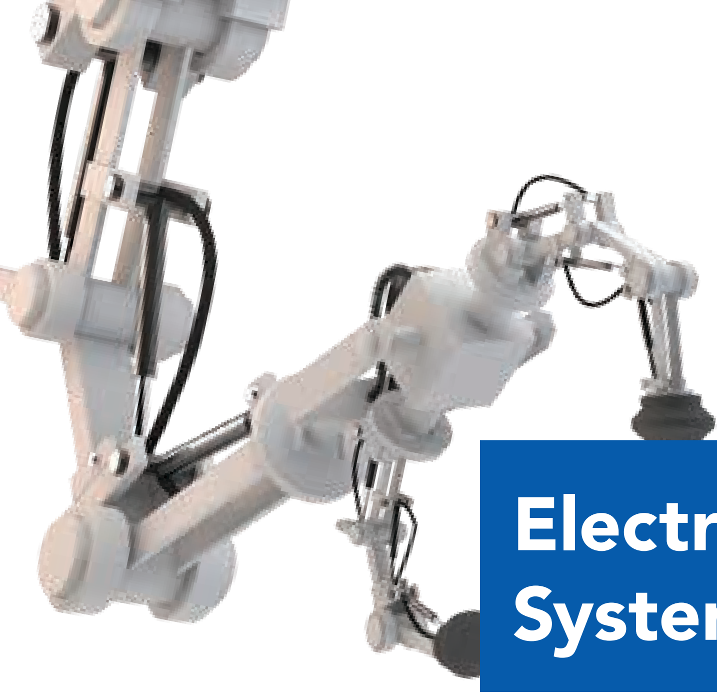

Chapter 6

Electromechanical Systems

Outline

Objectives

Upon completion of this chapter, you will be able to:

- Discuss the five basic subsystems that are common to all automated robotic systems.
- Describe mechanical systems as they relate to robotics.
- Explain how sensing, timing, and control systems are used in the operation of robots.
- Discuss rotary motion systems used for robotics.

Technical Terms

alternating current (ac)
armature
bifilar construction
brushes
commutator
comparator
compound-wound dc motor
control
counter electromotive force (cemf)
cycle
cycle timing system
dc stepping motor
delay timing system
detector
digital system
direct current (dc)
electric motor
electromechanical system
error detector
feedback
field winding
flux
indicator
interval timing system
light pipe
load
permanent-magnet dc motor
rectification
rotor
sensing system
series-wound dc motor
servo system
servomotor
shunt-wound dc motor
single-phase ac motor
single-phase induction motor
slip
squirrel cage rotor
stator
subsystem
synchronous motor
synchronous speed
synthesized system
system
three-phase ac motor
three-phase induction motor
three-phase synchronous motor
timing system
torque
transmission path
universal motor
work

Overview

At one time, all manufacturing operations were manually controlled. Gas-filled tubes, magnetic contacts, and electrical switchgears served as the primary control devices. Developments in solid-state electronics and miniaturization have brought a number of advances in system control. Electromechanical, light, hydraulic, and pneumatic systems are often combined in the control of a single industrial robot. This chapter provides an overview of the types of electromechanical systems used with robots.

6.1 Automated Systems and Subsystems

Nearly all manufactured products are manufactured using some type of electromechanical system. A ***system*** is a combination of components that work together to form a unit. An ***electromechanical system*** transfers power from one point to another through mechanical motion that is used to do work. ***Work*** occurs when energy is transformed into mechanical motion, heat, light, chemical action, or sound. Punch presses that move up and down, rotating machinery, and robots are all examples of electromechanical systems.

A robot is a unique type of system that may require several different types of components for proper operation. These various components are the ***subsystems*** that comprise a complete robot. When subsystems are combined, the result is referred to as a ***synthesized system***. Familiarity with each of the subsystems and the location of each within the overall system is important to understanding the system itself, **Figure 6-1**.

Various subsystems are used in virtually all automated systems. An electrical power system, for example, is needed to produce and distribute electrical energy. Hydraulic and pneumatic systems are used for motion and other functions. Light systems (also called photoelectronic or opto-electronic systems) are used for inspection operations and in many types of sensors. Mechanical systems are needed to hold objects for machining operations and to move parts and assemblies on a production line. Although each system has unique features, these basic subsystems are common to all automated systems: an energy source, transmission path, control, load, and indicators.

6.1.1 Energy Source

The energy source provides power for the system. The most common source of power for synthesized systems is ***alternating current (ac)***. In alternating current

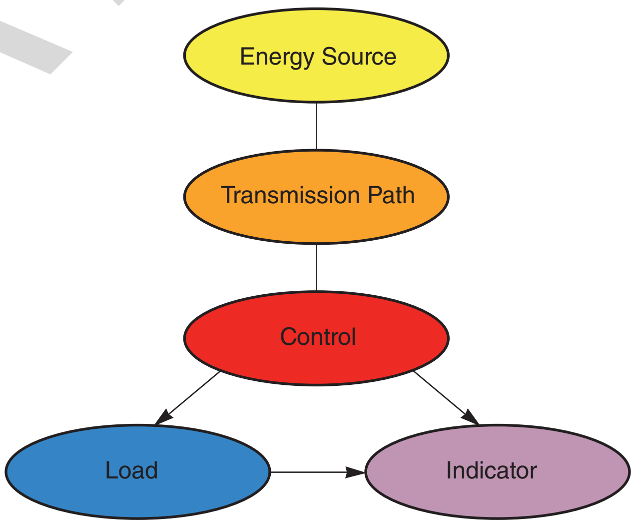

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Figure 6-1. The basic parts of an automated system must work together or the system will not function properly.

power, electrons flow first in one direction and then in the opposite direction. Each repeated pattern of direction change is called a ***cycle***, **Figure 6-2**. The alternating current required for an automated manufacturing system may be either single-phase or three-phase. Single-phase ac power consists of one alternating current, **Figure 6-2.** Three-phase ac power consists of three alternating currents that vary by 120°. Three-phase alternating current is ordinarily used for larger systems because it can handle heavier power needs. Three-phase motors are discussed later in this chapter.

Some machines used for automated manufacturing require ***direct current (dc)***. In direct current, electrons flow in only one direction. Many robotic systems have motors and other parts that use direct current. The process of converting alternating current to direct current is called ***rectification***. Rectification is the most convenient and inexpensive method of providing dc energy to machines.

6.1.2 Transmission Path

The ***transmission path*** is a subsystem that provides a channel for the transfer of energy. It begins at the energy source and continues through the system to the load device. The term ***load*** refers to a part (or parts) designed to produce work. This path may be a single feed line, electrical conductor, light beam, or pipe. Some systems may have a supply line and a return line between the source and the load. There may also be a number of alternate transmission paths in the system. These may be connected in series to a number of small load devices or in parallel to many independent devices.

6.1.3 Control

The ***control*** alters the flow of power and causes some type of operational change in the system, such as changes in electric current, hydraulic pressure, light intensity, or airflow. Control devices operate within the transmission path. In its simplest form, control occurs when a system is turned on or off. This type of control can take place anywhere between the source and the load device.

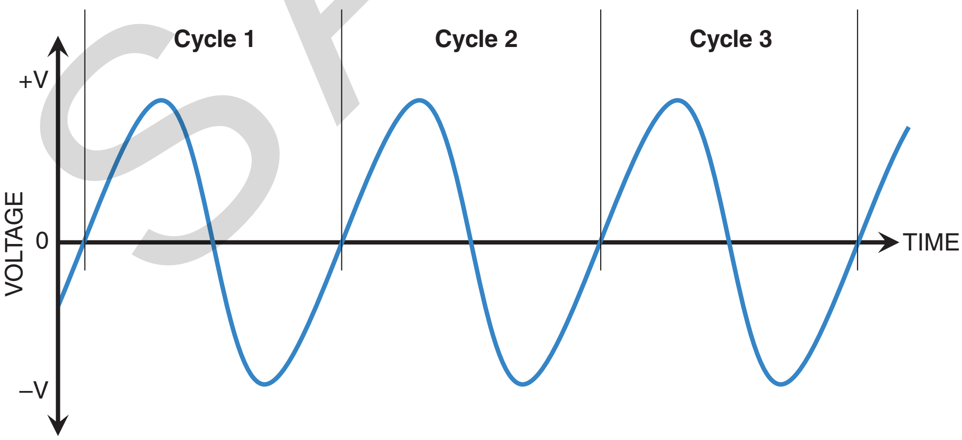

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Figure 6-2. This illustration depicts the voltage cycles in ac power. Each cycle contains two changes in direction—a high peak and a low peak.

6.1.4 Load

As stated earlier, the load is a part (or parts) designed to produce work. Work occurs when energy is transformed into mechanical motion, heat, light, chemical action, or sound. Normally, the largest portion of energy supplied by the source is consumed by the load device. Loads include electric motors, heating systems, lighting systems, alarms, horns, and mechanical actuators.

6.1.5 Indicators

The ***indicator*** is a subsystem that displays information about operating conditions at various points throughout the system. Some types of indicators include digital meters, pressure gauges, tachometers to measure speed, and thermometers to measure temperature. In some systems, the indicator is optional. In other systems, indicator readings are essential. When operations or adjustments are critical, indicator readings may affect how the robot functions.

6.2 Mechanical Systems

Mechanical systems transfer power from one point to another through mechanical motion that is used to do work. Automated applications use three kinds of motion: rotary (motors), linear (relays, actuators, and cylinders), and reciprocating (certain types of motors and cylinders). The energy source for these motions can be either electrical power or fluid power (hydraulic or pneumatic). The energy may be used to operate motors, relays, solenoids, actuators, or cylinders. As in other systems, the load is responsible for performing this action. Industrial loads are usually designed for continuous operation over long periods of time. The basic mechanical unit, such as the robot's manipulator, has several moving joints and performs the actual work function of the machine.

The transmission path of a mechanical system transfers power from the energy source to the rest of the system. The transmission path may consist of electrical conductors, belts, rotating shafts, pipes, tubes, or cables. For example, the power from an electric motor may be transferred by a belt or gear to operate a machine tool.

Control is accomplished by changing pressure, direction, force, and speed. Pressure regulators, valves, gears, pulleys, couplings, brakes, and clutches are used to control variables such as force, speed, and direction. Such changes alter the performance of the system, allowing adjustments to be made that optimize the functionality of the system.

In a mechanical system, indicators measure physical quantities. These physical quantities include pressure, flow rate, speed, direction, distance, force, torque, and electrical values. Many of these quantities must be monitored periodically. Some indicators are used to test system conditions during maintenance. Others are designed to measure physical changes that take place. Some examples of indicators are pressure gauges; flow meters; tachometers to measure speed; anemometers to measure wind direction; and multimeters to measure electrical voltage, current, and resistance.

A warehouse conveyor system is an example of a mechanical system. A conveyor moves materials, such as boxes, from one location to another. The energy source for a conveyor system is typically an electric motor. The transmission path includes pulleys, belts, or gears that connect the motor to a conveyor belt. Control is accomplished by changing speed or direction of the motor. Indicators in this type of mechanical system can measure speed or flow rate to determine the movement of boxes along the conveyor belt.

6.3 Electrical Systems for Sensing, Timing, and Control

There are many different types of electrical systems used in robotics. Electrical systems include those used for sensing, timing, control, and providing rotary motion (motors). The first three systems are discussed in this section of the chapter. Rotary motion systems are discussed in the following section.

6.3.1 Sensing Systems

A ***sensing system*** consists of components that signal a response to a particular form of energy, such as light. The light source, transmission path, control, and load device are essential parts of the system. The light is produced by electrical energy and may be in the form of incandescent lamps, flames, glow lamps, electric arcs, solid-state light, or laser light. Sensing systems have become one of the fastest growing and most diversified areas of industrial robotics. New systems that combine optics, electromagnetics, and electronics have revolutionized automated manufacturing. Light systems are the most common form of sensing systems. Other sensing systems include sound, pressure, flow, and magnetic sensors.

The transmission path of a sensing system is somewhat unique. In **Figure 6-3**, light energy travels in a straight line in the form of an intense beam of electromagnetic waves. If the light must go around corners or be directed to unusual locations, light pipes could be used as the transmission path. ***Light pipes*** are flexible, fiber-optic rods that may be extended over long distances to transfer light energy from its source to a distant location.

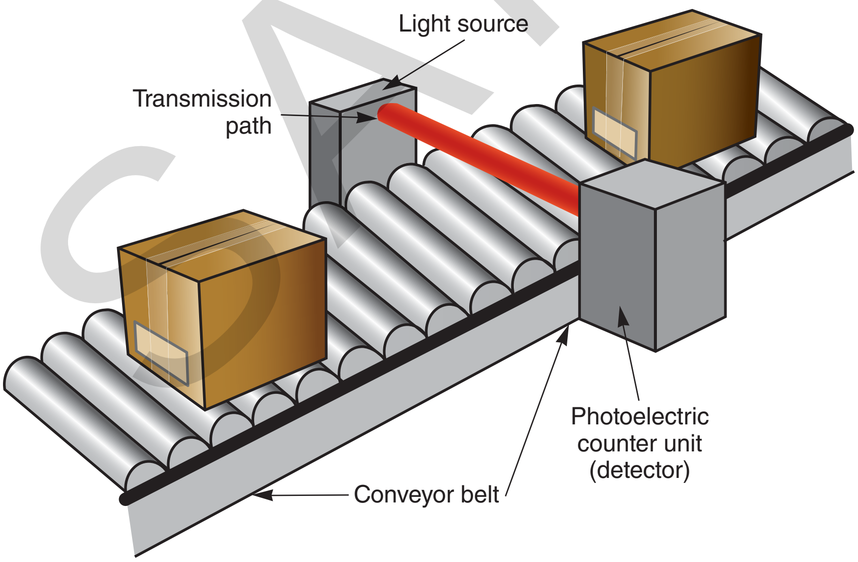

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Figure 6-3. This sensing system counts the units moving along the conveyor using system responses to light energy.

