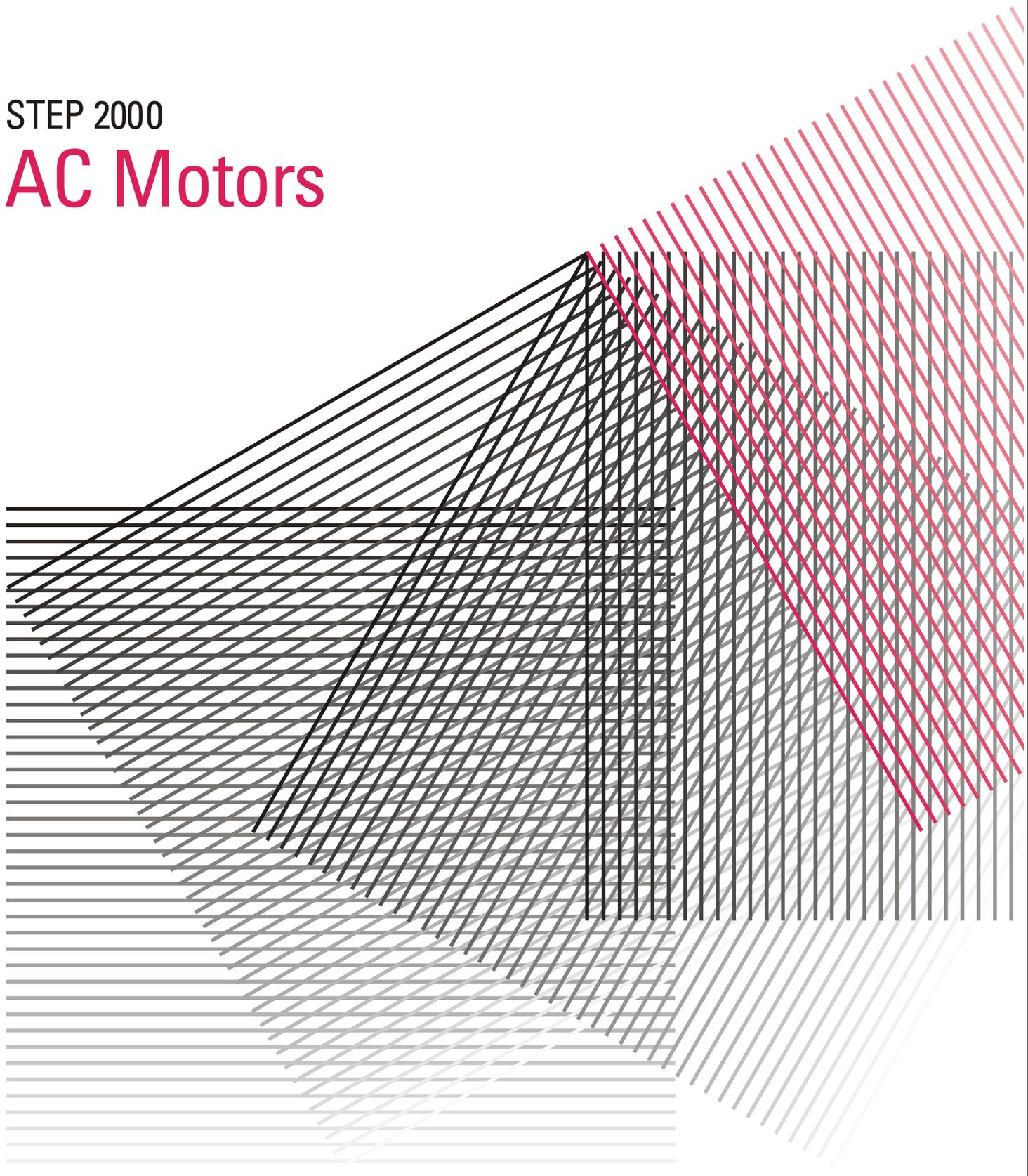


**SIEMENS**

STEP 2000

# AC Motors



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# Introduction

Welcome to another course in the STEP 2000 series, **Siemens Technical Education Program**, designed to prepare our distributors to sell Siemens Energy & Automation products more effectively. This course covers **AC Motors** and related products.

Upon completion of **AC Motors** you should be able to:

- Explain the concepts of force, inertia, speed, and torque
- Explain the difference between work and power
- Describe the construction of a squirrel cage AC motor
- Describe the operation of a rotating magnetic field
- Calculate synchronous speed, slip, and rotor speed
- Plot starting torque, accelerating torque, breakdown torque, and full-load torque on a NEMA torque curve
- Apply derating factors as required by an application
- Describe the relationship between V/Hz, torque, and horsepower
- Match an AC motor to an application and its load
- Identify NEMA enclosures and mounting configurations
- Describe Siemens Medallion™, PE-21 Plus™, vertical pump, and IEC motors
- Describe torque characteristics and enclosures of Siemens above NEMA motors

This knowledge will help you better understand customer applications. In addition, you will be better able to describe products to customers and determine important differences between products. You should complete **Basics of Electricity** before attempting **AC Motors**. An understanding of many of the concepts covered in **Basics of Electricity** is required for **AC Motors**. You may also want to complete **Basics of Control Components** which discusses the application of control devices for start, stop, and thermal protection of AC motors.

If you are an employee of a Siemens Energy & Automation authorized distributor, fill out the final exam tear-out card and mail in the card. We will mail you a certificate of completion if you score a passing grade. Good luck with your efforts.

