardwired circuit.

Pushbutton interlocking is one of the methods of preventing two loads from being energized simultaneously. The hardwired pushbutton interlocking circuit of Figure 6-50 is designed to prevent solenoids SOL-A and SOL-B from being energized at the same time. The interlocking feature of the circuit can be summarized as follows:

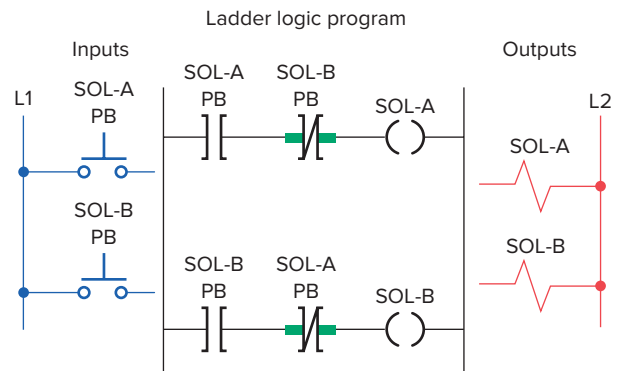
- Each pushbutton is equipped with a set of momentarily normally open (NO) and normally closed (NC) contacts mechanically connected together.
- The NC contact of SOL-A pushbutton is connected in series with the NO contact of SOL-B pushbutton.
- The NO contact of SOL-A pushbutton is connected in series with the NC contact of SOL-B pushbutton.



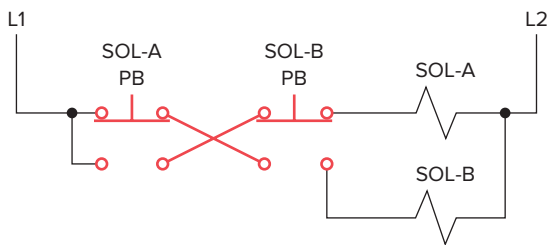
**Figure 6-49** PLC program equivalent of the hardwired sequential motor control circuit.

- When SOL-A pushbutton is pressed its NO contact completes the circuit to SOL-A and its NC contacts opens the current path to SOL-B.
- When SOL-B pushbutton is pressed its NO contact completes the circuit to SOL-B and its NC contacts opens the current path to SOL-A.
- When both buttons are pushed, neither solenoid will be energized.

Figure 6-51 shows a PLC program equivalent of the hardwired circuit implemented using two NO pushbuttons.



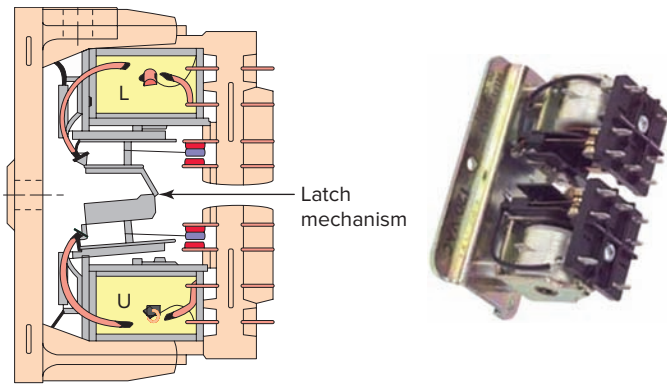
**Figure 6-51** PLC program equivalent of the hardwired pushbutton interlocking circuit.



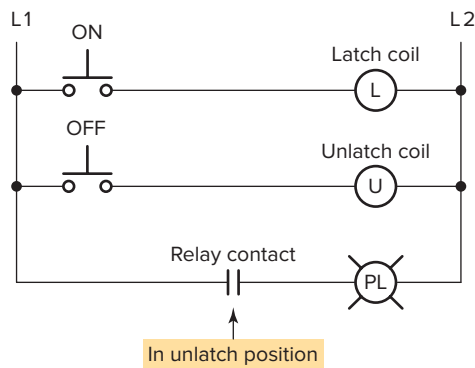
**Figure 6-50** Hardwired pushbutton interlocking circuit.

## 6.10 Latching Relays

Electromagnetic **latching relays** are designed to hold the relay closed after power has been removed from the coil. Latching relays are used where it is necessary for contacts to stay open and/or closed even though the coil is energized only momentarily. Figure 6-52 shows a latching relay that uses two coils. The **latch** coil is momentarily energized to set the latch and hold the relay in the latched



**Figure 6-52** Two-coil mechanical latching relay.  
Source: Courtesy Relay Service Company.



**Figure 6-53** Hardwired control circuit for an electromagnetic latching relay.

position. The **unlatch** or release coil is momentarily energized to disengage the mechanical latch and return the relay to the unlatched position.

Figure 6-53 shows a hardwired control circuit for an electromagnetic latching relay. The operation of the circuit can be summarized as follows:

- The contact is shown with the relay in the *unlatched* position.
- In this state the circuit to the pilot light is open and so the light is off.

- When the ON button is *momentarily* actuated, the latch coil is energized to set the relay to its latched position.
- The contacts close, completing the circuit to the pilot light, and so the light is switched on.
- The relay coil does *not* have to be continuously energized to hold the contacts closed and keep the light on.
- The only way to switch the lamp off is to actuate the OFF button, which will energize the unlatch coil and return the contacts to their open, unlatched state.
- In cases of power loss, the relay will remain in its original latched or unlatched state when power is restored.

An electromagnetic latching relay function can be programmed on a PLC to work like its real-world counterparts. The instruction set for the SLC 500 includes a set of output instructions that duplicates the operation of the mechanical latch. A description of the output latch (**OTL**) and output unlatch (**OTU**) instruction is given in Figure 6-54. The OTL and OTU instructions differ from the OTE instruction in that they must be used together. Both the latch and unlatch outputs must have the same address. The OTL (latch) instruction can only turn a bit on and the OTU (unlatch) instruction can only turn a bit off.

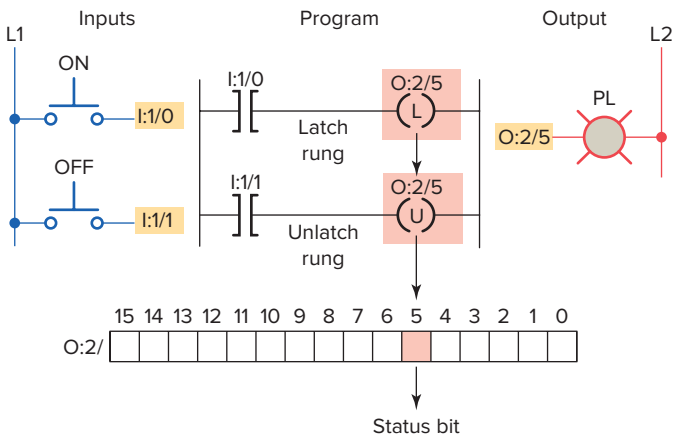
The operation of the output latch and output unlatch coil instruction is illustrated in the ladder program of Figure 6-55. The operation of the program can be summarized as follows:

- Both the latch (L) and the unlatch (U) coil have the *same* address (O:2/5).
- When the on pushbutton (I:1/0) is momentarily actuated, the latch rung becomes true and the latch status bit (O:2/5) is set to 1, and so the light output is switched on.