The ***detector*** is part of a sensing system that responds to energy from the source and outputs a signal that is used to control the load device. In some sensing systems, the load may be controlled directly by light-source energy. In other systems, the light energy must first be detected and amplified. There are even applications in which the detector itself serves as the load.

Sensing system control may be achieved by interrupting a light beam between the source and detector. Other control methods may alter the intensity, focus, shape, or wavelength of the light source. The detector's sensitivity can be adjusted to adapt it to specific operating conditions.

A common application of light-sensing systems in industrial processes is a counter (detector) on a conveyor line. An example may be a conveyor line that transports boxes from a packing area to a storage area. A light source can be placed along the conveyor line and aimed at the counter. As each box passes the light beam, the detector (counting device) adds another box to the count. Control is accomplished by breaking the light beam between the source and detector to count the number of boxes passing along the conveyor line.

6.3.2 Timing Systems

Timing systems turn a device on or off at a specific time or in step with an operating sequence. Types of timing systems include delay timing, interval timing, and cycle timing. ***Delay timing systems*** provide a lapse in time before the load device becomes energized. ***Interval timing systems*** are used after a load has been energized and operate using specified time periods. For example, an interval timing system may be set to allow the load to remain energized only for a certain period. ***Cycle timing systems*** are typically more complex and may include both interval and delay timing to provide energizing action in an operational sequence.

Timing systems also include thermal devices, motor-driven mechanisms, or other mechanical, electrical, or electrochemical devices. Hydraulic, pneumatic, mechanical, heat, and electrical energy sources may be used in various combinations to power timing systems. A type of timing operation is accomplished by a microprocessor in a computer. A microprocessor continually receives instructions, executes them, and continues to operate in a cyclic pattern. All actions occur at a precisely defined time interval. An orderly sequence of operations, such as this one, requires a type of precision timing system.

6.3.3 Control Systems

Control of an automated manufacturing system can be caused by input from an operator (person). It can also occur automatically due to a physical change. During production, control systems are continually at work making adjustments that alter machine operations. The complexity of an operation determines the number of control functions needed. In many cases, several control components are used in various parts of the system.

The control unit of an industrial robot determines its flexibility and efficiency. Some robots have only mechanical stops on each axis. Others have microprocessor (computer) control with memory to store position and sequence data. Some important factors in the selection of a control unit are speed of operation, repeatability, accuracy of positioning, and the speed and ease of reprogramming.

Non-servo, or open-loop, control systems are the most basic. They use sequencers and mechanical stops to control the end point positions of the robot arm. Pick-and-place (fixed-stop) robots use this type of control. Programmable servo-controlled robots are more complex. These continuous-path robots move from one point to another in a smooth, continuous motion.

Open-loop control systems are used almost exclusively for manual-control operations. There are two variations of the open-loop system: full control and partial control. Full control simply turns a system off or on. For example, in an electrical circuit, current flow stops when the circuit path is opened. Switches, circuit breakers, fuses, and relays are used for full control. Partial control alters system operations rather than causing them to start or stop. Resistors, inductors, transformers, capacitors, semiconductor devices, and integrated circuits are commonly used to achieve partial control.

To achieve automatic control, interaction between the control unit and the controlled element (load) must occur. In a closed-loop system, ***feedback*** is a signal or data that provide information about the interaction between the control unit and the controlled element (load). Feedback can be activated by electrical, thermal, light, chemical, or mechanical energy. Both full and partial control can be achieved through a closed-loop system, **Figure 6-4**. Many of the automated systems used in industry are of the closed-loop type.

In a closed-loop system with automatic correction control, **Figure 6-5**, energy goes to the control unit and proceeds to the controlled element. Feedback from the controlled element is directed to a ***comparator***, which is an element that compares the feedback signal to a reference signal or standard. A correction signal is developed by the comparator and sent to the control unit. This signal alters the system to conform to the data from the reference signal. Systems that function in this manner maintain a specific operating level regardless of external variations or disturbances.

Automatic fabrication methods, packaging, and machining operations have been improved through advances in digital systems. A ***digital system*** is a set of components that work together to process numeric information. Digital (numeric) instructions are supplied by variations in pressure, temperature, or electric current. These instructions are then changed into a series of on/off electrical signals. The signals are processed by the logic circuitry of a computer and are directed to specific subsystems that perform the necessary operations.

Electrical power energizes the load device, which performs the work. The load of a system may be electrical actuators or fluid-power cylinders designed to move parts of the robot. When appropriate signals are received, the robot performs the

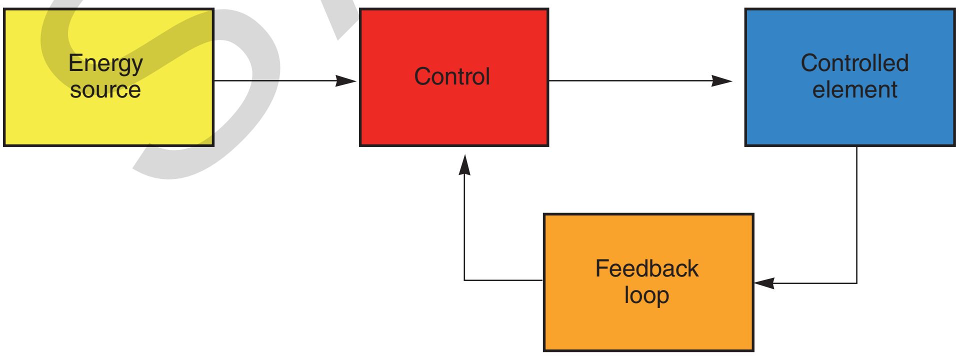

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Figure 6-4. A typical closed-loop system, as shown in this diagram, incorporates a feedback loop.

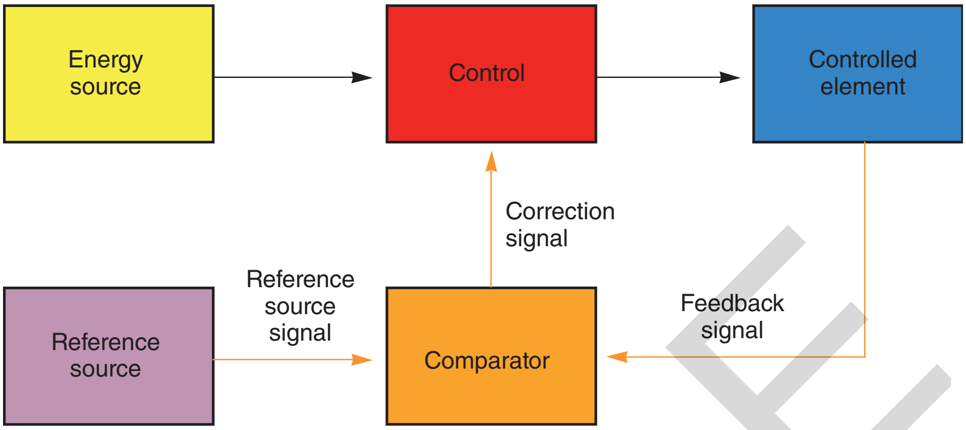

Figure 6-5. The comparator and reference source in this closed-loop control system allow automatic adjustments to be made to a process while it is running.

necessary tasks. Digital systems can control various operations, such as positioning and moving, clamping, and directing material flow.

6.4 Rotary Motion Systems

An ***electric motor*** is a device that converts electrical energy to mechanical movement in the form of rotary motion. Essentially, an electric motor is created by placing an electromagnet, called an ***armature***, between two permanent magnets. The north and south poles of the armature are aligned with the north and south poles of the permanent magnets. When a current is passed through the armature, it becomes magnetized and begins to rotate within the magnetic field of the permanent magnets. Rotation continues until the armature's north pole is opposite the south pole of a permanent magnet and the armature's south pole is opposite the magnet's north pole, **Figure 6-6**. If the current through the armature is reversed, its poles will reverse, and the armature will rotate again. The rotary motion, or turning force, that is produced is called ***torque***. The amount of torque produced by a motor depends on the strength of the magnetic fields and the amount of current

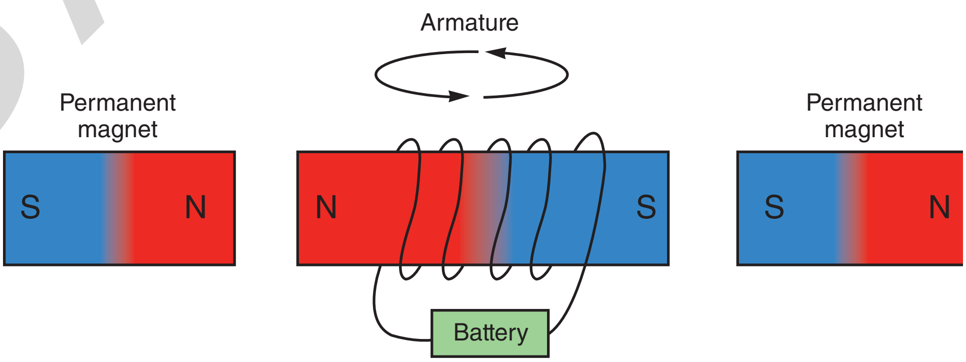

Figure 6-6. Matching magnetic poles that repel one another cause the armature to rotate in a motor.

flowing through the conductors. As either the magnetic field or current increases, the amount of torque also increases.

All motors have several parts in common. The ***stator*** is the stationary portion of a motor and includes the permanent magnets, a frame, and other stationary components. The ***rotor*** is the rotating component of a motor and includes the armature, shaft, and associated parts. Movement of the rotor creates torque. Auxiliary devices for dc motors and ac motors are discussed in the following sections.

6.4.1 DC Motors

DC motors are used when speed control is a critical factor. The basic parts of a dc motor are shown in **Figure 6-7**. A ***commutator*** is a part or assembly used to switch the direction of current flow alternately to produce a one-directional direct current (dc) through the windings (coils of wire) of the armature. The ***brushes*** are carbon devices that rub against the commutator in an electric motor and allow current to flow through them. The flow of current through the brushes to the commutator and armature windings transfers current from the stationary power source to energize the rotating armature conductors.

Most dc motors use electromagnetic windings rather than permanent magnets to create the magnetic field of the stator. The coil wires wrapped around the electromagnets in the stator are called ***field windings***. The interaction of the stationary electromagnetic field of the stator coils and the electromagnetic field of the rotating armature produces rotation of the dc motor.

The operational characteristics of dc motors are shown in **Figure 6-8**. As the armature of a dc motor rotates, it generates its own voltage called the ***counter electromotive force (cemf)***. This voltage flows against the voltage coming into the motor. The amount of cemf depends on the number of rotating conductors and the speed of rotation. As the mechanical load (amount of work effort demand on

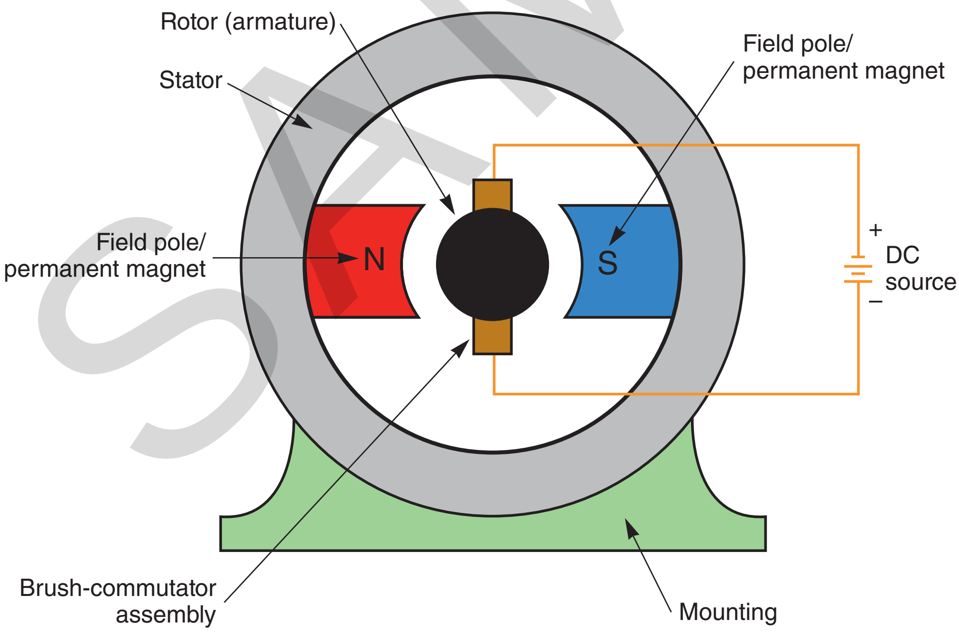

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Figure 6-7. The basic parts of a dc motor include a brush-commutator assembly for switching the current flow.