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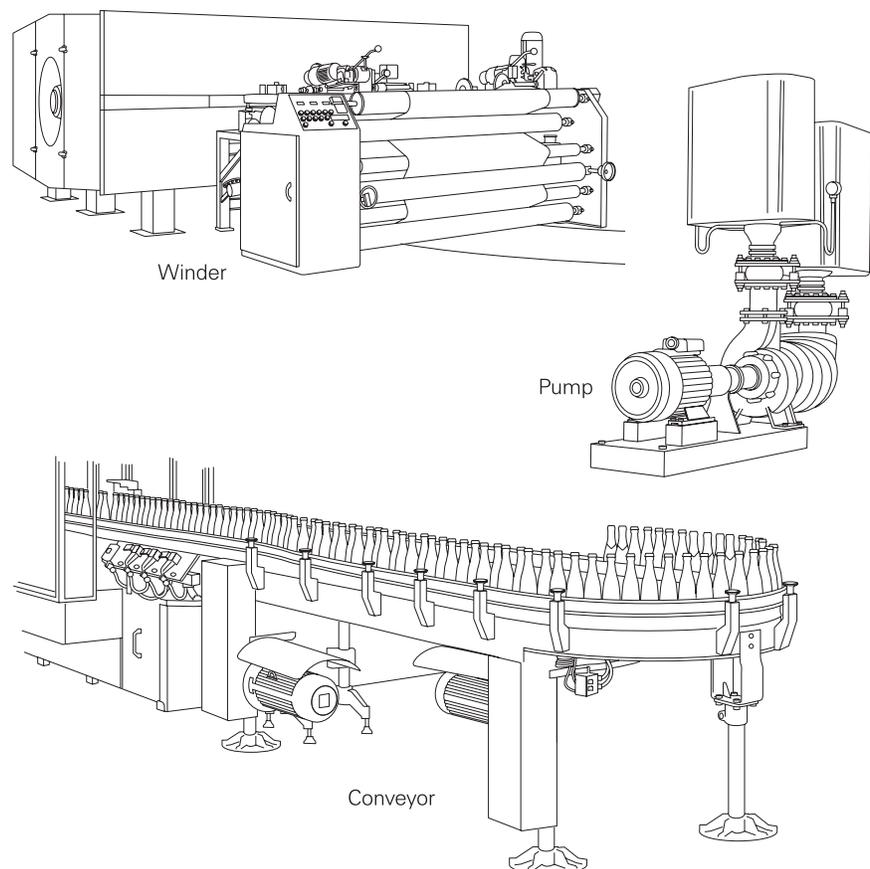
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# AC Motors

AC motors are used worldwide in many residential, commercial, industrial, and utility applications. Motors transform electrical energy into mechanical energy. An AC motor may be part of a pump or fan, or connected to some other form of mechanical equipment such as a winder, conveyor, or mixer. AC motors are found on a variety of applications from those that require a single motor to applications requiring several motors. Siemens manufactures a wide variety of motors for various applications. The material presented in this course will help in selection of a motor for a specific application.



## NEMA

Throughout this course reference is made to the National Electrical Manufacturers Association (NEMA). NEMA sets standards for a wide range of electrical products, including motors. NEMA is primarily associated with motors used in North America. The standards developed represent general industry practices and are supported by manufacturers of electrical equipment. These standards can be found in NEMA Standard Publication No. MG 1. Some large AC motors may not fall under NEMA standards. These motors are built to meet the requirements of a specific application. These are referred to as above NEMA motors.



## IEC

The International Electrotechnical Commission (IEC) is another organization responsible for motor standards. IEC are a group of recommended electrical practices developed by committees from participating IEC countries. These standards are different than NEMA standards. IEC standards are associated with motors used in many countries, including motors used in North America. These standards can be found in IEC 34-1-16. Motors which meet or exceed these standards are referred to as IEC motors.

# Force and Motion

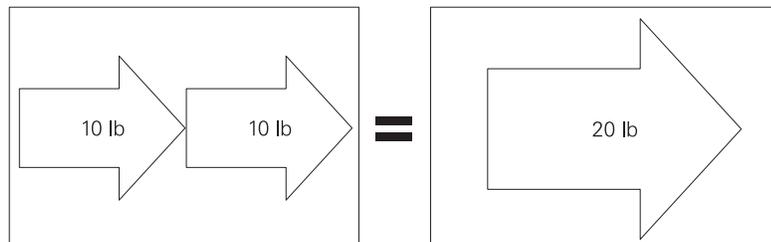
Before discussing AC motors it is necessary to understand some of the basic terminology associated with motor operation. Many of these terms are familiar to us in some other context. Later in the course we will see how these terms apply to AC motors.

## Force

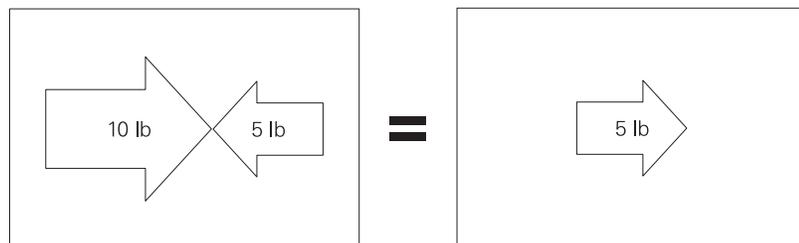
In simple terms, a force is a push or a pull. Force may be caused by electromagnetism, gravity, or a combination of physical means.

## Net force

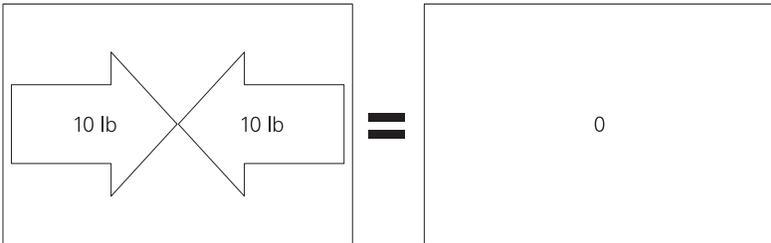
Net force is the vector sum of all forces that act on an object, including friction and gravity. When forces are applied in the same direction they are added. For example, if two 10 pound forces were applied in the same direction the net force would be 20 pounds.



If 10 pounds of force were applied in one direction and 20 pounds of force applied in the opposite direction, the net force would be 10 pounds and the object would move in the direction of the greater force.