Command	Name	Symbol	Description
<b>OTL</b>	Output latch	(L)	OTL sets the bit to "1" when the rung becomes true and retains its state when the rung loses continuity or a power cycle occurs.
<b>OTU</b>	Output unlatch	(U)	OTU resets the bit to "0" when the rung becomes true and retains it.



**Figure 6-54** Output latch and output unlatch instruction.



**Figure 6-55** Output latch and output unlatch operation.

- The status bit *will remain set to 1* when the pushbutton is released and logical continuity of the latch rung is lost.
- When the off pushbutton (I:1/1) is momentarily actuated, the unlatch rung becomes true and the latch status bit (O:2/5) is reset back to 0 and so the light is switched off.
- The status bit *will remain reset to 0* when the pushbutton is released and logical continuity of the latch rung is lost.

Output latch is an output instruction with a bit-level address. When the instruction is true, it sets a bit in the output image file. It is a retentive instruction because the bit remains set when the latch instruction goes false. In most applications it is used with an unlatch instruction. The output unlatch instruction is also an output instruction with a bit-level address. When the instruction is true, it resets a bit in the output image file. It, too, is a retentive instruction because the bit remains reset when the instruction goes false.

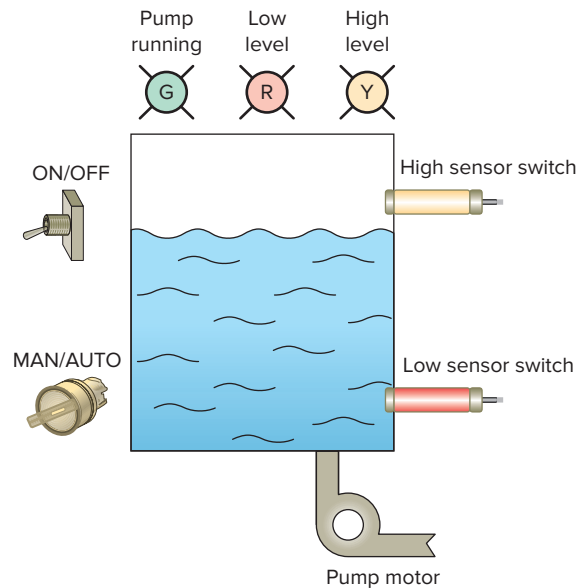
The process shown in Figure 6-56 is to be used to control the level of water in a storage tank by turning a discharge pump on or off. The modes of operation are to be programmed as follows:

**OFF Position**—The water pump will *stop* if it is running and will *not* start if it is stopped.

**Manual Mode**—The pump will start if the water in the tank is at any level except low.

**Automatic Mode**—If the level of water in the tank *reaches a high point*, the water pump will *start* so that water can be removed from the tank, thus lowering the level.

- When the water level *reaches a low point*, the pump will *stop*.

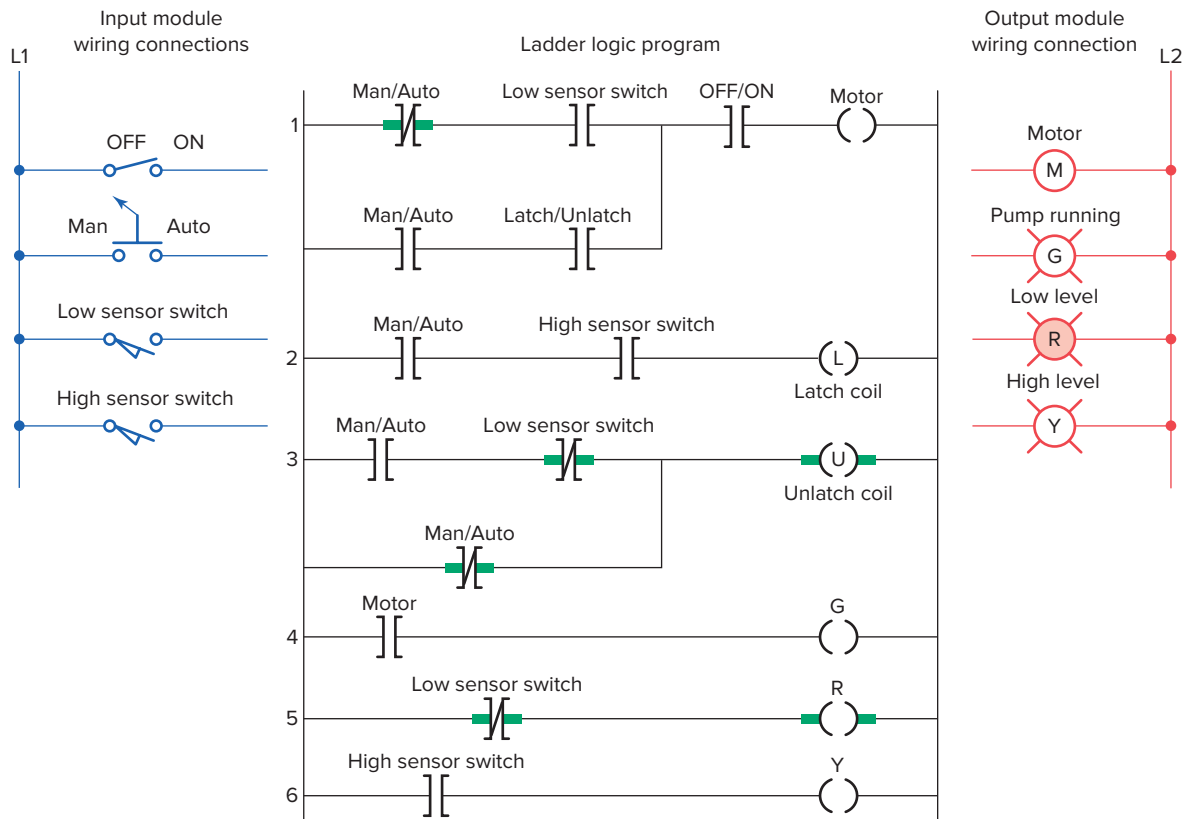


**Figure 6-56** Process used to control the level of water in a storage tank.

- Status Indicating Lights**—Water pump running light (green)
- Low water level status light (red)
  - High water level status light (yellow)

Figure 6-57 shows a program that can be used to implement control of the water level in the storage tank. The latch and unlatch instructions form part of the program. The operation of the program can be summarized as follows:

- An internal storage bit is used for the latch and address rather than an actual discrete output address. Both have the same addresses.
- The rung 1 Examine-on instruction addressed to the off/on switch prevents the pump motor from starting under any condition when in the off (open) state.
- In the MAN mode, the rung 1 Examine-on instruction addressed to the low sensor switch allows the pump motor to operate only when the low level sensor switch is closed.
- In the AUTO mode, whenever the high sensor switch is momentarily closed the Examine-on instruction of rung 1 addressed to it will energize the latch coil. The pump will begin running and continue to operate until the unlatch coil is energized by the rung 3 Examine-off instruction addressed to the low sensor switch.
- The pump running status light is controlled by the rung 4 Examine-on instruction addressed to the motor output.