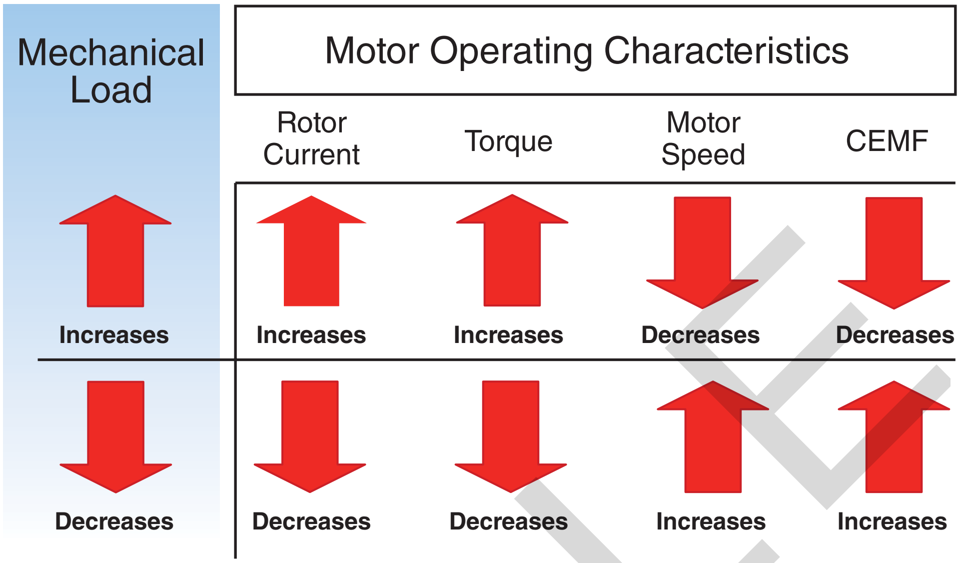

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Figure 6-8. This illustration depicts the effect of mechanical load on the operating characteristics of a dc motor.

the machine) increases, the motor speed decreases. The opposite is also true. As the mechanical load decreases, the motor speed increases. The amount of cemf increases or decreases in direct relation to the speed of rotation.

Since the cemf flows against the supply voltage, the actual working voltage of the motor increases as the cemf decreases. When the working voltage increases, more current flows through the rotor windings. The torque of the motor is directly proportional to the amount of current flowing through the armature. Therefore, torque increases as armature current increases and decreases as armature current decreases. The amount of torque also varies with changes in load. As the load on a motor increases, torque increases to handle the greater load. The increase in torque causes the motor to draw more current from the power source.

When a motor starts, it draws a very large initial current (compared to the current it draws at full speed) because of the absence of cemf. To reduce the starting current of a motor, resistors wired in series with the armature circuit are often used. Once the motor reaches full speed, these resistors are bypassed by an automatic or manual switching system. This allows the motor to produce maximum torque.

Horsepower is a measure of the amount of work performed over a specified amount of time. The horsepower rating of a motor represents the power of a motor. It is based on the amount of torque produced at the rated full-load values and is a very common rating for electric motors used for robotic applications. As torque or the work requirement increases for any application, the horsepower of the motor used to drive the machine must also increase. This can be expressed mathematically as:

$$hp = \frac{2\pi ST}{33{,}000}$$

$$hp = \frac{ST}{5252}$$

(hp = Horsepower rating, π = Constant, S = Speed of the motor expressed in rpm, T = Torque developed by the motor expressed in ft/lbs.)

As noted earlier, an important feature of dc motors is the ability to control speed. By changing the applied dc voltage, speed can vary from zero to the maximum rpm. Some types of dc motors have more desirable speed characteristics than others in terms of the motor's ability to maintain a constant speed under varying load conditions. The difference between no-load motor speed (rpm) and the rated full-load motor speed (rpm) is used to determine the percentage of speed regulation for different dc motors. Lower speed regulation values mean better speed regulation capabilities. Thus, a motor that operates at nearly constant speeds under varying load situations provides good speed regulation.

There are four basic categories of commercially available dc motors: permanent-magnet, series-wound, shunt-wound, and compound-wound. Each type has different characteristics that result from the basic circuit arrangement and physical properties.

The ***permanent-magnet dc motor*** is used when a low amount of torque is needed for applications, such as motor-driven timers and printers connected to computer systems, **Figure 6-9**. The dc power supply is connected directly to the conductors of the rotor through the brush-commutator assembly. The magnetic field is produced by permanent magnets mounted in the stator.

In a ***series-wound dc motor***, the armature and field circuits are connected in a series arrangement, **Figure 6-10**. This is the only type of dc motor that also can be operated using ac power. For this reason, series-wound motors are sometimes called

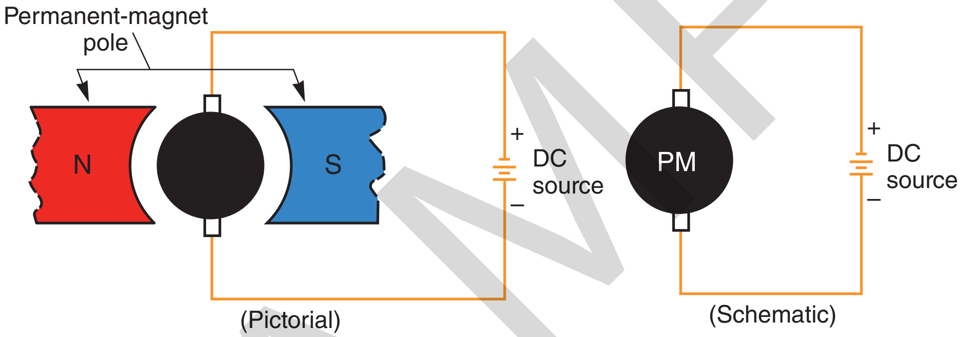

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Figure 6-9. A permanent-magnet dc motor is used for applications in which low torque is required.

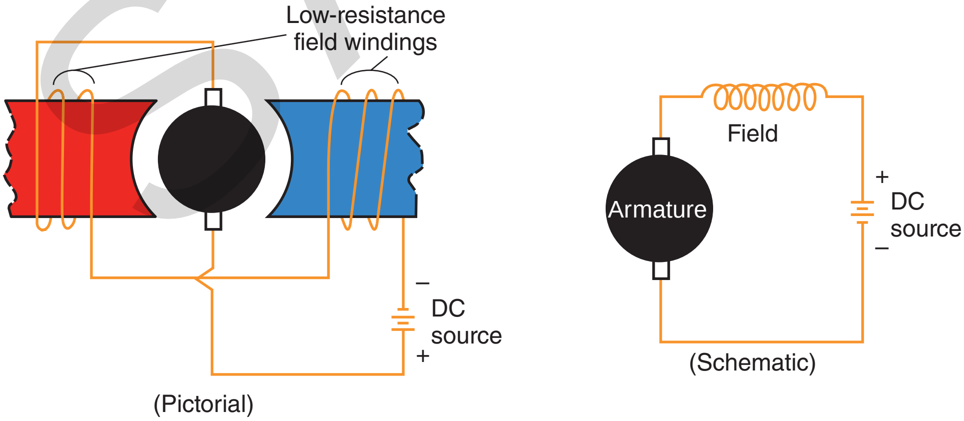

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Figure 6-10. A series-wound dc motor produces high torque, but it has poor speed regulation.

universal motors. In this type of motor, there is only one path for current to flow from the dc voltage source. Therefore, the field has a low resistance. Changes in load applied to the motor shaft cause changes in current though the field. If the mechanical load increases, the current also increases. This creates a stronger magnetic field. The speed of a series-wound motor ranges from very fast when there is no load to very slow under a heavy load. Since large currents may flow through the low-resistance field, series-wound motors produce high torque. Series-wound motors are used when heavy loads must be moved and speed regulation is not as important.

The ***shunt-wound dc motor*** is the most commonly used type of dc motor, **Figure 6-11**. The motor's field windings have relatively high resistance and are connected in parallel with the armature. Since the magnetic field is a high-resistance parallel path, a small amount of current flows through it.

Most of the current drawn by a shunt-wound motor flows in the armature circuit. Since the armature current has only a slight effect on the field strength, variations in load have little effect on motor speed. The field current, however, can be controlled by placing a variable resistance in series with the field windings. Since the current in the field circuit is low, a low-wattage resistor (or rheostat) can be used to vary the motor's speed. As the field resistance increases, the field current decreases. The opposite also applies. A decrease in field resistance increases the field current. Changes in the field current result in corresponding changes in the ***flux*** (strength) of the electromagnetic field. As field flux decreases, the armature rotates faster; as it increases, armature rotation slows.

Shunt-wound dc motors are commonly used for industrial applications because of their effective speed control characteristics. Many types of variable-speed machine tools are driven by shunt-wound dc motors.

A ***compound-wound dc motor*** has two sets of field windings. One set of field windings is in series with the armature; the other is in parallel with the armature, **Figure 6-12**. It has the high torque of a series-wound motor and good speed regulation like a shunt-wound motor. However, compound-wound motors are more expensive than the other types.

6.4.2 AC Motors

AC motors are commonly used in industrial settings as well as in commercial and residential applications. ***Single-phase ac motors*** operate using a single-phase ac

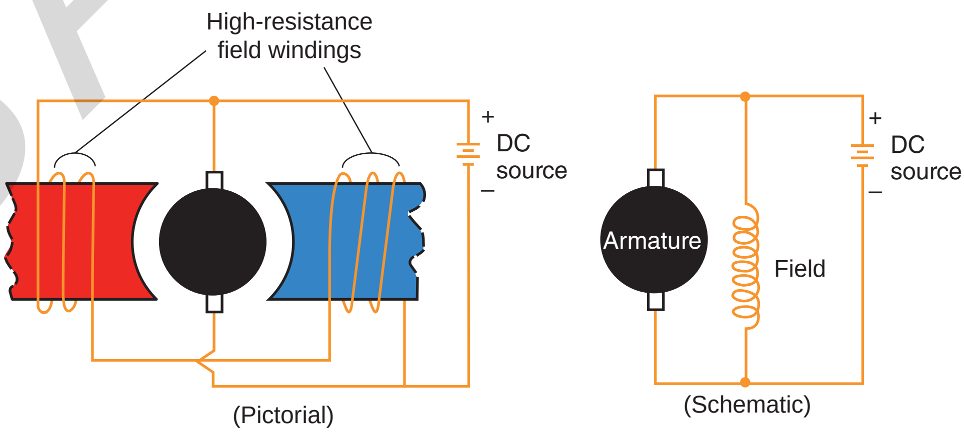

Figure 6-11. Shunt-wound dc motors are commonly used in industry because their speed is easily regulated.

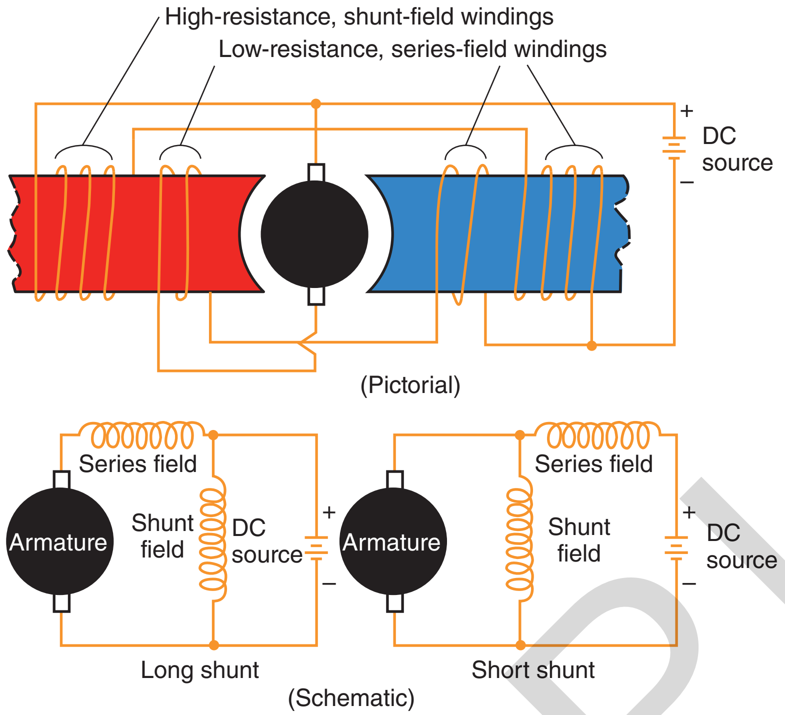

Figure 6-12. The compound-wound dc motor combines the best features of the series-wound and shunt-wound motors.

power source. There are three types of single-phase ac motors: universal motors, induction motors, and synchronous motors.

A ***universal motor*** can be powered by either an ac power source or a dc power source and is built like a series-wound dc motor, **Figure 6-13**. It has concentrated field windings and speed and torque characteristics similar to those of series-wound dc motors. Universal motors are used mainly for portable tools and small equipment.

The ***single-phase induction motor*** has a solid rotor, called a ***squirrel cage rotor*** (**Figure 6-14**). The top and bottom of large-diameter copper conductors are soldered to connecting plates. When current flows in the stator windings, a current is induced in the rotor. The stator polarity changes in step with the applied ac frequency. This develops a rotating magnetic field around the stator. The rotor becomes polarized and rotates in step with the stator's magnetic field. However, due to inertia, the rotor must be set into motion by some auxiliary starting method.