If 10 pounds of force were applied equally in both directions, the net force would be zero and the object would not move.



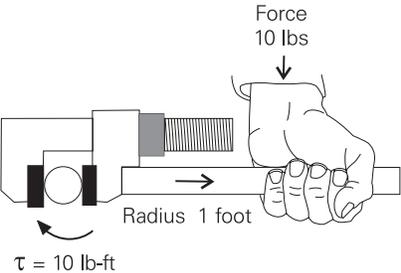
**Torque**

Torque is a twisting or turning force that causes an object to rotate. For example, a force applied to the end of a lever causes a turning effect or torque at the pivot point.

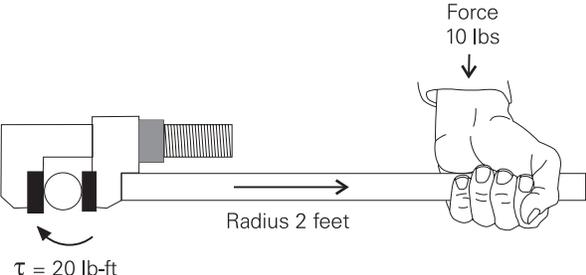
Torque ( $\tau$ ) is the product of force and radius (lever distance).

$$\tau = \text{Force} \times \text{Radius}$$

In the English system torque is measured in pound-feet (lb-ft) or pound-inches (lb-in). If 10 lbs of force were applied to a lever 1 foot long, for example, there would be 10 lb-ft of torque.



An increase in force or radius would result in a corresponding increase in torque. Increasing the radius to two feet, for example, results in 20 lb-ft of torque.



## Speed

An object in motion travels a distance in a given time. Speed is the ratio of the distance traveled and the time it takes to travel the distance.

$$\text{Speed} = \frac{\text{Distance}}{\text{Time}}$$

## Linear Speed

The linear speed of an object is a measure of how long it takes the object to get from point A to point B. Linear speed is usually given in a form such as meters per second (m/s). For example, if the distance between point A and point B were 10 meters, and it took 2 seconds to travel the distance, the speed would be 5 m/s.



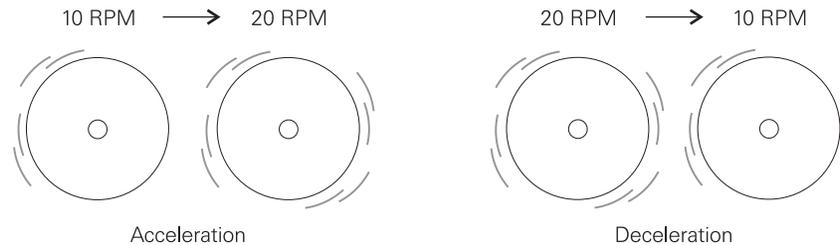
## Angular (Rotational) Speed

The angular speed of a rotating object is a measurement of how long it takes a given point on the object to make one complete revolution from its starting point. Angular speed is generally given in revolutions per minute (RPM). An object that makes ten complete revolutions in one minute, for example, has a speed of 10 RPM.



## Acceleration

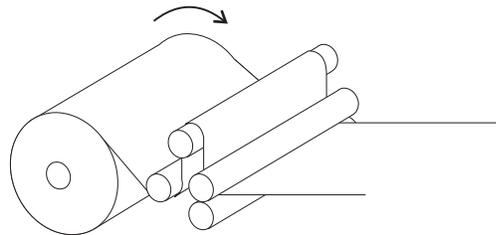
An object can change speed. An increase in speed is called acceleration. Acceleration occurs only when there is a change in the force acting upon the object. An object can also change from a higher to a lower speed. This is known as deceleration (negative acceleration). A rotating object, for example, can accelerate from 10 RPM to 20 RPM, or decelerate from 20 RPM to 10 RPM.



## Inertia

Mechanical systems are subject to the law of inertia. The law of inertia states that an object will tend to remain in its current state of rest or motion unless acted upon by an external force. This property of resistance to acceleration/deceleration is referred to as the moment of inertia. The English system of measurement is pound-feet squared ( $\text{lb}\cdot\text{ft}^2$ ).

If we look at a continuous roll of paper, for example, we know that when the roll is stopped it would take a certain amount of force to overcome the inertia of the roll to get it rolling. The force required to overcome this inertia can come from a source of energy such as a motor. Once rolling, the paper will continue unwinding until another force acts on it to bring it to a stop.



## Friction

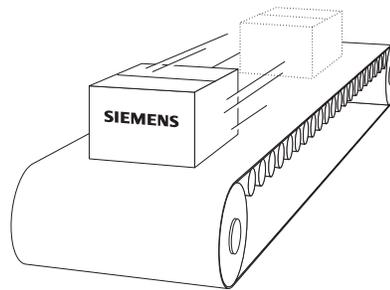
A large amount of force is applied to overcome the inertia of the system at rest to start it moving. Because friction removes energy from a mechanical system, a continual force must be applied to keep an object in motion. The law of inertia is still valid, however, since the force applied is needed only to compensate for the energy lost.

Once the system is in motion only the energy required to compensate for various losses need be applied to keep the conveyor in motion. In the previous illustration, for example, these losses include:

- Friction within motor and driven equipment bearings
- Wind losses in the motor and driven equipment
- Friction between material on winder and rollers

## Work

Whenever a force of any kind causes motion, work is accomplished. For example, work is accomplished when an object on a conveyor is moved from one point to another.