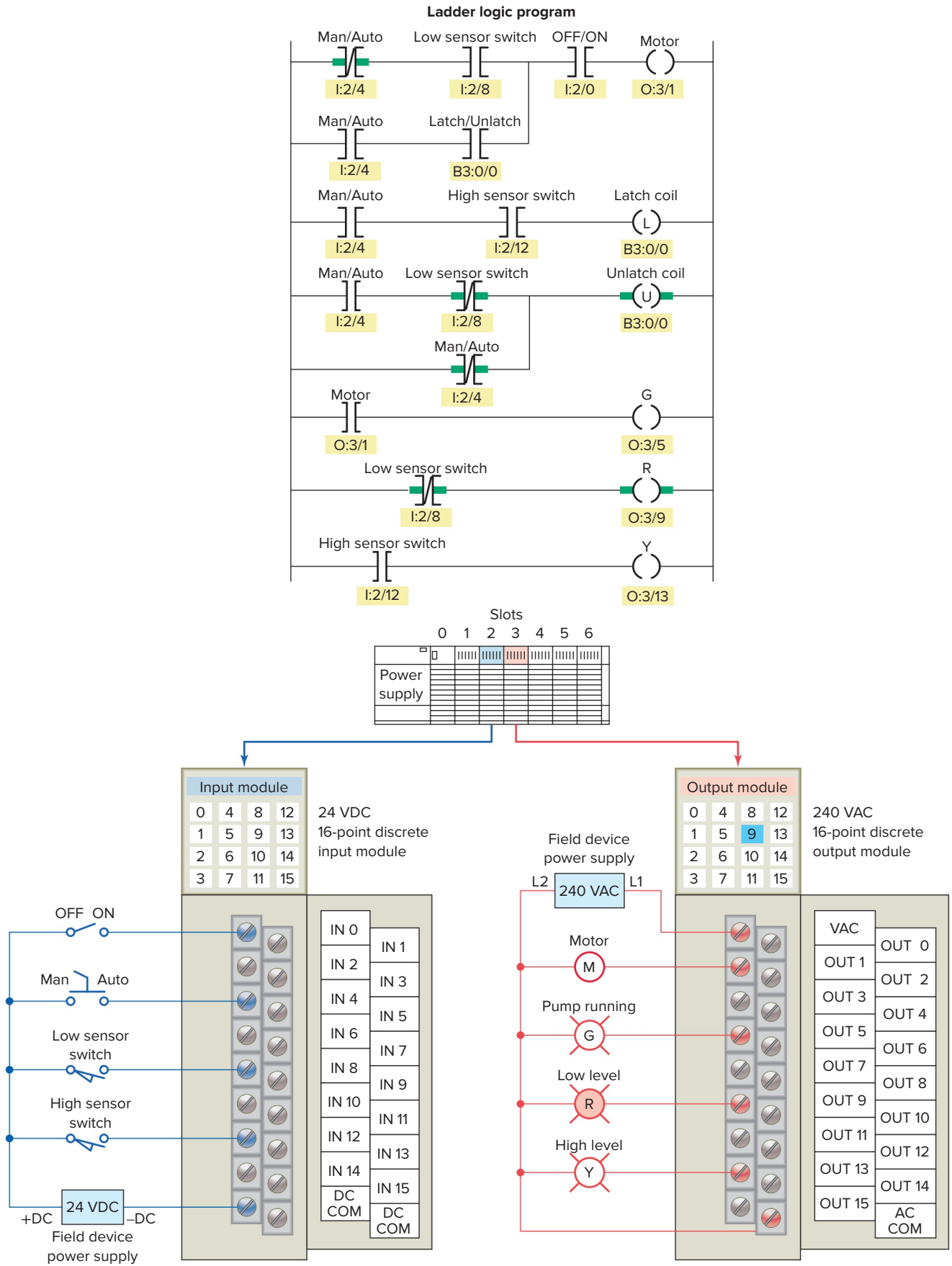
**Figure 6-57** Program used to implement control of the water level in the storage tank.

- The low-level status light is controlled by the rung 5 Examine-off instruction addressed to the low sensor switch.
- The high-level status light is controlled by the rung 6 Examine-on instruction addressed to the high sensor switch.

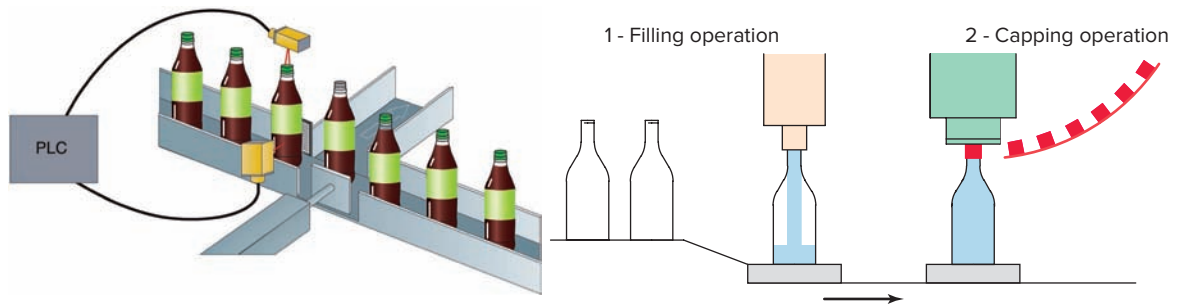
Figure 6-58 shows a typical I/O module wiring diagram and addressing format for the water level control program implemented using an Allen-Bradley modular SLC 500 controller. The chassis power supply has a

relatively small power rating and is used to supply DC power to all devices physically mounted in the backplane of the PLC rack. In this application a 24 VDC field power supply is used for the input devices and a 120 VAC field power supply for the output devices. This allows a low-voltage 24-volt control signal to control 240-volt output devices. SLC 500 controllers use a rack/slot-based address system where the slot location of the I/O modules in the rack establishes the PLC address. The addresses for the field devices of this particular application are shown below:

FIELD DEVICE	ADDRESS	Signifies
OFF/ON Switch	I:2/0	The input module in slot 2 and screw terminal 0
MAN/AUTO Switch	I:2/4	The input module in slot 2 and screw terminal 4
LOW SENSOR Switch	I:2/8	The input module in slot 2 and screw terminal 8
HIGH SENSOR Switch	I:2/12	The input module in slot 2 and screw terminal 12
MOTOR	O:3/1	The output module in slot 3 and screw terminal 1
PUMP RUNNING Light	O:3/5	The output module in slot 3 and screw terminal 5
LOW LEVEL Light	O:3/9	The output module in slot 3 and screw terminal 9
HIGH LEVEL Light	O:3/13	The output module in slot 3 and screw terminal 13
	B3:0/0	Internal retentive bit instruction that does not drive a real-word device



**Figure 6-58** Water-level control program implemented using an Allen-Bradley modular SLC 500 controller.



**Figure 6-59** Sequential control process.  
Source: Photo courtesy Omron Industrial Automation, [www.ia.omron.com](http://www.ia.omron.com).