The speed of an ac induction motor is based on the speed of the rotating magnetic field and the number of stator poles. The speed of the rotating magnetic field (rpm) is developed by the frequency of ac voltage (Hz) and the number of poles in stator windings. The stator speed is also referred to as ***synchronous speed***. A two-pole motor operating with a 60 Hz source has a synchronous speed of 3600 rpm. For 60 Hz operation, the following synchronous speeds may be obtained:

- Two-pole, 3600 rpm.
- Four-pole, 1800 rpm.
- Six-pole, 1200 rpm.
- Eight-pole, 900 rpm.
- Ten-pole, 720 rpm.
- Twelve-pole, 600 rpm.

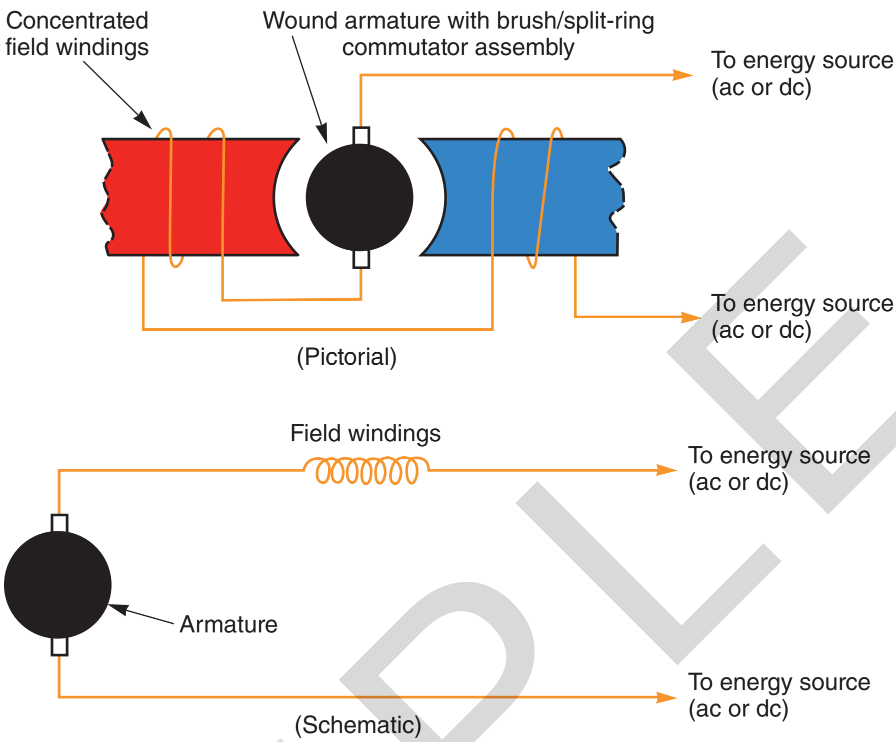

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Figure 6-13. Universal motors can operate on either ac or dc energy and are often used to power portable tools.

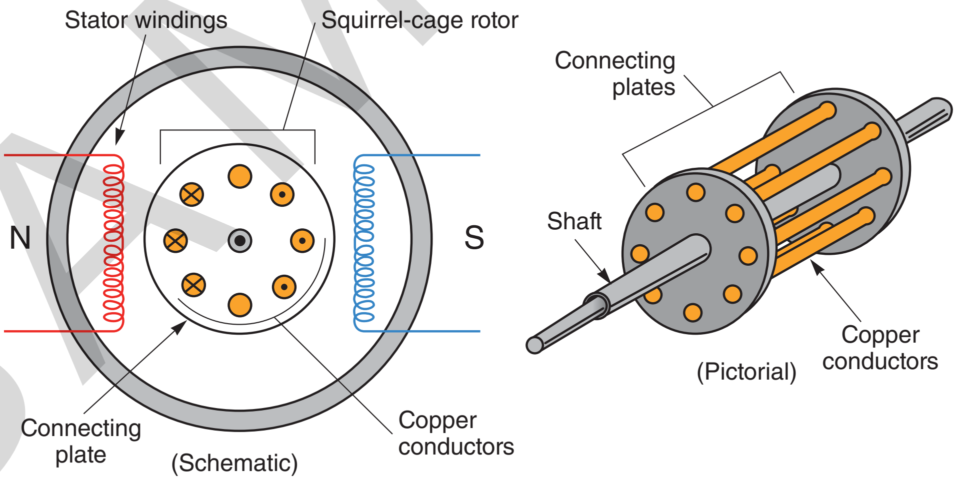

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Figure 6-14. The components of a squirrel cage rotor on an induction motor include copper conductors, connecting plates, and a shaft.

The rotor speed must be somewhat less than the synchronous speed in order to develop torque. The difference between the synchronous speed and the rotor speed is called ***slip***. The greater the difference between the rotor speed and the synchronous speed, the more torque is produced. As the difference between the rotor speed and the synchronous speed becomes smaller, the percentage of slip decreases as well.

Most motors used in industry operate using a three-phase ac power source. ***Three-phase ac motors*** are often called the workhorses of industry. The two basic types are induction motors and synchronous motors.

Three-phase induction motors have a squirrel cage rotor. Since three-phase voltage is applied to the stator, no external starting mechanisms are needed. Three-phase induction motors are made in a number of sizes and have good starting and running torque characteristics. Three-phase induction motors are used in industrial applications, such as machine tools, pumps, elevators, hoists, and conveyors.

In **Figure 6-15**, the three-phase power source is connected directly to the windings of the stator. Phase A is connected to windings A1 and A2, which are located 180° apart. Phase B connects to windings B1 and B2, also 180° apart. Phase C follows the same pattern. The windings are distributed 360° around the entire stator. The beginnings of each phase winding (A1, B1, C1) are located 120° apart. This is equivalent to 360° divided by three (or the total number of phases). Likewise, the ends of the windings (A2, B2, C2) are located 120° apart. The stator windings are energized with the three-phase voltages, causing the rotor to rotate in a constant direction. Reversing any two of the winding connections (A and B, B and C, or A and C) of a three-phase ac motor causes the rotor to rotate in the opposite direction.

Three-phase synchronous motors are unique and very specialized. These motors deliver constant speed and can be used to correct power factors of three-phase systems. Direct current is applied to the wound rotor to produce an electromagnetic field. Three-phase ac power is applied to the stator, which also has windings.

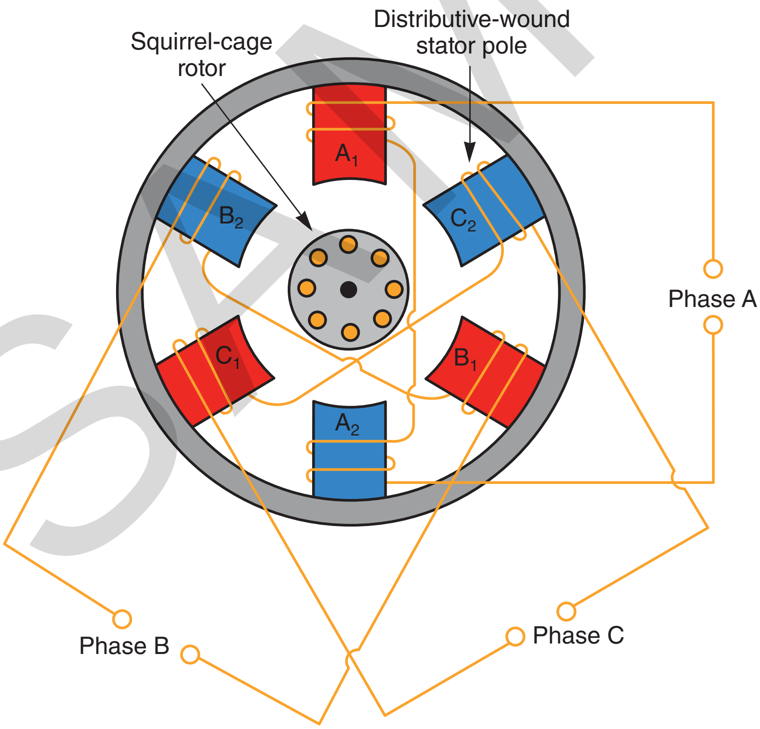

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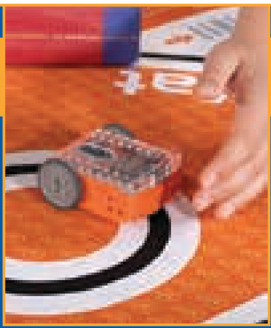
Figure 6-15. Three-phase ac induction motors are widely used for industrial applications and do not require an external starting mechanism.



Robotics Innovations: Edison Robot

The Edison robot is a low-cost robotic solution designed for use in schools. The robot has a surface that is compatible with LEGO® blocks and allows students to build unique robot designs on top of the programmable base. Lesson plans and activities have been developed that are available for download from the Edison website. Programs can be entered with a computer or by simply printing out bar codes that the robot drives over and scans. Onboard sensors can detect light, sound, lines, and infrared signals. Standard TV and DVD remotes can be used to control the robot. The low cost and versatility of the robot make it ideal for schools with small budgets.

Photo courtesy of Edison Robot

A basic three-phase synchronous motor has no starting torque. Some external means must be used to start it. A synchronous motor will rotate at the same speed as the revolving stator field. At synchronous speed, rotor speed equals stator speed, and the motor has zero slip.

6.4.3 Servo Systems

Servo systems are machines that change the position or speed of a mechanical object in response to system feedback or error signals. Positioning applications include numerical control machinery, process control indicating equipment, and robotic systems. Changing the speed of a mechanical object applies to conveyor belt control units, spindle speed control in machine tool operations, and disk or magnetic tape drives for computers. In general, servo systems follow a closed-loop control path, **Figure 6-16**.

The input of a servo system is the reference source to which the load responds. By changing the input in some way, a command is applied to the ***error detector***. This device receives data from both the input source and the output device. If a correction is needed, the signal is amplified and applied to the actuator. The actuator is normally a servomotor that produces controlled shaft displacements. The output device is usually a synchro system that relays information back to the error detector for position comparison.

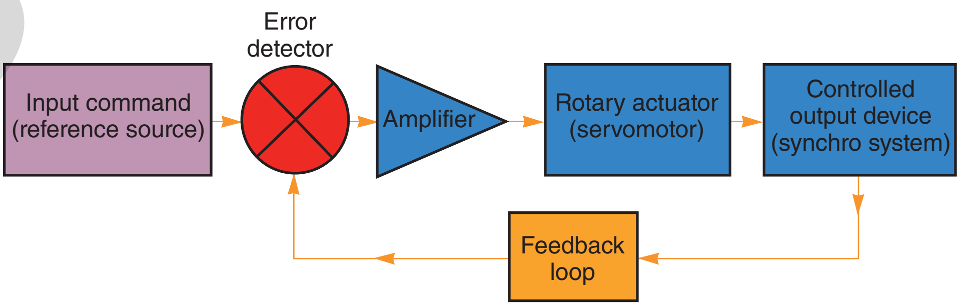


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Figure 6-16. A typical servo system uses feedback signals to adjust the position or speed of a mechanical object.

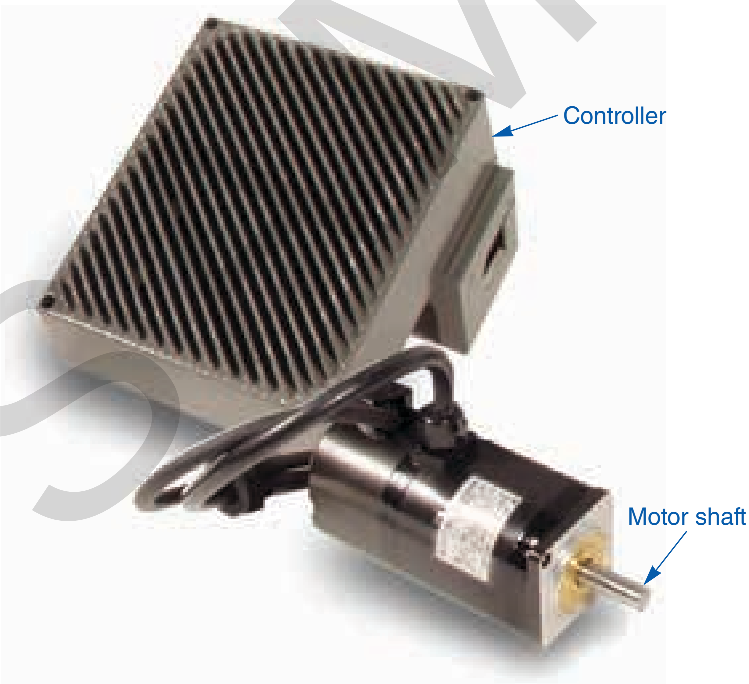
A ***servomotor*** is a component of a servo system that produces controlled shaft displacements used to achieve a precise degree of rotary motion, **Figure 6-17**. Servomotors must respond accurately to error signals and be capable of reversing direction quickly. The amount of torque developed by a servomotor must be high. There are two types of servomotors: the synchronous motor and the stepping motor.

A ***synchronous motor*** contains no brushes, commutators, or slip rings. It is comprised of a rotor and a stator assembly, but there is no direct contact between the rotor and stator poles. An air gap must be carefully maintained in order for synchronous motors to operate.

The speed of a synchronous motor is directly proportional to the ac frequency and the number of pairs of stator poles. Since the number of stator poles cannot be altered after the motor has been manufactured, frequency is the most significant factor in controlling speed. Speeds of 28, 72, and 200 rpm are typical. A speed of 72 rpm is commonly used in numerical control applications.