Work is generally expressed in foot-pounds and is defined by the product of the net force (F) applied and the distance (d) moved. If twice the force is applied, twice the work is done. If an object moves twice the distance, twice the work is done.

$$W = F \times d$$

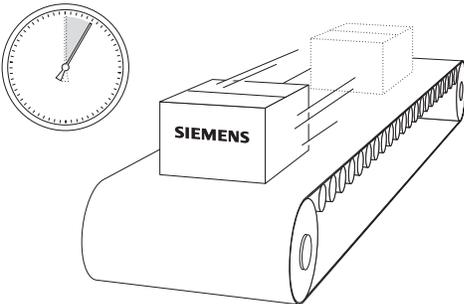
## Power

Power is the rate of doing work, or work divided by time.

$$\text{Power} = \frac{\text{Force} \times \text{Distance}}{\text{Time}}$$

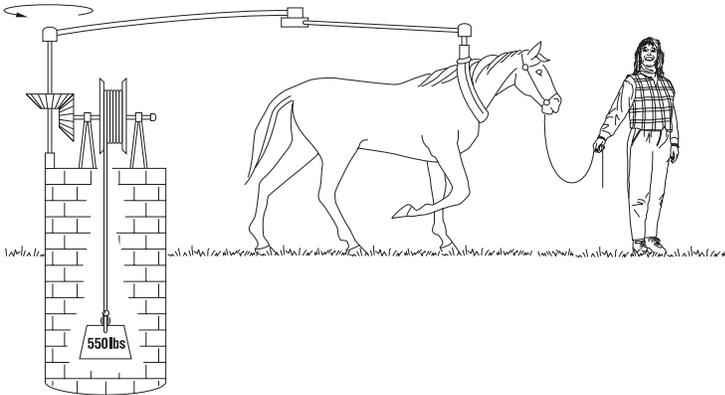
$$\text{Power} = \frac{\text{Work}}{\text{Time}}$$

In other words, power is the amount of work it takes to move the package from one point to another point, divided by the time.



**Horsepower**

Power can be expressed in foot-pounds per second, but is often expressed in horsepower (HP). This unit was defined in the 18th century by James Watt. Watt sold steam engines and was asked how many horses one steam engine would replace. He had horses walk around a wheel that would lift a weight. He found that each horse would average about 550 foot-pounds of work per second. One horsepower is equivalent to 550 foot-pounds per second or 33,000 foot-pounds per minute.



The following formula can be used to calculate horsepower when torque (in lb-feet) and speed are known. An increase of torque, speed, or both will cause an increase in horsepower.

$$HP = \frac{T \times RPM}{5250}$$

## Horsepower and kilowatts

AC motors manufactured in the United States are generally rated in horsepower (HP). Equipment manufactured in Europe is generally rated in kilowatts (KW). Horsepower can be converted to kilowatts with the following formula:

$$KW = .746 \times HP$$

For example, a 25 HP motor is equivalent to 18.65 KW.

$$18.65 \text{ KW} = .746 \times 25 \text{ HP}$$

Kilowatts can be converted to horsepower with the following formula:

$$HP = 1.341 \times KW$$

The power formula for a single-phase system is:

$$KW = \frac{V \times I \times PF}{1000}$$

The power formula for three-phase power is:

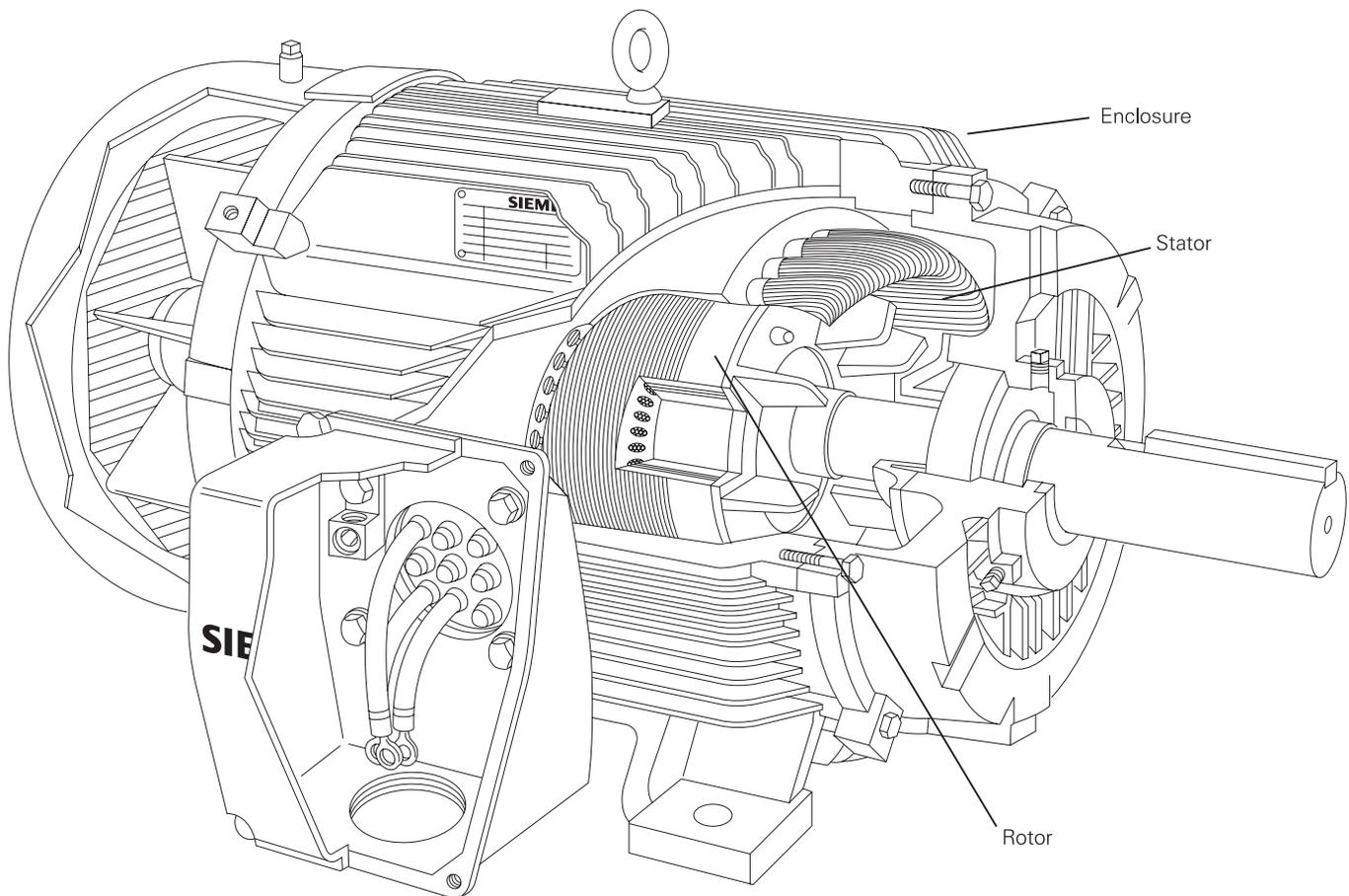
$$KW = \frac{V \times I \times PF \times 1.732}{1000}$$