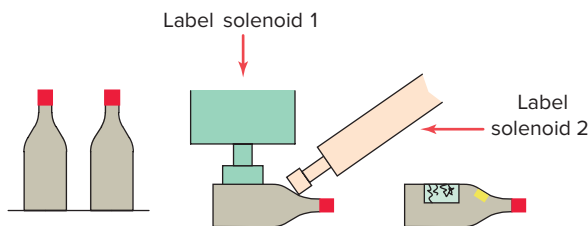
## 6.11 Converting Relay Schematics into PLC Ladder Programs

The best approach to developing a PLC program from a relay schematic is to understand first the operation of each relay ladder rung. As each relay ladder rung is understood, an equivalent PLC rung can be generated. This process will require access to the relay schematic, documentation of the various input and output devices used, and possibly a process flow diagram of the operation.

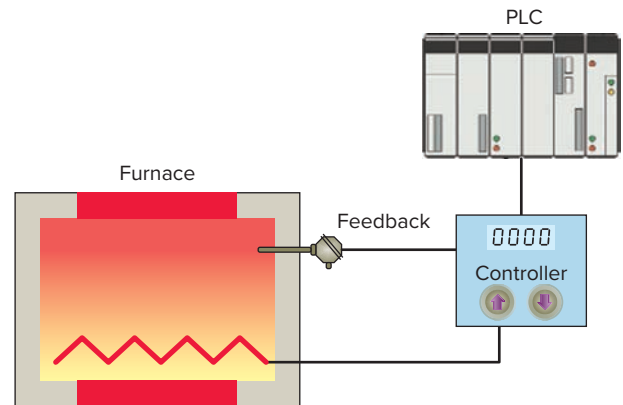
Most control processes require the completion of several operations to produce the required output. Manufacturing, machining, assembling, packaging, finishing, or transporting of products requires the precise coordination of tasks.

A **sequential** control process is required for processes that demand that certain operations be performed in a specific order. Figure 6-59 illustrates part of a bottle filling process. In the filling and capping operations, the tasks are (1) fill bottle and (2) press on cap. These tasks must be performed in the proper order. Obviously we could not fill the bottle after the cap is pressed on. This process, therefore, requires sequential control.

**Combination** controls require that certain operations be performed without regard to the order in which they are performed. Figure 6-60 illustrates another part of the same bottle filling process. Here, the tasks are (1) place label 1 on bottle and (2) place label 2 on bottle. The order in which the tasks are performed does not really matter. In fact, however, many industrial processes that are not inherently sequential in nature are performed in a sequential manner for the most efficient order of operations.



**Figure 6-60** Combination control process.

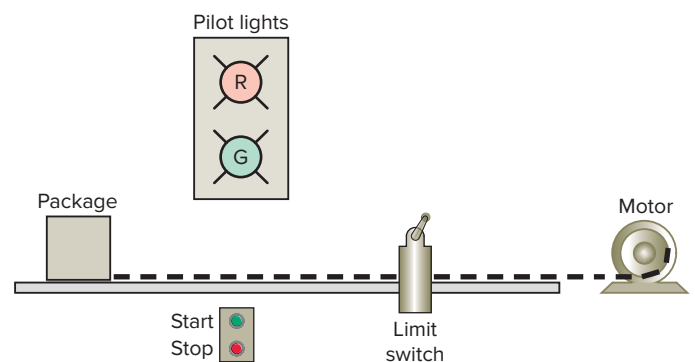


**Figure 6-61** Automatic control process.

**Automatic** control involves maintaining a desired set point at an output. One example is maintaining a certain set-point temperature in a furnace as illustrated in Figure 6-61. If there is deviation from that set point, an error is determined by comparing the output against the set point and using this error to make a correction. This requires feedback from the output to the control for the input.

The converting of a simple sequential process can be examined with reference to the process flow diagram illustrated in Figure 6-62. The sequential task is as follows:

1. Start button is pressed.
2. Table motor is started.



**Figure 6-62** Sequential process flow diagram.

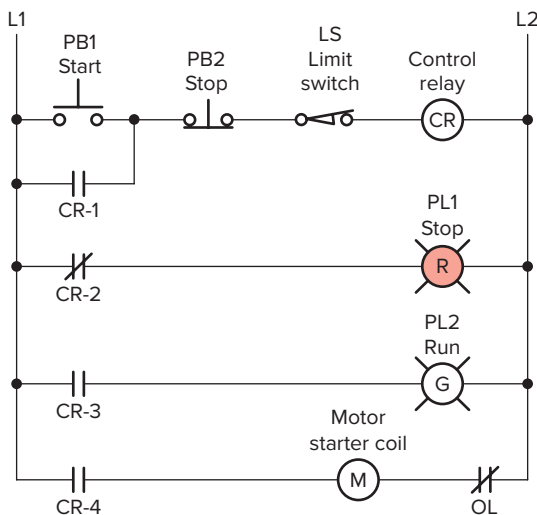
- Package moves to the position of the limit switch and automatically stops.

Other auxiliary features include:

- a stop button that will stop the table, for any reason, before the package reaches the limit switch position;
- a red pilot light to indicate the table is stopped; and
- a green pilot light to indicate the table is running.

A relay schematic for the sequential process is shown in Figure 6-63. The operation of this hardwired circuit can be summarized as follows:

- Start button is actuated; CR is energized if stop button and limit switch are not actuated.
- Contact CR-1 closes, sealing in CR when the start button is released.
- Contact CR-2 opens, switching the red pilot light from on to off.
- Contact CR-3 closes, switching the green pilot light from off to on.
- Contact CR-4 closes to energize the motor starter coil, starting the motor and moving the package toward the limit switch.
- Limit switch is actuated, de-energizing relay coil CR.
- Contact CR-1 opens, opening the seal-in circuit.
- Contact CR-2 closes, switching the red pilot light from off to on.
- Contact CR-3 opens, switching the green pilot light from on to off.
- Contact CR-4 opens, de-energizing the motor starter coil to stop the motor and end the sequence.



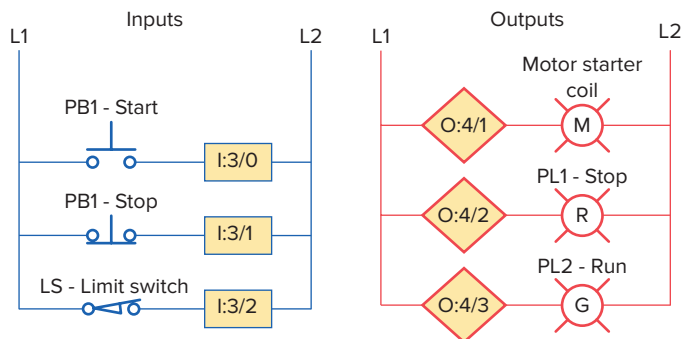
**Figure 6-63** Relay schematic for the sequential process.