Single-phase ac synchronous motors are commonly used in low-power applications, **Figure 6-18**. This type of motor is normally limited to low-power applications because it develops excessive amounts of heat during starting conditions. A typical low-power application of single-phase ac synchronous motors is for precision timing circuits that require precise and constant speed.

The stator layout of a two-phase synchronous motor with four poles per phase is illustrated in **Figure 6-19**. This motor can start, stop, and reverse quickly. In this example, there is room for 48 teeth around the inside of the stator. However, one tooth per pole must be eliminated to provide space for the windings. This leaves a total of 40 teeth. The four coils of each phase are connected in series to achieve the correct polarity.



Adept

Figure 6-17. A typical servomotor is used for robot axis positioning. The controller provides signals to position the axis accurately and the motor shaft connects to the robot axis.

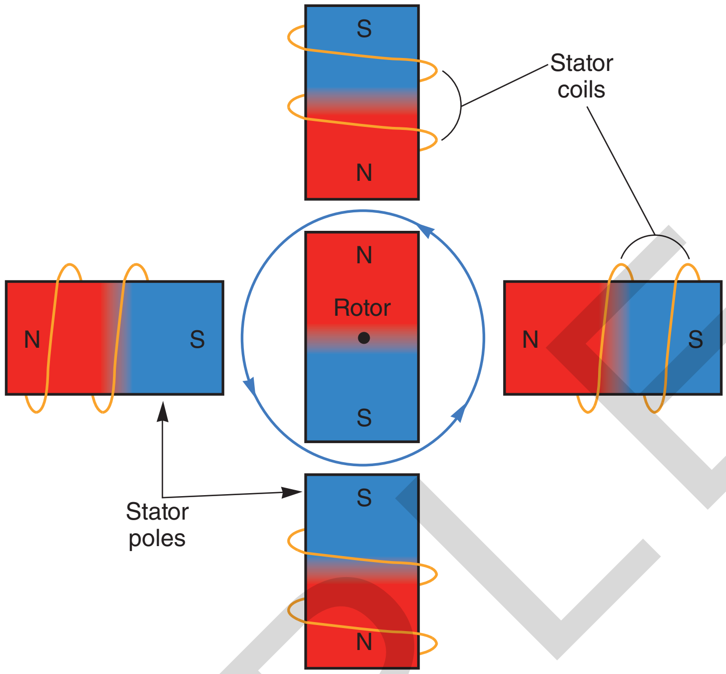


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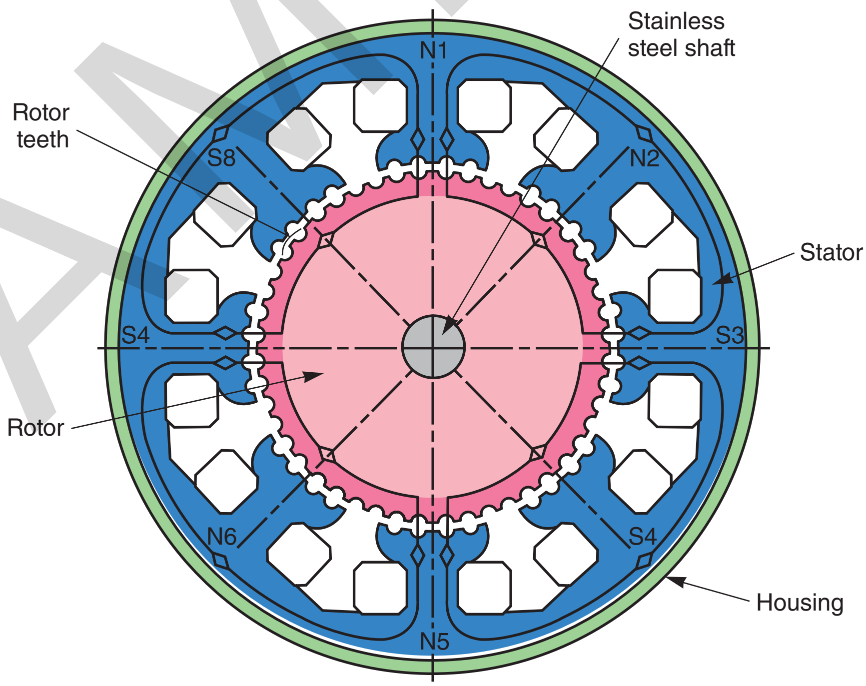
Figure 6-18. A single-phase synchronous motor has a simple construction. The rotor turns without making direct contact with the stator poles.



Superior Electric Co.

Figure 6-19. This illustration shows the stator layout of a two-phase synchronous motor with four poles per phase. Poles N_1 to S_3 and N_5 to S_7 represent one phase. Poles N_2 to S_4 and N_6 to S_8 represent the second phase.

The rotor of the synchronous motor has a permanent magnet. There are 50 teeth cast into the form of the rotor. The front section of the rotor has one polarity while the back section has the opposite polarity. The difference in the number of stator teeth (40) and rotor teeth (50) means that only two teeth of each part can be properly aligned at the same time. Since the rotor's sections have opposing polarities, the rotor can stop very quickly and can reverse direction without hesitation.

Because of its gear configuration, the synchronous motor can start in one and one-half cycles of the applied ac frequency and can stop in 5° of mechanical rotation. Synchronous motors of this type draw the same amount of current when stalled as they do when operating. This is very important in automatic machine tool applications that involve heavy mechanical loads.

Nearly all high-power servomechanisms use ***dc stepping motors***, **Figure 6-20**. This is a type of motor in which the rotor has a permanent magnet. These motors are primarily used to change electrical pulses into rotary motion. They are more efficient and develop significantly more torque than synchronous servomotors. The shaft of a dc stepping motor rotates a specific number of degrees with each pulse of electrical energy. The amount of rotary movement, or angular displacement, can be repeated precisely.

The velocity, direction, and travel distance of a piece of equipment can be controlled by a dc stepping motor. Stepping motors are energized by a dc drive amplifier that is controlled by a computer system. The movement error is generally less than 5% per step. The construction of a dc stepping motor is very similar to that of an ac synchronous motor. Some manufacturers make servomotors that can be operated as either ac synchronous or dc stepping.

The stator coils are wound using ***bifilar construction***, in which two separate wires are wound into the coil slots at the same time. The two wires are small, permitting twice as many turns as with a larger wire. This simplifies control circuitry and dc energy source requirements.

Anaheim Automation, Inc.

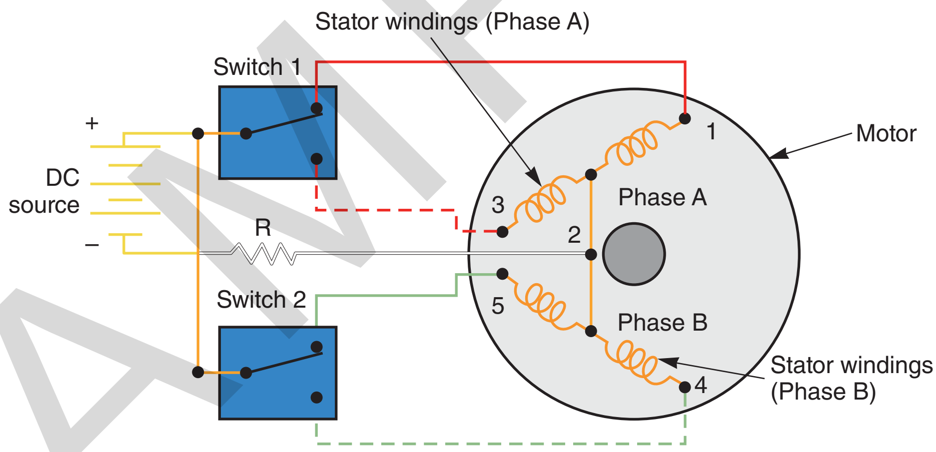
Figure 6-20. These stepping motors are used to power linear actuators.

Operation of a stepping motor is achieved using a four-step switching sequence. Any of the four combinations of switches 1 or 2 will produce an appropriate rotor position. The switching cycle then repeats itself. Each switching combination causes the motor to move one-fourth step.

The rotor in the circuit illustrated in **Figure 6-21** permits four steps per tooth, or 200 steps per revolution. The amount of linear displacement, or step angle, is determined by the number of teeth on the rotor and the switching sequence. A stepping motor that takes 200 steps to produce one revolution moves 360°/200 or 1.8° per step. It is not unusual for stepping motors to require eight switching combinations to achieve one step.

6.4.4 Rotary Electric Actuators

Robots require rotary electric actuators to produce rotary motion different from that produced by an electric motor. This type of rotary motion controls the angular position of a shaft. Using rotary electric actuators, rotary motion is transmitted between locations without direct mechanical linkage. Servomotors and synchronous motors are types of rotary actuators. For these applications, computer signals are applied to the actuators and translated into precise amounts of rotary motion. The electrical signals are applied to the motor, causing mechanical (rotary) movement.



Switching Sequence*

Step	Switch #1	Switch #2
1	1	5
2	1	4
3	3	4
4	3	5
1	1	5

*To reverse direction, read chart from bottom to top.

Superior Electric Co.

Figure 6-21. This dc stepping motor is similar in construction to an ac synchronous motor.

Summary

- Electromechanical systems transfer power from one point to another through mechanical motion used to perform work.
- A robot is a unique type of system that may require several different types of subsystems for proper operation.
- An energy source provides power for a robotic system. The most common source of power for synthesized systems is alternating current (ac).
- A transmission path provides a channel for the transfer of energy in a system.
- A system control alters the flow of power and causes some type of operational change in the system, such as changes in electric current or hydraulic pressure.
- The load of a system is a part or parts designed to produce work. Work occurs when energy is transformed into mechanical motion, heat, light, chemical action, or sound.
- Indicators are used to display information about the operational condition throughout the system.
- Mechanical systems, such as motors, linear actuators, cylinders, and reciprocating devices, produce some form of mechanical motion.
- An electrical sensing system signals a response to a particular form of energy, such as light. Some sensing systems combine optics, electromagnetics, and electronics.
- Electrical timing systems turn a device on or off at a specific time or in step with an operating sequence.
- Control systems are used to make adjustments that alter machine operations. Open-loop and closed-loop systems are used to provide control.
- Electric motors are rotary motion systems that convert electrical energy to rotary motion.
- Direct current (dc) motors are used when speed control is essential. Permanent-magnet, series-wound, shunt-wound, and compound-wound are types of dc motors.
- Single-phase ac motors operate using a single-phase ac power source. Three types of single-phase ac motors include universal motors, induction motors, and synchronous motors.
- Servo systems are machines that change the position or speed of a mechanical object in response to system feedback or error signals.
- Servomotors are used with robotic systems for precise control of rotary motion. DC stepping motors are used with robotic systems for precision motion control.
- Robots require rotary electric actuators to produce rotary motion different from that produced by an electric motor.

Know and Understand

Answer the following questions using the information provided in this chapter.

1. Which of the following best describes a subsystem?
   A. The collection of systems that make up the total systems of a robot.
   B. Systems that hold objects for machining operations.
   C. Systems that are open loop.
   D. Systems that are closed loop.
2. Which of the following best describes a synthesized system?
   A. A simulation of a robotic system using computer software.
   B. A combination of subsystems that makes up a robotic system as a whole.
   C. A simulation of a mechanical system.
   D. When electrical subsystems are used in place of mechanical subsystems.
3. Which of the following is *not* one of the five subsystems common to all automated systems?
   A. Energy source
   B. Transmission path
   C. Vision
   D. Load
4. The term _____ refers to a part (or parts) designed to produce work.
   A. control
   B. load
   C. current
   D. indicator
5. Which of the following best describes the function of a mechanical system?
   A. Components that signal a response to a particular form of energy.
   B. System that turns devices on or off at a specific time.
   C. System that transfers power from one point to another through mechanical motion that is used to do work.
   D. System that converts electrical energy to mechanical energy.
6. Which of the following is *not* one of the three kinds of motion used in automated applications of mechanical systems?
   A. Rotary
   B. Linear
   C. Servo
   D. Reciprocating
7. Which of the following describes a way in which sensing, timing, or control is used in the operation of industrial robots?
   A. A switch detects when a robot has reached the limit of its travel.
   B. A clock indicates that it is the end of the day.
   C. An operator turns on the room lights at the start of the day.
   D. A robot overheats because it was lifting loads beyond its designed limit.
8. What is the difference between a servo and non-servo robotic system?
   A. Non-servo systems have feedback from sensors while servo is open loop.
   B. Servo systems have feedback from sensors while non-servo is open loop.
   C. Servo systems use servo motors while non-servo use stepper motors.
   D. Servo systems do not require program code while non-servo systems do require code.