## Review 1

1. A \_\_\_\_\_ is a push or a pull.
2. An object has 20 pounds of force applied in one direction and 5 pounds of force applied in the opposite direction. The net force is \_\_\_\_\_ pounds.
3. A twisting or turning force that causes an object to rotate is known as \_\_\_\_\_ .
4. If 40 pounds of force were applied to a lever 2 feet long, the torque would be \_\_\_\_\_ lb-ft.
5. The law of \_\_\_\_\_ states that an object will tend to remain in its current state of rest or motion unless acted upon by an external force.
6. \_\_\_\_\_ is the ratio of distance traveled and time.
7. The speed of a rotating object is generally given in \_\_\_\_\_ per \_\_\_\_\_ .
8. \_\_\_\_\_ only occurs when there is a change in an object's state of motion.

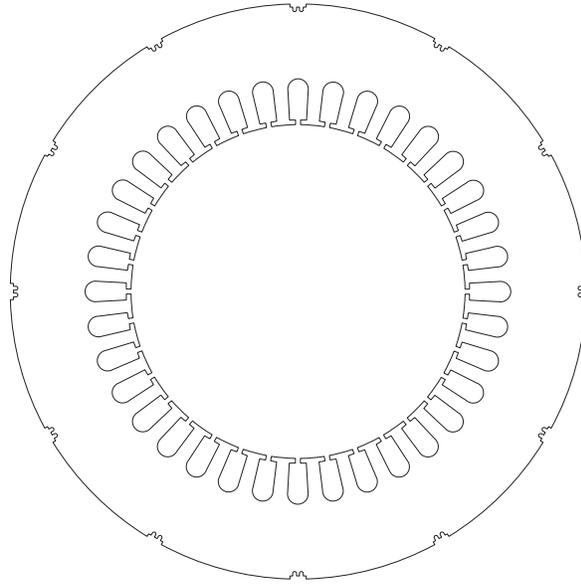
# AC Motor Construction

AC induction motors are commonly used in industrial applications. The following motor discussion will center around three-phase, 460 VAC, asynchronous, induction motors. An asynchronous motor is a type of motor where the speed of the rotor is other than the speed of the rotating magnetic field. This type of motor is illustrated below. The three basic parts of an AC motor are the rotor, stator, and enclosure.



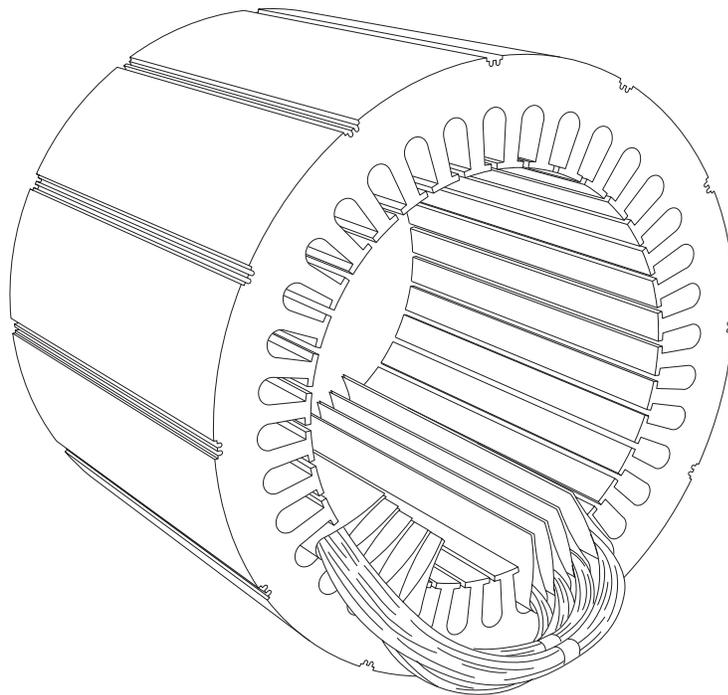
## Stator Construction

The stator and the rotor are electrical circuits that perform as electromagnets. The stator is the stationary electrical part of the motor. The stator core of a NEMA motor is made up of several hundred thin laminations.