Figure 6-64 shows an I/O connection diagram for a programmed version of the sequential process. Each input and output device is represented by its symbol and associated address. These addresses will indicate what PLC input is connected to what input device and what PLC output will drive what output device. The address code, of course, will depend on the PLC model used. This example uses SLC 500 addressing for the process. Note that the electromagnetic control relay CR is *not* needed because its function is replaced by an *internal* PLC control relay.

The hardwired relay schematic for the sequential process can be converted to the PLC ladder logic program shown in Figure 6-65. In converting the process to a program the operation of each rung must be understood. The pushbuttons PB1, PB2 as well as limit switch LS are all programmed using the examine-closed (–) [–] instruction to produce the desired logic control. Also, internal relay B3:1/0 is used to replace control relay CR. To obtain the desired control logic, all internal relay contacts are programmed using the PLC contact instruction that matches the coil de-energized state. The internal relay implemented in software requires one coil address the contacts of which can be examined for an ON or OFF condition as many times as you like.

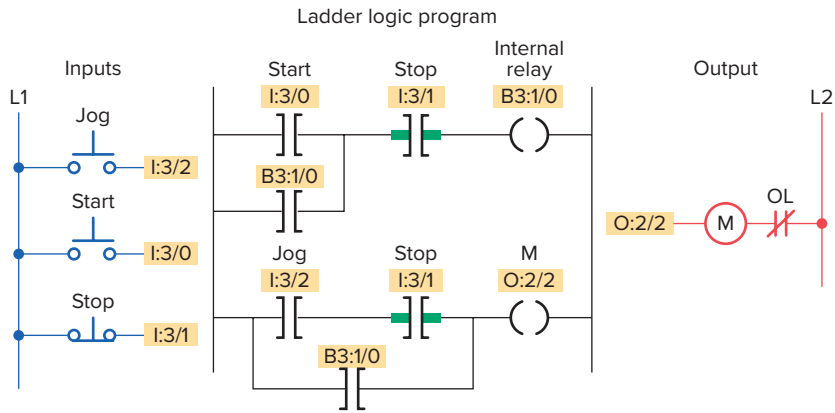
There is more than one method to correctly design the ladder logic program for a given control process. In some cases one arrangement may be more efficient in terms of the amount of memory used and the time required to scan the program. Figure 6-66 illustrates an example of an arrangement of series instructions of a rung programmed for optimum scan time. The series instructions are programmed from the most likely to be *false* (far left) to the least likely to be *false* (far right). Once the processor sees a false input instruction in series, the processor stops checking the rung at the false condition and sets the output false.

Figure 6-67 illustrates an example of an arrangement of parallel instructions of a rung programmed for optimum scan time. The parallel path that is most often *true* is



**Figure 6-64** I/O connection diagram.





**Figure 6-69** PLC program equivalent of the hardwired relay jog circuit.

## 6.12 Writing a Ladder Logic Program Directly from a Narrative Description

In most cases, it is possible to prepare a ladder logic program directly from the narrative description of a control process. Some of the steps in planning a program are as follows:

- Define the process to be controlled.
- Draw a sketch of the process, including all sensors and manual controls needed to carry out the control sequence.

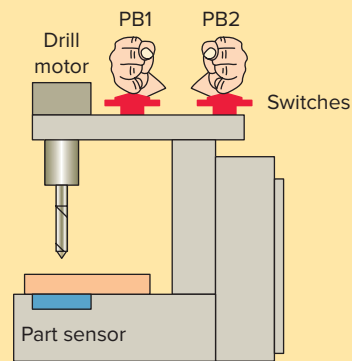
- List the sequence of operational steps in as much detail as possible.
- Write the ladder logic program to be used as a basis for the PLC program.
- Consider different scenarios where the process sequence may go astray and make adjustments as needed.
- Consider the safety of operating personnel and make adjustments as needed.

The following are examples of ladder logic programs derived from narrative descriptions of control processes.

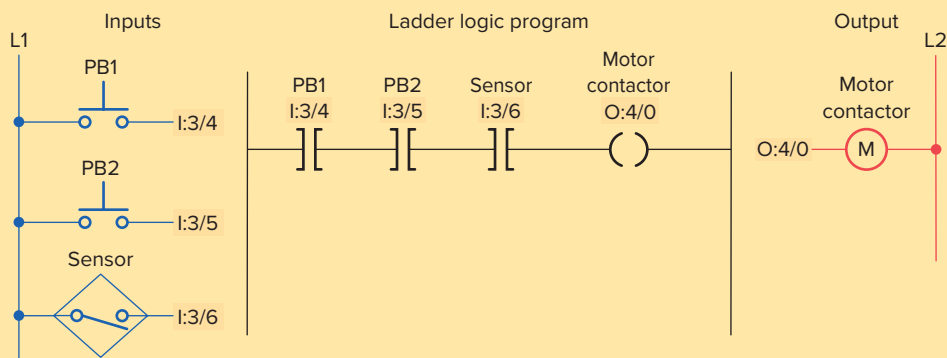
### EXAMPLE 6-1

Figure 6-70 shows the sketch of a drilling process that requires the drill press to turn on only if there is a part present and the operator has one hand on each of the start switches. This precaution will ensure that the operator's hands are not in the way of the drill.

The sequence of operation requires that switches 1 and 2 and the part sensor all be activated to make the drill motor operate. Figure 6-71 shows the ladder logic program required for the process implemented using an SLC 500 controller.