9. What is the main difference between full and partial control in an open-looped system?
   A. Full control only powers a system on or off while partial control alters the system but does not fully stop it.
   B. Full control systems allow the operator total control while partial control systems limit operator control.
   C. Full control systems have feedback loops while partial control systems do not.
   D. Full control systems are servo while partial control are non-servo.
10. *True or False?* Both full and partial control can be achieved through a closed-loop system.
11. Which of the following best describes the function of feedback in a closed-loop system?
   A. Feedback compares signals to a reference signal or standard.
   B. Feedback is data that provides information about the interaction between the control unit and the controlled element (load).
   C. Feedback allows the robot to cool down between cycles.
   D. Feedback is part of an open loop system, not a closed loop system.
12. Which of the following is *not* one of the basic components of an electric motor?
   A. Rotor
   B. Stator
   C. Brushes
   D. Error detectors
13. Which of the following best defines horsepower as it relates to an electric motor?
   A. Measure of work performed over a specified period of time.
   B. Amount of current a motor draws per volt.
   C. Amount of voltage a motor requires to spin at a specified RPM.
   D. The average time a motor runs × (voltage/current).
14. Which of the following is a benefit of the permanent-magnet dc motor?
   A. The motor can run on ac or dc power.
   B. It is the most commonly used motor and the easiest to repair.
   C. It is useful when high amounts of torque are required.
   D. It is useful when low amounts of torque are needed.
15. What happens to the current drawn by an electric motor when load increases?
   A. Current increases.
   B. Current decreases.
   C. Current stays the same.
   D. Not enough information to determine.
16. A _____ motor can be powered by either an ac power source or a dc power source and is built like a series-wound dc motor.
   A. single-phase induction motor
   B. compound-wound dc
   C. universal
   D. shunt-wound

17. Which of the following is a factor that contributes to the speed of an ac induction motor?
    A. The frequency of the ac voltage applied.
    B. The dc voltage that is applied to the motor.
    C. The diameter of the wire powering the motor.
    D. The type of rotor used.
18. A(n) _____ motor is comprised of a rotor and a stator assembly, but does not contain brushes, commutators, or slip rings.
    A. stepping
    B. synchronous
    C. induction
    D. universal
19. Which of the following best describes a stepping motor?
    A. An ac motor that is controlled by frequency.
    B. A dc motor that is controlled by varying current.
    C. A motor that uses dc power and moves by receiving small steps or pulses.
    D. A dc motor that is controlled by varying voltage.

Apply and Analyze

1. Select a piece of equipment or a machine and identify the parts of its system (energy source, transmission path, control, load, indicators).
2. Choose a type of electric motor and search the Internet to find the specs and operational information, such as horsepower ratings available, cost, and common applications.
3. Make a sketch of a type of electric motor that includes illustrations of a simplified rotor and stator. Describe how rotation is achieved.
4. Go to the websites for manufacturers and obtain information on rotary actuators that may be used with robotic systems.

Critical Thinking

1. What are some typical applications of an industrial environment system? Perform research as needed.

Activity 6-1
Electrical Meters

Objectives

Electrical meters are used to measure voltage, current, resistance, and other electrical quantities. There are two general types of electrical meters: analog and digital. Analog meters have a hand or pointer that moves according to the amount of the quantity being measured. This type of meter is seldom used today. The other type, digital meters, display numbers indicating the amount of the quantity that is measured. Digital meters are by far the most common type of meter used today. Measurements are made in many types of circuits.

You should learn the proper procedure for measuring resistance, voltage, and current for working with robotic systems. These three measurements are the most common for electrical circuits. Meters used for testing electrical circuits are often referred to as multimeters, such as a DMM (digital multimeter), which is used to measure voltage, current, or resistance. A representative type of digital multimeter will be discussed in this activity.

Measuring Resistance and General Meter Use

Many important electrical tests can be made by measuring resistance. Resistance is opposition to the flow of current in an electrical circuit. The current that flows in a circuit depends on the amount of resistance in that circuit. You should learn to measure resistance in an electrical circuit by using a meter.

A multimeter is used to measure resistance, voltage, or current. The type of measurement can be changed by adjusting the function-select switch (or push button) to the desired measurement. Often, the current range is labeled *mA* (milliamperes) for measuring current, *V* for voltage, and the ohm symbol (Ω) for measuring resistance. Also, a function-select switch or push button is pressed so that the meter may be used to measure alternating current (ac) values or direct current (dc) values.

The ohms measurement function of a DMM is typically divided into ranges, such as 200 Ω, 2 kΩ, 20 kΩ and 20 MΩ. This type of meter is called a multirange meter and there are many different types used. The meter may be adjusted to any of the positions for measuring resistance.

The test leads used with the meter are ordinarily black and red. These colors are used to help identify which lead is the positive or negative side. The positive (red) lead is inserted into the meter for voltage, resistance, and current measurements. The black lead (negative) is used as the *common* (COM) lead of the meter. Resistance values are sometimes indicated as *K ohms* (multiply by 1000) on the digital scale of the meter for some of the resistance ranges of the meter.

Another type of digital meter is an autoranging meter. The range values do not need to be changed for larger or smaller voltages, currents, or resistances. To measure resistance with this meter, the negative (black) lead is inserted in the COM jack and the positive (red) lead is placed in the V/Ohm jack. The function select switch of the meter is rotated to the ohm (resistance) symbol. Resistance values are indicated on the digital scale of the meter.

Measuring Voltage

Voltage is applied to electrical equipment to initiate operation. A technician should to be able to measure voltage in order to check the operation of equipment. Many electrical problems develop due to either too much or too little voltage being applied to the equipment. Multimeters are used to measure voltage in an electrical circuit. Typical voltage ranges of a DMM might be 200mV (millivolts), 2V, 20V, 200V and 1000V. When the function-select switch or push button is adjusted to 1000V on the dc volts range, for example, the meter can measure up to 1000 volts dc. The same is true for the other ranges of dc voltage. The voltage value of each range is the *maximum* voltage that may be measured on that range. When making voltage measurements, adjust the function-select switch or push button to the highest range of dc voltage to be measured. The red test lead should be put into the V-Ω-A jack. The black test lead should be put into the COM jack. Voltage values are measured with the meter connected *in parallel* with the circuit or component being measured. Voltage values are indicated in volt units on the digital scale of the meter.

To measure voltage with an autoranging meter, the negative (black) lead is inserted in the COM jack and the positive (red) lead is placed in the V/Ohm jack. The function select switch is placed in one of the voltage settings: mV for millivolts, V for dc voltage, or $\tilde{V}$ for ac voltage. Voltage values are usually indicated directly in volts on the digital scale of the meter for each range.

Measuring Current

Current flows through a complete electrical circuit when voltage is applied. Many important tests are made by measuring current flow in an electrical circuit. The current values in an electrical circuit depend on the amount of resistance in the circuit. Learning to use a multimeter to measure current in an electrical circuit is also important.

To measure the current through a circuit, first make sure no voltage is applied to the circuit while you are connecting the meter. Current is measured with the meter *in series* with the circuit. The first step of the procedure for measuring current is to remove a connecting wire from the circuit at the point where the current will be measured. Set the multimeter to the *highest* current range. Connect the negative test lead to the most negative point of the circuit and the positive test lead nearest the positive power source terminal. After the meter has been connected in this manner, voltage may be applied to the circuit. If necessary, adjust the meter to a lower range to get an accurate current reading. The current value should never exceed the value of the range setting of the meter. The current value is read directly on the scale of the meter.

Now look at the controls of a typical multimeter being used for measuring current. The current ranges might be 2 mA (milliamperes), 20 mA, and 200 mA. For example, when the function-select switch or push button is adjusted to 2000 mA on the current range, the meter measures up to 2000 mA (2 amperes). The same is true for the other ranges of current in terms of the maximum current reading. The current value of each range is the *maximum* current that may be measured on that range. When making current measurements, adjust the function-select switch or push button to the highest range of current. The red test lead should be put into the mA jack. The black test lead should be put into the COM jack. Current values are usually indicated in milliampere units on the digital scale of the meter.

To measure current with an autoranging multimeter, the range values do not need to be changed for larger or smaller values. The negative (black) lead is inserted in the COM jack and the positive (red) lead is placed in the mA jack of the meter. The function select switch is adjusted to the mA (milliamperes) or μA (microamperes) setting, either dc or ac. Current values are indicated in milliamperes or microamperes, corresponding with the setting on the digital scale of the meter.

The multimeters discussed are representative of the types of digital meters used. The most common type has separate ranges that need to be set for making resistance, voltage, and current measurements. The autoranging meter needs only to be set for the desired function for measuring voltage, current, or resistance.

Analysis

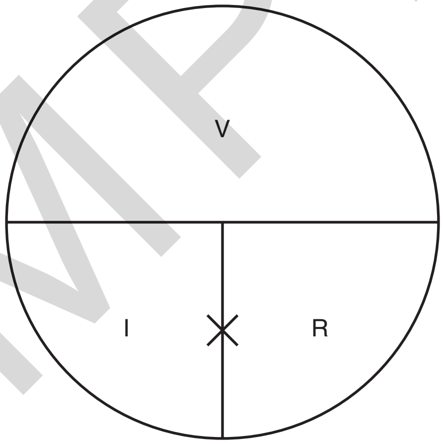
Obtain a meter to use for completing your lab activities. Study the meter and answer each of the following questions. Indicate N/A (not applicable) if the item does not apply to your meter. Explain at the end of the item.

1. What company manufactured the meter?
2. What is the model number of the meter?
3. The meter will measure up to what A of dc?
4. *True or False?* Ohms-adjust control is used each time the resistance range is changed.
5. To measure dc current greater than1 A, the range switch is placed in what position?
6. For measuring current in a circuit, the meter should be connected how (series or parallel)?
7. For measuring voltage, the meter should be connected how (series or parallel)?
8. To measure 18 mA of current, the range switch should be placed in what position?
9. To measure 10 μA of current, the range switch should be placed in what range?
10. To measure resistance, the red test lead must be placed in the jack with what marking? The black test lead must be placed in the jack with what marking?
11. *True or False?* Polarity must be observed when measuring ac voltage.
12. *True or False?* Polarity is not important when measuring resistance.
13. Up to how many volts dc can be measured with the meter?
14. For measuring a resistor valued at 10 Ω, what range should be used?
15. *True or False?* Polarity should be observed when measuring dc voltage.
16. *True or False?* It is correct to measure the resistance of a circuit with voltage applied.
17. *True or False?* When measuring an unknown value of voltage, one should start at the highest range and work down to the lowest value without exceeding the measured value.
18. *True or False?* Meters should always be handled with care and safety.

Activity 6-2
Basic Electrical Problem Solving

Objectives

Basic electrical problems are often encountered in any area which involves electrical control systems. Robotics is no exception. The most basic problems in electrical systems involve Ohm's law. Ohm's law is a mathematical formula which explains the relationship between voltage, current, and resistance. This relationship must be understood before electrical concepts are meaningful. In this activity, you will complete some practical problems by applying Ohm's law.



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Ohm's law circle: V, voltage; I, current; R, resistance. To use the circle, cover the value you want to find and read the other values as they appear in the formula: $V = I \times R$, $I = V/R$, $R = V/I$.

Analysis

1. A doorbell requires 0.2 ampere of current in order to ring. The voltage supplied to the bell is 120 volts. What is its resistance?
2. A relay used to control a motor is rated at 25 ohms resistance. What voltage is required to operate the relay if it draws a current of 0.25 ampere?
3. An automobile battery supplies a current of 7.5 amperes to a headlamp with a resistance of 0.84 ohm. What is the voltage delivered by the battery?
4. What voltage is needed to light a lamp if the current required is 2 amperes and the resistance of the lamp is 50 ohms?
5. If the resistance of a radio receiver circuit is 240 ohms and it draws a current of 0.6 ampere, what voltage is needed?

6. A television circuit draws 0.15 ampere of current. The operating voltage is 120 volts. What is the resistance of the circuit?
7. The resistance of the motor windings of an electric vacuum cleaner is 20 ohms. If the voltage is 120 volts, what is the amount of current drawn?
8. The coil of a relay carries 0.05 ampere when operated from a 50-volt source. Find its resistance.
9. How much current is drawn from a 12-volt battery when operating an automobile horn of 8 ohms resistance?
10. Find the resistance of an automobile starting motor if it draws 90 amperes from the 12-volt battery.
11. What current is drawn by a 5000-ohm electric clock when operated from a 120-volt line?
12. Find the current drawn by a 50-ohm toaster from a 120-volt line.

Activity 6-3

Control Systems Overview

Objectives

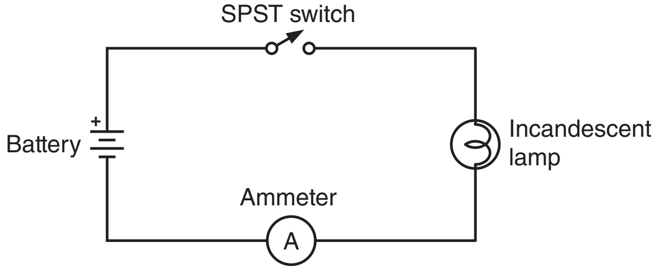
The term *system* is commonly defined as a combination of parts that work together to form a complete operating unit. In this respect, the term can apply to a variety of different systems used by industry to achieve some operation in the manufacturing process. An application of this term is the industrial electronic system. Further application of this term includes a wide variety of subsystems under the heading of industrial electronics. Opto-electronic systems, timing systems, digital systems, and environment control systems are all included in this study of industrial systems.

Each industrial system includes a number of unique features or characteristics that distinguish it from other systems. More importantly, however, there are a number of basic functions common to all electronic systems. Energy source, transmission path, control, load, and indicator are terms commonly used to describe these basic system functions.

In this activity, you will have an opportunity to study a representative system and pick out the basic parts of the system. By doing this, you will become more familiar with the systems concept and be able to apply it to a specific situation.