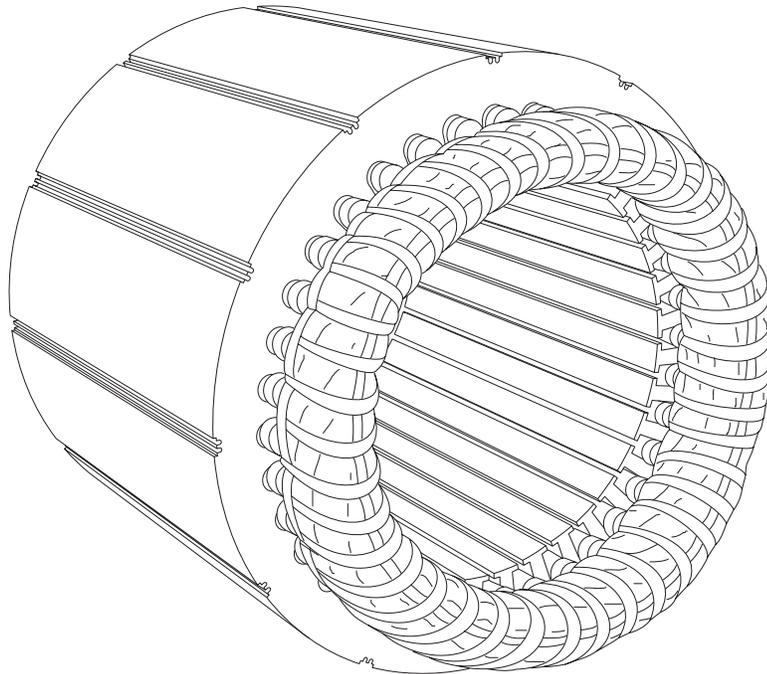


## Stator Windings

Stator laminations are stacked together forming a hollow cylinder. Coils of insulated wire are inserted into slots of the stator core.

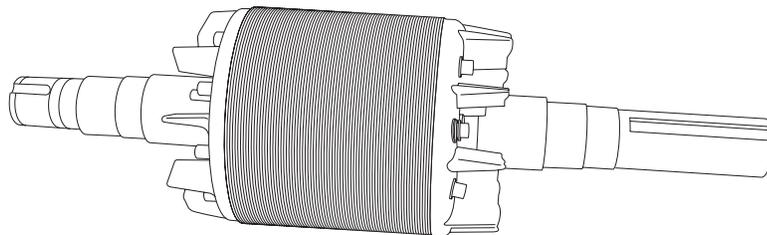


Each grouping of coils, together with the steel core it surrounds, form an electromagnet. Electromagnetism is the principle behind motor operation. The stator windings are connected directly to the power source.

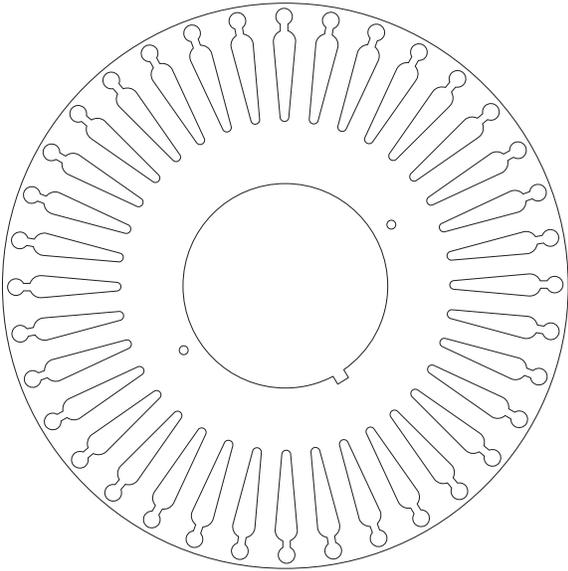


## **Rotor Construction**

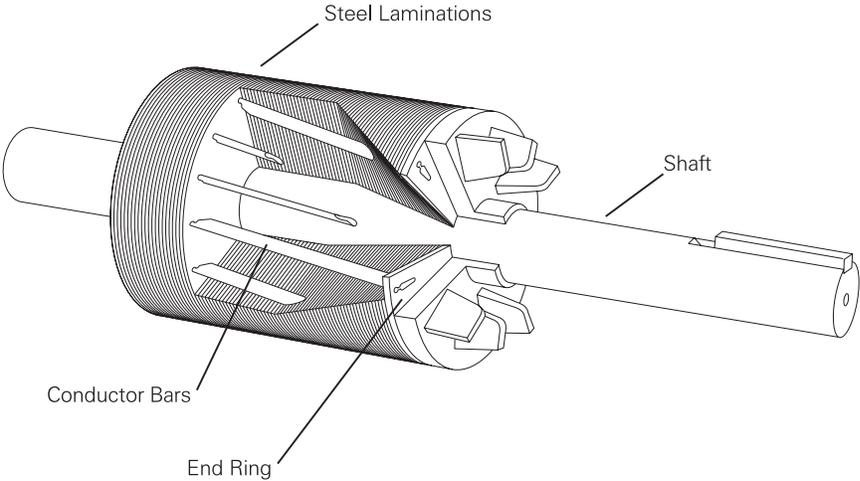
The rotor is the rotating part of the electromagnetic circuit. The most common type of rotor is the "squirrel cage" rotor. Other types of rotor construction will be mentioned later in the course. The construction of the squirrel cage rotor is reminiscent of rotating exercise wheels found in cages of pet rodents.



The rotor consists of a stack of steel laminations with evenly spaced conductor bars around the circumference.

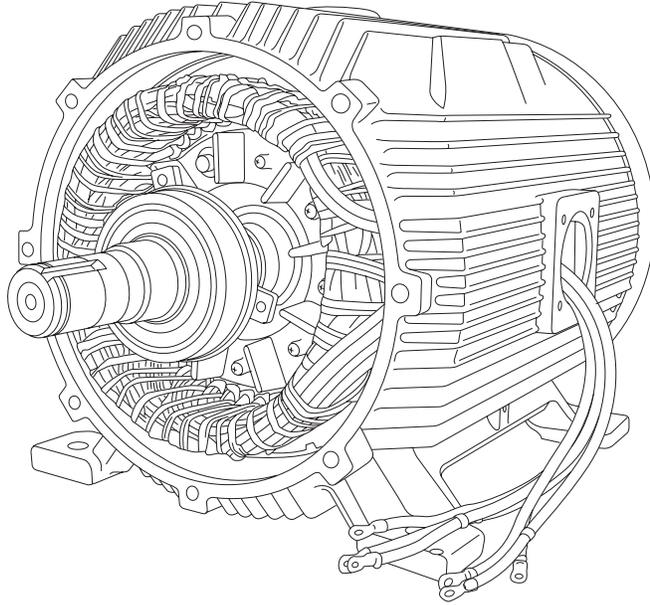


The laminations are stacked together to form a rotor core. Aluminum is die cast in the slots of the rotor core to form a series of conductors around the perimeter of the rotor. Current flow through the conductors form the electromagnet. The conductor bars are mechanically and electrically connected with end rings. The rotor core mounts on a steel shaft to form a rotor assembly.