**Figure 6-70** Sketch of the drilling process.



**Figure 6-71** Drilling process PLC program.

## EXAMPLE 6-2

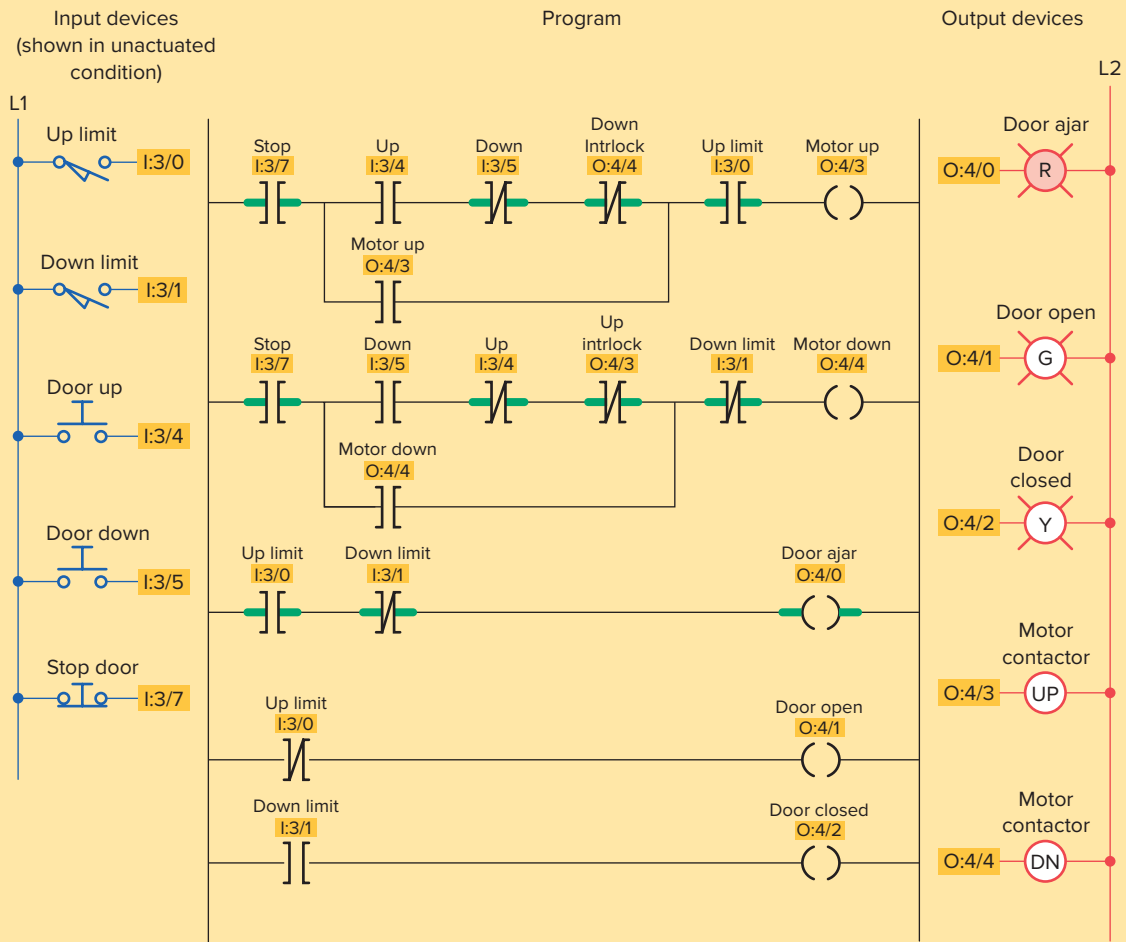
A motorized overhead garage door is to be operated automatically to preset open and closed positions. The field devices include one of each of the following:

- Reversing *motor contactor* for the up and down directions.
- Normally open *down limit switch* to sense when the door is fully closed.
- Normally open-held closed *up limit switch* to sense when the door is fully opened.
- Normally open *door up button* for the up direction.
- Normally open *door down button* for the down direction.
- Normally closed *door stop button* for stopping the door.
- Red *door ajar light* to signal when the door is partially open.
- Green *door open light* to signal when the door is fully open.
- Yellow *door closed light* to signal when the door is fully closed.

The sequence of operation requires that:

- When the up button is pushed, the up motor contactor energizes and the door travels upward until the up limit switch is actuated.
- When the down button is pushed, the down motor contactor energizes and the door travels down until the down limit switch is actuated.
- When the stop button is pushed, the motor stops. The motor must be stopped before it can change direction.

Figure 6-72 shows the ladder logic program required for the operation implemented using an SLC 500 controller.



**Figure 6-72** Motorized overhead garage door PLC program.

### EXAMPLE 6-3

Figure 6-73 shows the sketch of a continuous filling operation. This process requires that boxes moving on a conveyor be automatically positioned and filled.

The sequence of operation for the continuous filling operation is as follows:

- Start the conveyor when the start button is momentarily pressed.
- Stop the conveyor when the stop button is momentarily pressed.
- Energize the run status light when the process is operating.
- Energize the standby status light when the process is stopped.
- Stop the conveyor when the right edge of the box is first sensed by the photosensor.
- With the box in position and the conveyor stopped, open the solenoid valve and allow the box to fill. Filling should stop when the level sensor goes true.
- Energize the full light when the box is full. The full light should remain energized until the box is moved clear of the photosensor.

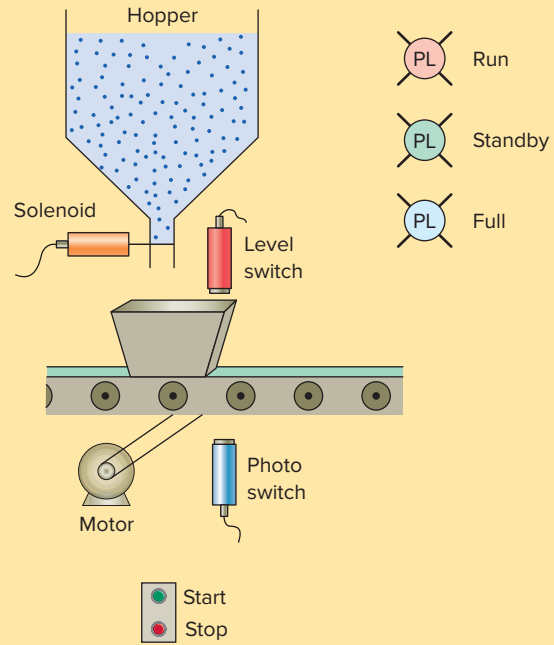


Figure 6-73 Sketch of the continuous filling operation.

Figure 6-74 shows the ladder logic program required for the operation.

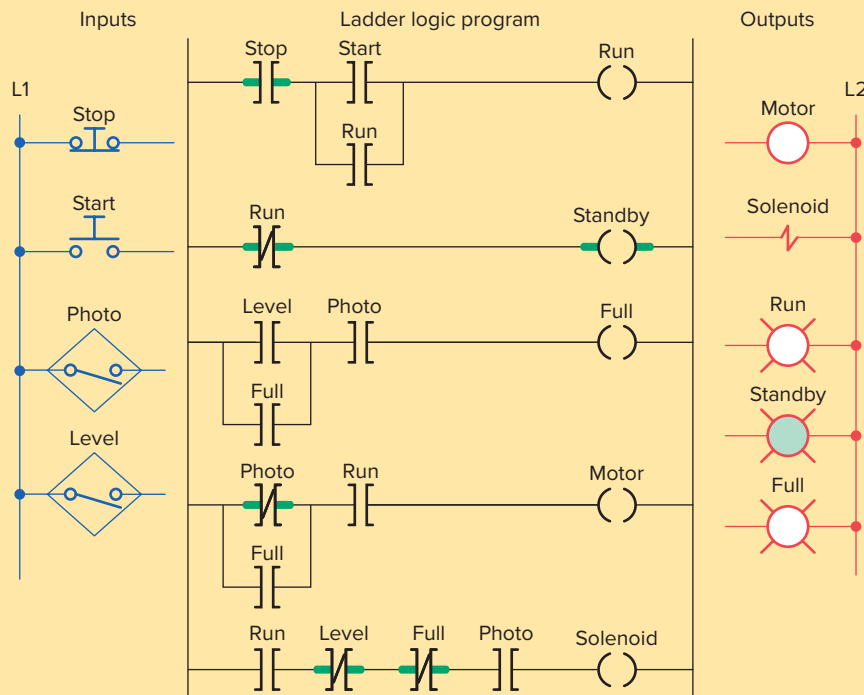


Figure 6-74 Continuous filling operation PLC program.