Procedure

1. Briefly define the function of the following basic system parts. Use general terms that would apply to all basic industrial electronic systems.
   - Energy source.
   - Transmission path.
   - Control.
   - Load.
   - Indicator.
2. Explain how the systems concept could be applied to an electrical power system used to supply an industrial plant site.
3. How could the systems concept be applied to a simple electrical circuit?



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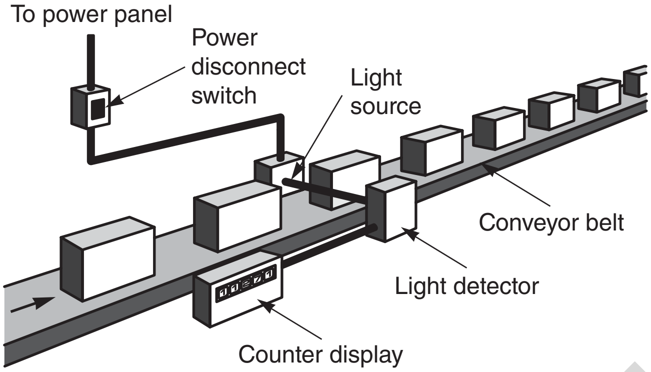
Electrical circuit.

4. The photoelectric box counter is a typical industrial system. What are the basic parts of this system?



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Industrial electronic system.

Analysis

1. Of what significance is the basic systems concept in industry?
2. What is an opto-electronic system?
3. What are some applications of an industrial timing system?
4. What does the term *digital system* mean?

Activity 6-4
AC Synchronous Motors

Objectives

The ac synchronous motor used in robotic systems is commonly classified as a constant-speed device. It has extremely rapid starting, stopping, and reversing abilities. Motors of this type require only a simple clockwise-stop-counter-clockwise rotary switch for control. The starting and running currents of a synchronous motor are identical, which is unique for ac motors. This characteristic means that a motor of this type can withstand a high inrush of current when direction changes occur. As a general rule, the synchronous motor can even be stalled without damaging the motor.

Motors of this type are commonly used as drive mechanisms for robotic systems in machinery operations. Starting begins within 1 1/2 cycles of the line frequency, and stopping occurs in five mechanical degrees of rotation. This motor represents a unique part of all servomechanisms used in precision rotary control applications today. In this activity, a simple test circuit will be constructed so you may observe starting and stopping of an ac synchronous motor and the current flow characteristics of the motor.

Equipment and Materials

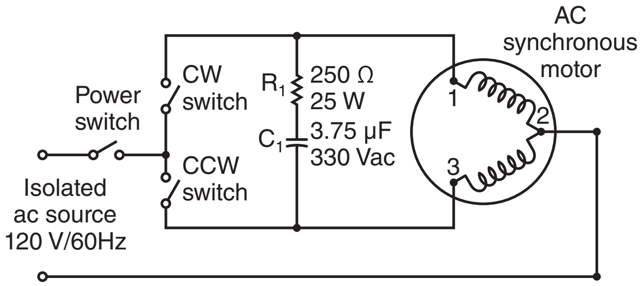
- AC synchronous motor—Superior Electric Type SS150 or equivalent motor rated at no more than 200 in/oz.
- Capacitor—3.75 µF, 330V ac.
- Resistor—250 Ω, 25 W.
- 3 — SPST switches.
- Isolated ac power source—120V.
- AC ammeter—0–5 A.
- Piece of wood.

Safety

Use protective eyewear during this activity.

Procedure

1. Construct the ac synchronous motor test circuit shown in the following figure. Ensure that the motor is mounted securely.



AC synchronous motor test circuit.

2. Turn on the switch for clockwise rotation.
3. Momentarily turn on the power switch and observe the rotation of the motor.
4. With a tachometer, measure and record the speed of rotation.
5. Momentarily turn off the power switch and observe the stopping action of the synchronous motor. You may want to run several trials to see the quickness of the stopping action. How does this compare with other ac motors?
6. Note each time that the motor is turned on, how quickly it comes to speed.
7. With an ac ammeter, measure and record the running current and starting current of the synchronous motor.
8. Carefully wedge a piece of wood between the rotating shaft and the bench while holding the motor. This will provide a simple loading method for test purposes.
9. When the motor is loaded down, how does the running current respond?
10. If the motor is completely stalled, how does the running current respond?
11. Remove the load from the motor, turn off the clockwise switch, and turn on the counterclockwise switch. The motor should rotate equally well in the counterclockwise direction and have the same basic characteristics. Test these again to verify the theory.
12. Switch off the counterclockwise switch, then switch on the clockwise switch. Notice the ease with which direction change occurs.
13. Turn off the ac power source and disconnect the circuit. Return all parts to the storage area.

Analysis

1. Discuss the operation of an ac synchronous motor.

Activity 6-5

DC Stepping Motors

Objectives

DC stepping motors represent a unique electromechanical rotary actuator that is used in robotic systems. These motors are designed to change electrical pulses into rotary motion. The amount of rotary movement or angular displacement produced by each pulse is repeated precisely for each succeeding pulse. The resulting rotation of these motors may be used to locate or position worktables or fixtures accurately for automatic machining operations. Very precise degrees of accuracy can be achieved with these devices.

In this activity, you will construct a simple test circuit for a dc stepping motor. You will be able to produce very accurate shaft movements by using different switching step combinations. Both the four-step and eight-step switching combinations will be tested. Through this activity, you will be able to observe the physical operation and test the accuracy of motor shaft rotation. The switching operation of this activity is achieved automatically by logic devices in actual operating circuits. Precise switching operations obviously improve the accuracy of this circuit.

Equipment and Materials

- DC stepping motor—Superior Electric Type M061-FD02 or equivalent.
- 4 — SPST switches.
- Resistor—50 Ω, 20 W.
- Resistor—1000 Ω, 1/2 W.
- DC power supply—0–25V, 1 A.
- 4 — Diodes—1N4004.

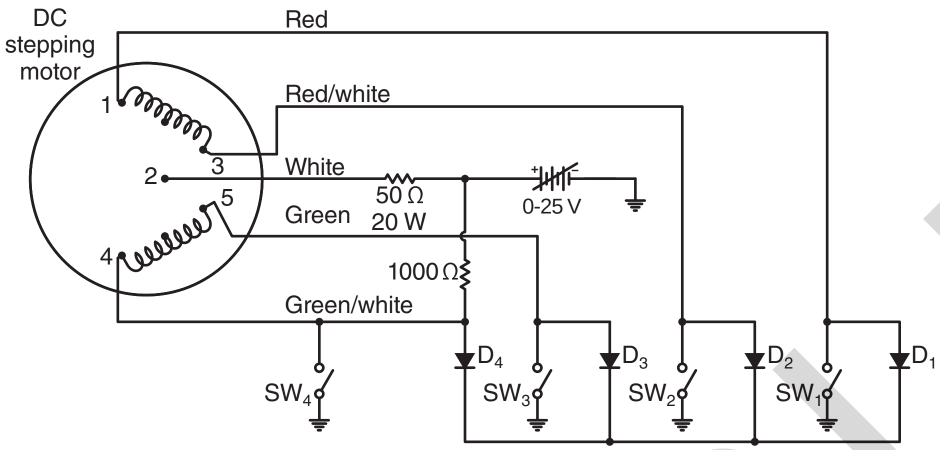
Safety

Use protective eyewear during this activity.

Procedure:

1. Construct the stepping motor test circuit as shown in the next figure.
2. The physical movement of the stepping motor shaft is small and rather difficult to observe. By attaching a simple indicating device, such as a small wire or paper pointer, to the motor shaft the mechanical rotation can be readily observed.
3. The switching sequence in the full-step mode will produce 1.8 steps for each switching combination.

4. Adjust the dc power supply to 15 volts. Set the indicator to a starting position and mark it as the starting reference. Then turn on the switch combinations for Step 1 of the full-step mode.



Four-step input (full-step mode)

Step	SW_1	SW_2	SW_3	SW_4
1	On	Off	On	Off
2	On	Off	Off	On
3	Off	On	Off	On
4	Off	On	On	Off
1	On	Off	On	Off

Eight-step input (half-step mode)

Step	SW_1	SW_2	SW_3	SW_4
1	On	Off	On	Off
2	On	Off	Off	Off
3	On	Off	Off	On
4	Off	Off	Off	On
5	Off	On	Off	On
6	Off	On	Off	Off
7	Off	On	On	Off
8	Off	Off	On	Off
1	On	Off	On	Off

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DC stepping motor test circuit and stepping tables.

5. Go to the next switching combination indicated by Step 2 of the chart. Each combination will produce a rotary step.
6. Follow the stepping procedure through at least two of the four-step cycles. Notice that the switching step combination repeats itself after Step 4.
7. Mark the indicator location as the stopping position for reference.
8. Calculate the rotational degrees by multiplying the number of steps by 1.8.
9. If a protractor is available, measure the number of degrees of rotation between the starting indicator mark and the last switching location mark of the motor shaft.
10. Repeat the procedure outlined in Steps 2 through 9 of this activity for the eight-step sequence. In this stepping mode, each step produces 0.9° of rotation.
11. Disconnect the circuit and return all components to the storage area.

Analysis

1. Explain how a dc stepping motor operates.
2. How many steps are required by a dc stepping motor in the full-step mode to produce one revolution?
3. How many steps are required by a dc stepping motor in the half-step mode to produce one revolution?
4. Describe a typical application of the dc stepping motor.

Activity 6-6
Solenoids

Objectives

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

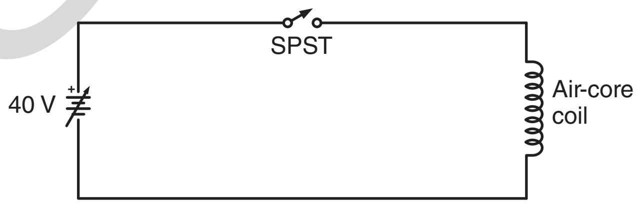
Solenoids are used for a variety of applications. For example, most door chime circuits use one or more solenoids to cause the chime to sound. Many gas and fuel oil furnaces use solenoid valves to turn the fuel supply on or off automatically on demand. Most dishwashers use one or more solenoids to control the flow of water. The solenoid is representative of the many types of electromechanical control devices used in conjunction with robotic systems. In this activity, you will learn the basic operation of the solenoid by observing a solenoid as it is used to operate door chimes.

Equipment and Materials

- Digital multimeter.
- Door chimes (low voltage, 6–24V).
- Variable dc power supply.
- Air-core coil (200 turns, No. 24 wire) or equivalent.
- Cold-rolled steel core, 3/4″ diameter, 6″ long or suitable substitute.
- SPST switch.
- Connecting wires.

Procedure

1. Adjust the multimeter to measure resistance. Measure and record the resistance of the air-core coil to be used in this activity.
2. Connect the circuit as shown in the following.



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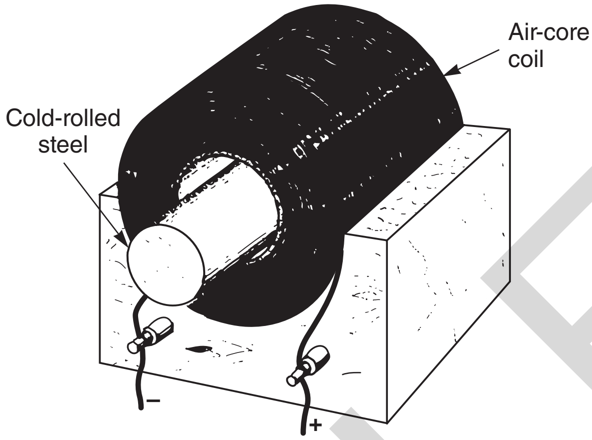
Solenoid test circuit.

3. Place about 2″ of the end of the cold-rolled steel bar into the coil.



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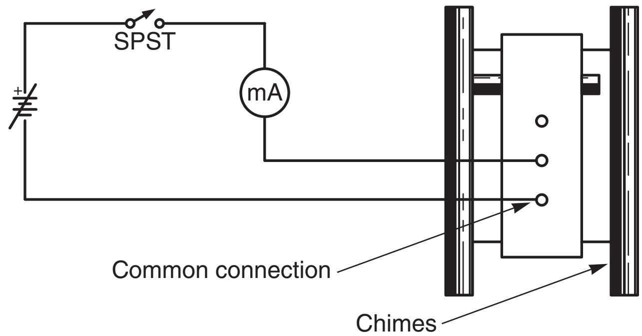
Air-core coil and steel core.

4. Close the SPST switch and describe what happens to the cold-rolled steel core. To prevent the coil from heating, do not allow the SPST switch to remain closed for more than 20 seconds.
5. Place the bar inside the coil and close the SPST switch. Try to remove the bar with the power on. Describe what happens. Do not allow the coil to remain energized for more than 20 seconds.
6. How could the above solenoid be used as a pusher or puller coil?
7. Disconnect the circuit.
8. Acquire a door chime assembly. Examine it to determine if it is to be powered by 6, 12, 18, or 24 volts. Record the voltage used for the chime assembly.
9. Remove the protective chime cover to expose the spring-loaded solenoids and solenoid connections. Measure and record the resistance of the solenoid coil.
10. There should be three solenoid connections. One will be common to the other two. Connect the common connection and either of the remaining connections to the power supply.



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Solenoid circuit with door chime.

11. Close the SPST switch and slowly adjust the power supply from zero until the plunger of the solenoid is drawn into the core. Record the current necessary to pull the plunger.
12. Open the SPST switch; adjust the power supply to the voltage indicated in Step 8.
13. Open and close the SPST switch several times. Describe what happens.
14. Disconnect the circuit and return all components to the storage area.