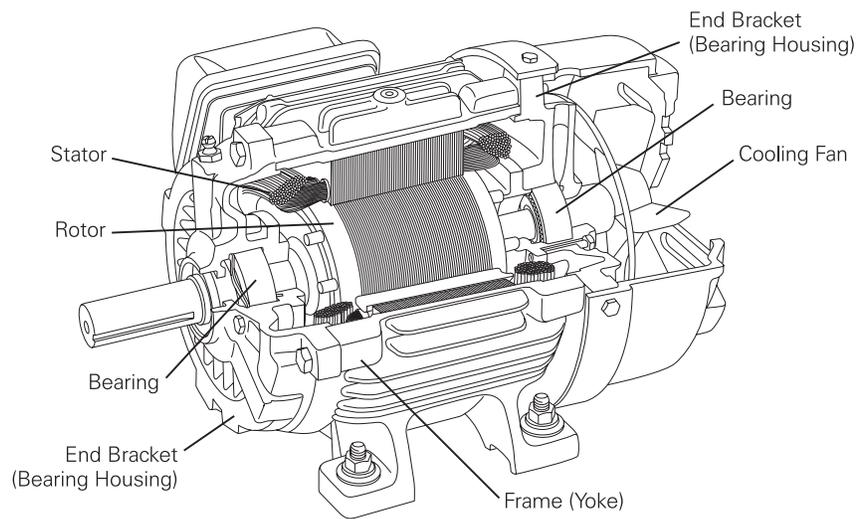


## Enclosure

The enclosure consists of a frame (or yoke) and two end brackets (or bearing housings). The stator is mounted inside the frame. The rotor fits inside the stator with a slight air gap separating it from the stator. There is no direct physical connection between the rotor and the stator.



The enclosure also protects the electrical and operating parts of the motor from harmful effects of the environment in which the motor operates. Bearings, mounted on the shaft, support the rotor and allow it to turn. A fan, also mounted on the shaft, is used on the motor shown below for cooling.



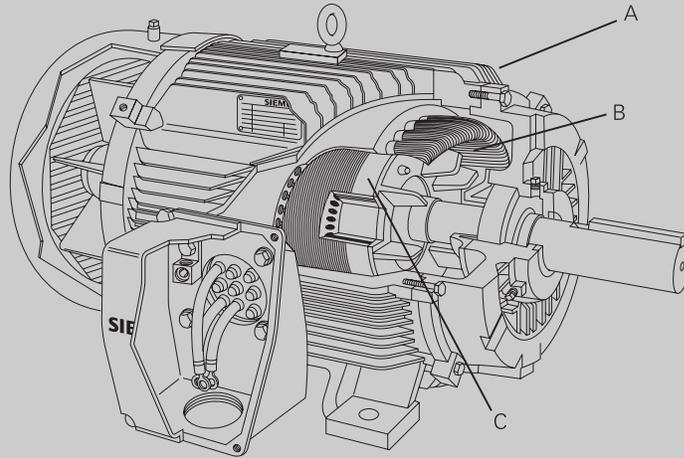
## Review 2

1. Identify the following components from the illustration:

A. \_\_\_\_\_

B. \_\_\_\_\_

C. \_\_\_\_\_



2. The \_\_\_\_\_ and the \_\_\_\_\_ are two parts of an electrical circuit that form an electromagnet.

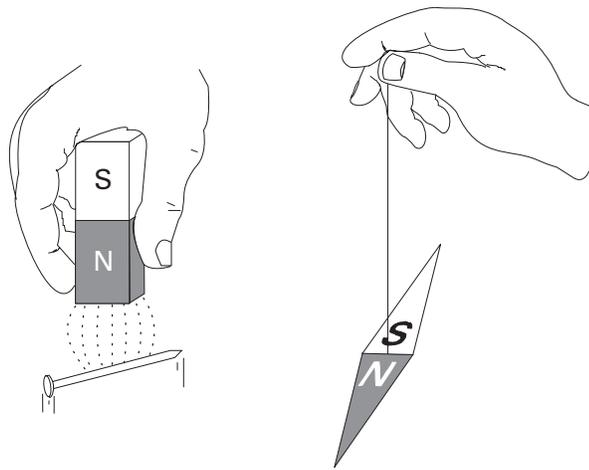
3. The \_\_\_\_\_ is the stationary electrical part of an AC motor.

4. The \_\_\_\_\_ is the rotating electrical part of an AC motor.

5. The \_\_\_\_\_ \_\_\_\_\_ rotor is the most common type of rotor used in AC motors.

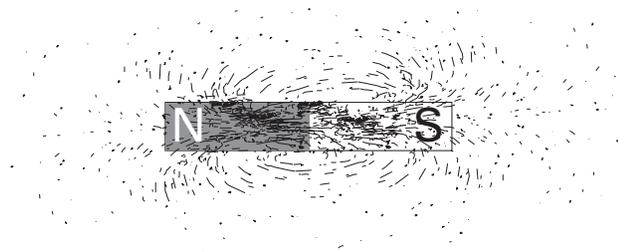
# Magnetism

The principles of magnetism play an important role in the operation of an AC motor. All magnets have two characteristics. They attract and hold metal objects like steel and iron. If free to move, like the compass needle, the magnet will assume roughly a north-south position.