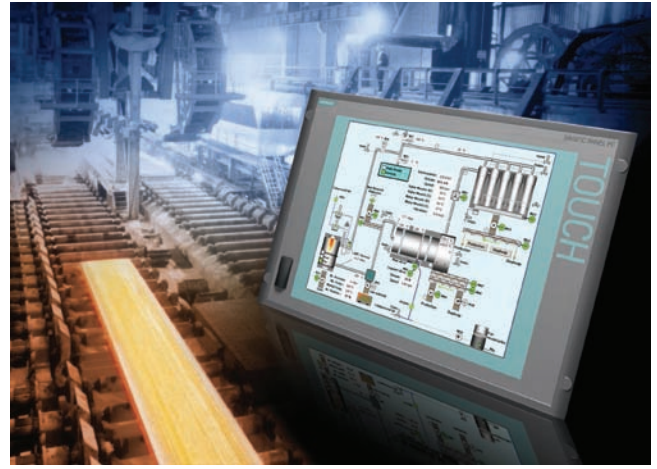
## 6.13 Instrumentation

**Instrumentation** is the use of measuring instruments to monitor and control a process. It involves the design and calibration of systems used to measure, record, and control industrial process variables. These variables may include pressure, temperature, flow rate, weight, and chemical consistency. An **instrument** is a device that measures and/or acts to control any kind of physical process and may include flow devices, level devices, thermocouples, and pressure switches.

Every instrument has at least one input and one output.

- For a pressure sensor, the input could be some fluid pressure and the output a 4- to 20-mA current signal.
- For a loop indicator, the input could be a 4- to 20-mA current signal and the output an electronic display.
- For a variable-speed motor drive, the input could be an electronic signal and the output electric power to the motor.

To **calibrate** an instrument means to check, and if necessary adjust, its response so the output accurately corresponds to its input throughout a specified range. Instrument calibration involves exposure of the instrument to an actual input stimulus of precisely known quantity. For a pressure gauge, this would mean subjecting the pressure instrument to known fluid pressures and comparing

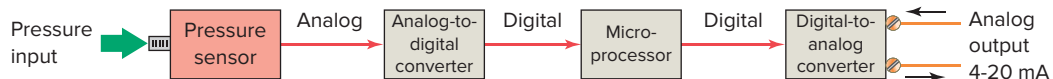


**Figure 6-76** Process parameters display.

Source: Courtesy of Siemens.

the instrument response against those known pressure quantities. **Smart instruments** (Figure 6-75) that contain microprocessors have built-in diagnostic ability, greater accuracy, and the ability to communicate digitally with host devices for reporting of various parameters.

The PLC's role as part of an industrial instrumentation system is to receive, process, and send signals from input and to output devices. With the use of programming software the PLC can control, monitor, and display all the parameters associated with a given process (Figure 6-76).



**Figure 6-75** Smart instruments.

Source: Photo courtesy Emerson.

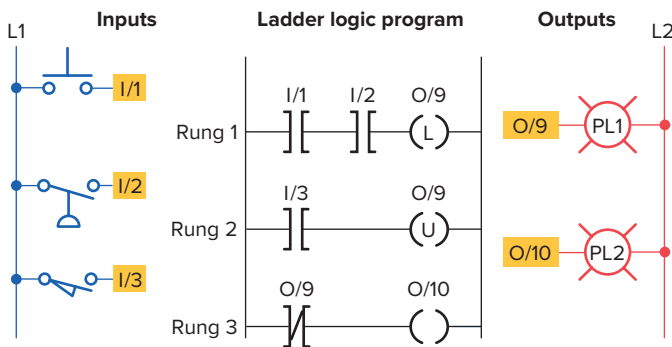


## CHAPTER 6 REVIEW QUESTIONS

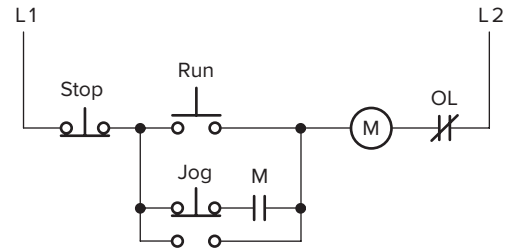
1. Explain the basic operating principle of an electro-magnetic control relay.
2. What is the operating difference between a normally open and a normally closed relay contact?
3. In what ways are control relay coils and contacts rated?
4. How do contactors differ from relays?
5. What is the main difference between a contactor and a magnetic motor starter?
6.
  - a. Draw the schematic for an across-the-line AC magnetic motor starter.
  - b. With reference to this schematic, explain the function of each of the following parts:
    - i. Main contact M
    - ii. Control contact M
    - iii. Starter coil M
    - iv. OL relay coils
    - v. OL relay contact
7. The current requirement for the control circuit of a magnetic starter is normally much smaller than that required by the power circuit. Why?
8. Compare the method of operation of each of the following types of switches:
  - a. Manually operated switch
  - b. Mechanically operated switch
  - c. Proximity switch
9. What do the abbreviations NO and NC represent when used to describe switch contacts?
10. Draw the electrical symbol used to represent each of the following switches:
  - a. NO pushbutton switch
  - b. NC pushbutton switch
  - c. Break-make pushbutton switch
  - d. Three-position selector switch
  - e. NO limit switch
  - f. NC temperature switch
  - g. NO pressure switch
  - h. NC level switch
  - i. NO proximity switch
11. Outline the method used to actuate inductive and capacitive proximity sensors.
12. How are reed switch sensors actuated?
13. Compare the operation of a photovoltaic solar cell with that of a photoconductive cell.
14. What are the two basic components of a photoelectric sensor?
15. Compare the operation of the reflective-type and through-beam photoelectric sensors.
16. Give an explanation of how a scanner and a decoder act in conjunction with each other to read a bar code.
17. How does an ultrasonic sensor operate?
18. Explain the principle of operation of a strain gauge.
19. Explain the principle of operation of a thermocouple.
20. What is the most common approach taken with regard to the measurement of fluid flow?
21. Explain how a tachometer is used to measure rotational speed.
22. How does an optical encoder work?
23. Draw an electrical symbol used to represent each of the following PLC control devices:

a. Pilot light	f. Heater
b. Relay	g. Solenoid
c. Motor starter coil	h. Solenoid valve
d. OL relay contact	i. Motor
e. Alarm	j. Horn
24. Explain the function of each of the following actuators:
  - a. Solenoid
  - b. Solenoid valve
  - c. Stepper motor
25. Compare the operation of open-loop and closed-loop control.
26. What is a seal-in circuit?
27. In what way is the construction and operation of an electromechanical latching relay different from a standard relay?
28. Give a short description of each of the following control processes:
  - a. Sequential
  - b. Combination
  - c. Automatic
29. Compare the type of sensor signal obtained from a thermocouple with that from an RTD.
30. Explain how a magnetic reed float switch works.
31. What is the function of an electrical interlocking circuit?
32. What is the role of instrumentation in an industrial process?
33. You have been assigned the task of calibrating an instrument. How would you proceed?