Analysis

1. What is a solenoid?
2. Where are solenoids used?
3. Why are solenoids sometimes called pusher coils?
4. Why are solenoid plungers spring-loaded?

Activity 6-7

Electromagnetic Relays

Objectives

Relays are electromagnetic switches and are excellent examples of how a magnetic field attracts a magnetic material. These devices contain a coil that creates an electromagnetic field; an armature, which is constructed of a magnetic material attracted by the coil; and a number of contacts or switches that open or close when the magnetic field attracts the armature.

In this activity, you will study the electromagnetic characteristics of a relay. Relays are a popular type of control device that might be used with robotic systems.

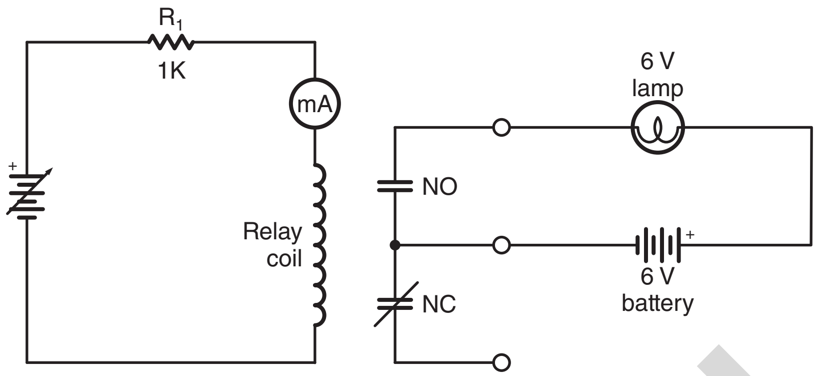
Equipment and Materials:

- Multicontact relay.
- 6V lamp with socket.
- Variable dc power supply.
- Resistor—1 kΩ.
- 6V battery.
- Connecting wires.
- Multimeter.

Procedure

1. Prepare the multimeter to measure resistance. Measure and record the resistance of the relay coil.
2. Using the multimeter, determine how many normally open and normally closed contacts are used with your relay.

3. Construct the circuit shown. Be sure that the variable dc power supply is adjusted to zero. The multimeter should be adjusted to measure dc current on the highest range.



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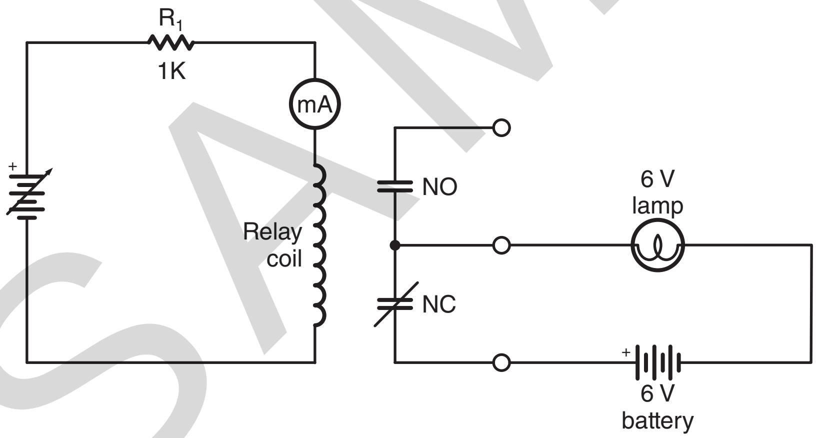
Circuit using electromagnetic relay.

4. Slowly adjust the variable dc power supply from zero until the 6V lamp is turned on. Record the current measured by the multimeter when the relay is energized. This is the pickup current.
5. Slowly adjust the variable dc power supply toward zero until the 6V lamp is turned off. Record the current measured by the multimeter when the relay de-energized. This is the dropout current.
6. Turn the variable power supply off.
7. Alter the circuit as shown.



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Circuit with relay contacts reversed.

8. You will notice that the only difference in the two circuits is the type of contacts used. In step 3, the normally open contacts were used. In this procedure, the normally closed contacts are used, causing the lamp to remain on until the relay is energized.
9. Adjust the variable dc power supply and record the pickup and dropout currents as you did in steps 4 and 5.

10. How do the currents recorded in step 9 compare with the current recorded in steps 4 and 5?
11. How did the action of the 6V lamp in steps 4 and 5 compare with the action of the lamp in step 9?

Analysis

1. What are normally open contacts?
2. What are normally closed contacts?
3. What is the meaning of the term *pickup current*?
4. What is the meaning of the term *dropout current*?
5. Using Ohm's law, compute the voltage across the relay coil when the relay is energized (see steps 1 and 4).

Activity 6-8

Motor-Driven Timers

Objectives

The motor-driven timer provides a wide variety of timing actions for industrial circuit applications. In its simplest form, this timer has an electric drive motor, a ratchet release coil, and a ratchet dial that is held stationary until released. When the timing cycle reaches its set-time, the ratchet is released and the dial resets itself by spring action. Both on delay and off delay reset timers are available. More sophisticated reset timers permit a wide range of timing operations in a single unit.

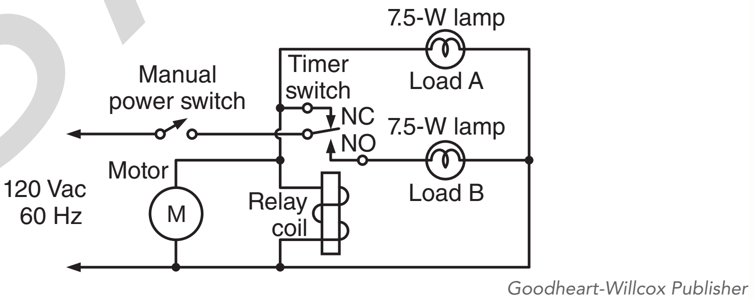
In this activity, a simple reset timer will be used to build a load control circuit that produces either interval or delay timing operations. Initially, when the timer is energized by the control switch, load A is turned on and load B is turned off. After the expired time setting or the time out condition has been reached, load A is turned off and load B is turned on. The action of a motor-driven timer is used to represent a type of timing application that might be used in conjunction with robotic system applications.

Equipment and Materials

- Reset timer (Eagle Signal HD-50 Series) or equivalent.
- 2—7.5 W incandescent lamps with sockets.
- SPST toggle switch.

Procedure

1. Refer to the timer manufacturer's product manual before attempting to complete this activity.
2. Wire the reset timer for the on delay operation as shown in the following.



Reset timer with on delay operation.

3. Adjust the time setting dial by pulling it out and turning it to a desired setting. Releasing the dial automatically locks it in the new setting.
4. Turn on the manual power switch and describe the operating condition of loads A and B.
5. When the dial setting trips, describe the operating condition of the load and the motor.
6. Start a new operation cycle by opening the control switch momentarily and then turning it on again. After the cycle has been in operation for a few seconds, momentarily open the control switch and then close it. What action does this initiate?

Analysis

1. What are some industrial applications of a reset timer?
2. Could this timer be modified to achieve a different function of some type? Explain.
3. Explain the difference between interval and delay timers.

Activity 6-9
Digital Timers

Objectives

Digital timers employ a time base generator (oscillator), a counter, and a load-driver circuit. The counter circuit frequently has several output terminals that permit selection of time ranges. Control ranges of 1T, 2T, 4T, 8T, 16T, and 32T are typical. Each output is rated in terms of the time base (T) of the generator circuit.

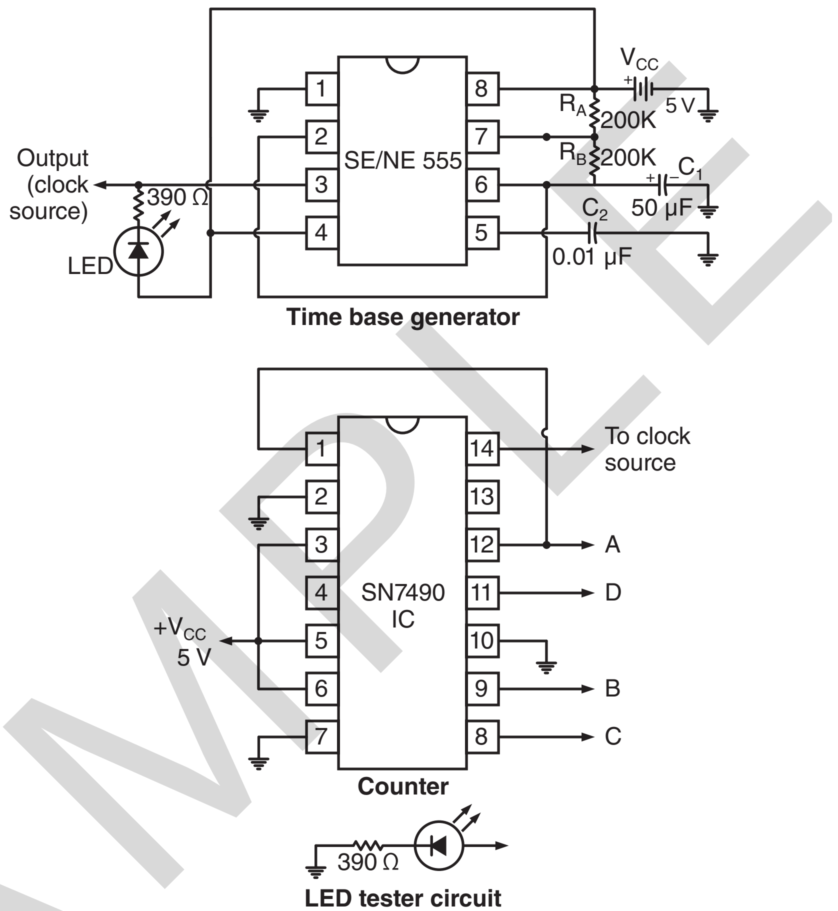
In this activity, you will employ the SE/NE555 timer IC as the time base generator of a simple digital timing system. The output of the generator will be counted and divided to some extent by the range of the system. Through this circuit investigation, you will see and work with the basic parts of a simple digital timing system. Commercially designed timers of this type are usually housed in an enclosure that does not permit access to component parts. These timers generally do not employ moving parts and are all solid state. The timing period is very accurate, and it usually ranges from microseconds to hours. Again, this type of device is being studied to represent the various types of timing control applications that might be used with robotic systems.

Equipment and Materials

- SE/NE555 IC.
- 2—200 kΩ, 1/8 W resistors.
- 390 Ω, 1/8 W resistor.
- Light-emitting diode.
- 4 μF, 25V dc capacitor.
- 0.01 μF, 100V capacitor.
- 50 μF, 25V capacitor.
- SPST toggle switches or pushbuttons.
- SN7490 IC.
- Circuit mounting board.

Procedure

1. Construct the experimental digital timer circuit of the following by first connecting the time base generator. Do not energize the SN7490 at this time.



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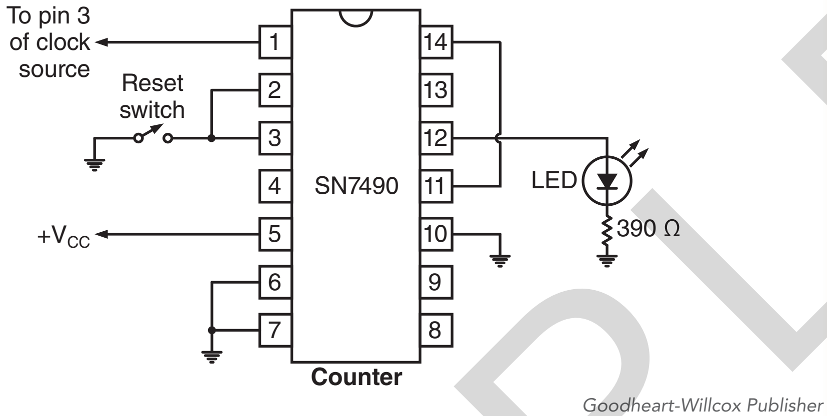
Digital timer circuit.

2. Determine the charging time of the circuit by the $t_c = 0.693 (R_A + R_B) C_1$ formula. Test the accuracy of the circuit. Record your findings.
3. Determine the discharge time of the circuit by the $t_d = 0.693R_B C_1$ formula. Test the accuracy of the circuit. Record your findings.
4. Turn off the power supply and complete the SN7490 counter IC. Connect it to the same power source used by the 555. Connect the second LED indicator to the D output of the 7490 IC. Connect the IC clock source to the output (pin 3) of the 555.

5. Turn on the power source and count the number of timing cycles needed to energize the 7490 LED readout. What mathematical function does this represent?
6. Turn off the power source and move the LED readout of the 7490 to output A. Turn on the power again and determine the counting cycles needed to energize the LED. What mathematical function does this represent?
7. Turn off the power supply and alter the SN7490 circuitry. Change C_1 of the time base generator to 4 µF.



Modified counter circuit.

8. Turn on the power supply and open the reset switch. Close the switch during a time when the time base generator LED is off. Count the number of timing cycles needed to energize the SN7490 LED. Also, count the number of timing cycles needed to turn off the LED. What does this represent as an output of the IC?

Analysis

1. How could the digital timer of this experiment be extended? Name two ways.
2. How can the digital timer of this experiment be made variable?
3. Would it be advantageous to have a reset switch on an actual digital timer? Why?