- Design and draw the schematic for a conventional hardwired relay circuit that will perform each of the following circuit functions when a normally closed pushbutton is pressed:
  - Switch a pilot light on
  - De-energize a solenoid
  - Start a motor running
  - Sound a horn
- Design and draw the schematic for a conventional hardwired circuit that will perform the following circuit functions using two break-make pushbuttons:
  - Turn on light L1 when pushbutton PB1 is pressed.
  - Turn on light L2 when pushbutton PB2 is pressed.
  - Electrically interlock the pushbuttons so that L1 and L2 cannot both be turned on at the same time.
- Study the ladder logic program in Figure 6-77, and answer the questions that follow:
  - Under what condition will the latch rung 1 be true?
  - Under what conditions will the unlatch rung 2 be true?
  - Under what condition will rung 3 be true?
  - When PL1 is on, the relay is in what state (latched or unlatched)?
  - When PL2 is on, the relay is in what state (latched or unlatched)?
  - If AC power is removed and then restored to the circuit, what pilot light will automatically come on when the power is restored?
  - Assume the relay is in its latched state and all three inputs are false. What input change(s) must occur for the relay to switch into its unlatched state?
  - If the examine if closed instructions at addresses I/1, I/2, and I/3 are all true, what state will the relay remain in (latched or unlatched)?
- Design a PLC program and prepare a typical I/O connection diagram and ladder logic program that



**Figure 6-77** Ladder logic program for Problem 3.



**Figure 6-78** Hardwired control circuit for Problem 4.

will correctly execute the hardwired control circuit in Figure 6-78.

Assume: Stop pushbutton used is an NO type.

Run pushbutton used is an NO type.

Jog pushbutton used has one set of NO contacts.

OL contact is hardwired.

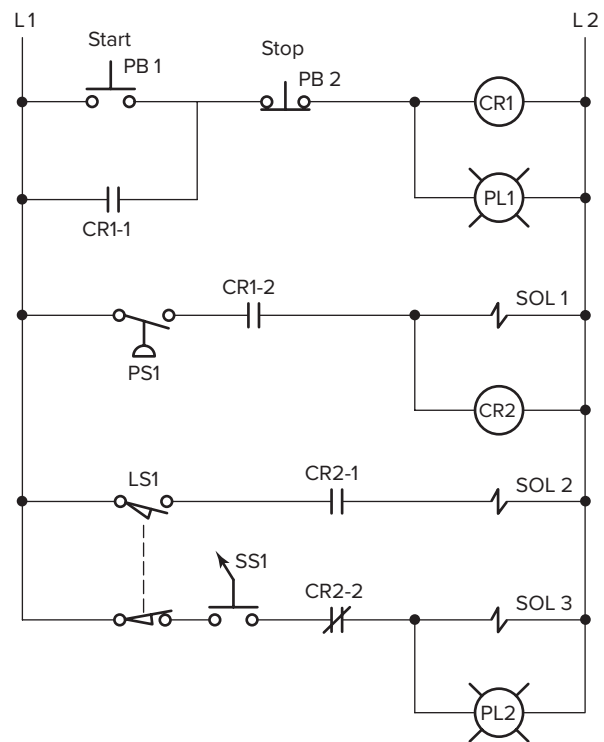
- Design a PLC program and prepare a typical I/O connection diagram and ladder logic program that will correctly execute the hardwired control circuit in Figure 6-79.

Assume: PB1 pushbutton used is an NO type.

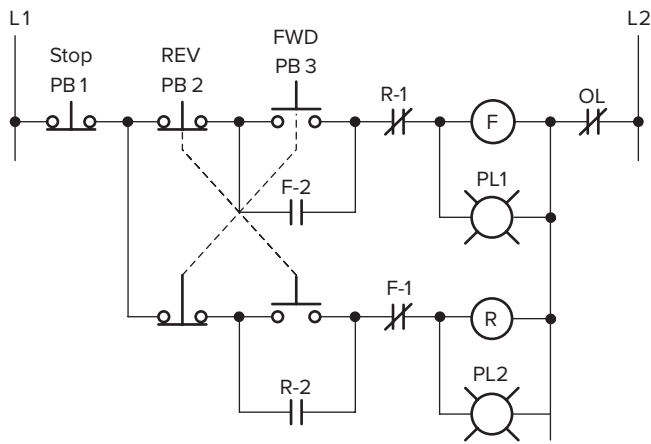
PB2 pushbutton used is an NC type.

PS1 pressure switch used is an NO type.

LS1 limit switch used has only one set of NC contacts.



**Figure 6-79** Hardwired control circuit for Problem 5.



**Figure 6-80** Hardwired control circuit for Problem 6.

6. Design a PLC program and prepare a typical I/O connection diagram and ladder logic program that will correctly execute the hardwired control circuit in Figure 6-80.

Assume: PB1 pushbutton used is an NC type.

PB2 and PB3 are each wired using one set of NO contacts.

OL contact is hardwired.

7. Design a PLC program and prepare a typical I/O connection diagram and ladder logic program for the following motor control specifications:
- A motor must be started and stopped from any one of three start/stop pushbutton stations.
  - Each start/stop station contains one NO start pushbutton and one NC stop pushbutton.
  - Motor OL contacts are to be hardwired.
8. Design a PLC program and prepare a typical I/O connection diagram and ladder logic program for the following motor control specifications:
- Three starters are to be wired so that each starter is operated from its own start/stop pushbutton station.
  - A master stop station is to be included that will trip out all starters when pushed.

- Overload relay contacts are to be programmed so that an overload on any one of the starters will automatically drop all of the starters.
- All pushbuttons are to be wired using one set of NO contacts.

9. A temperature control system consists of four thermostats controlling three heating units. The thermostat contacts are set to close at 50°, 60°, 70°, and 80°F, respectively. The PLC ladder logic program is to be designed so that at a temperature below 50°F, three heaters are to be ON. From 50° to 60°F, two heaters are to be ON. For 60° to 70°F, one heater is to be ON. Above 80°F, there is a safety shutoff for all three heaters in case one stays on because of a malfunction. A master switch is to be used to turn the system ON and OFF. Prepare a typical PLC program for this control process.
10. A pump is to be used to fill two storage tanks. The pump is manually started by the operator from a start/stop station. When the first tank is full, the control logic must be able to automatically stop flow to the first tank and direct flow to the second tank through the use of sensors and electric solenoid valves. When the second tank is full, the pump must shut down automatically. Indicator lamps are to be included to signal when each tank is full.
- a. Draw a sketch of the process.
  - b. Prepare a typical PLC program for this control process.
11. Write the optimum ladder logic rung for each of the following scenarios, and arrange the instructions for optimum performance:
- a. If limit switches LS1 or LS2 or LS3 are on, or if LS5 and LS7 are on, turn on; otherwise, turn off. (Commonly, if LS5 and LS7 are on, the other conditions rarely occur.)
  - b. Turn on an output when switches SW6, SW7, and SW8 are all on, or when SW55 is on. (SW55 is an indication of an alarm state, so it is rarely on; SW7 is on most often, then SW8, then SW6.)