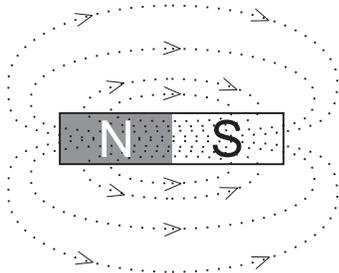


## Magnetic Lines of Flux

We know that a magnet attracts an iron or steel object by an invisible force. The magnet's invisible force is called lines of flux. These lines of flux make up an invisible magnetic field. Every magnet has two poles, one north pole and one south pole. Invisible magnetic lines of flux leave the north pole and enter the south pole. While the lines of flux are invisible, the effects of magnetic fields can be made visible. When a sheet of paper is placed on a magnet and iron filings loosely scattered over it, the filings will arrange themselves along the invisible lines of flux.

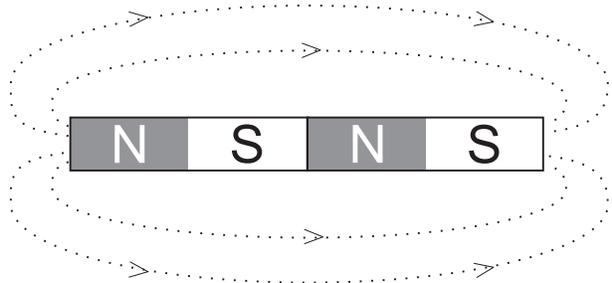


By drawing lines the way the iron filings have arranged themselves, the following illustration is obtained. Magnetic lines of flux always form closed loops, leaving the north pole and entering the south pole. They return to the north pole through the magnet.



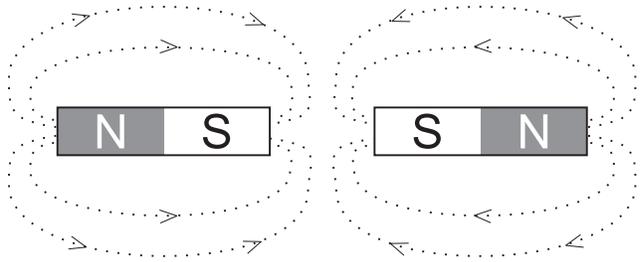
**Unlike Poles Attract**

The polarity of the magnetic field affects the interaction between magnets. For example, when the opposite poles of two magnets are brought within range of each other the lines of flux combine and tend to pull or attract the magnets.



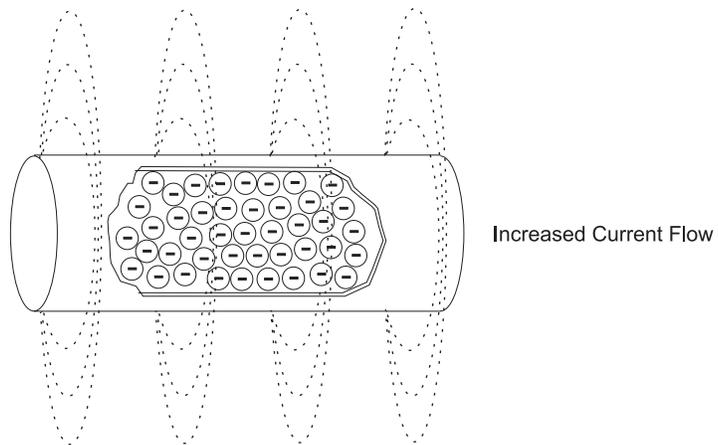
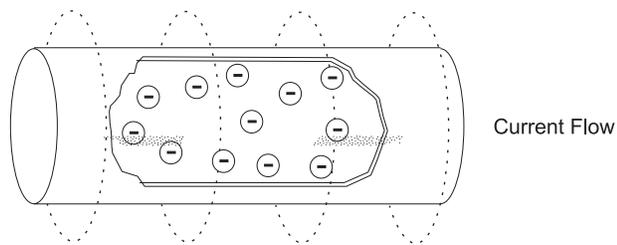
**Like Poles Repel**

When poles of like polarity of two magnets are brought within range of each other the lines of flux produce a force that tends to push or repel the magnets. For this reason it is said that unlike poles attract and like poles repel. The attracting and repelling action of the magnetic fields is important in the operation of AC motors.



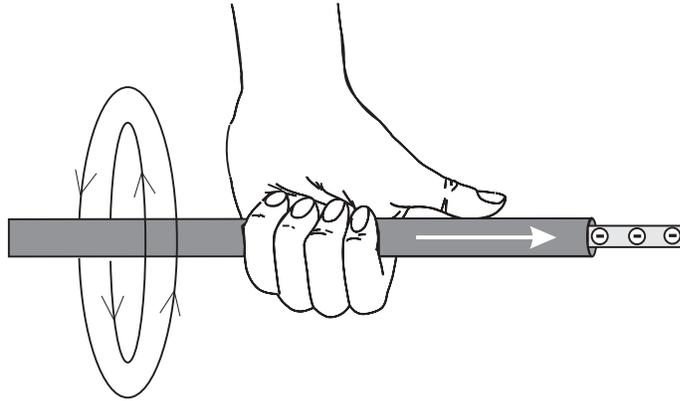
# Electromagnetism

When current flows through a conductor a magnetic field is produced around the conductor. The magnetic field is made up of lines of flux, just like a natural magnet. The size and strength of the magnetic field will increase and decrease as the current flow strength increases and decreases.

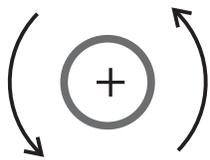


## Left-Hand Rule for Conductors

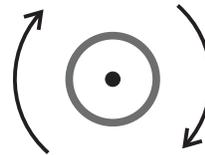
A definite relationship exists between the direction of current flow and the direction of the magnetic field. The left-hand rule for conductors demonstrates this relationship. If a current-carrying conductor is grasped with the left hand with the thumb pointing in the direction of electron flow, the fingers will point in the direction of the magnetic lines of flux.



In the following illustration it can be seen that when the electron flow is away from the viewer (indicated by the plus sign) the lines of flux flow in a counterclockwise direction around the conductor. When the electron flow reverses and current flow is towards the viewer (indicated by the dot) the lines of flux reverse direction and flow in a clockwise direction.



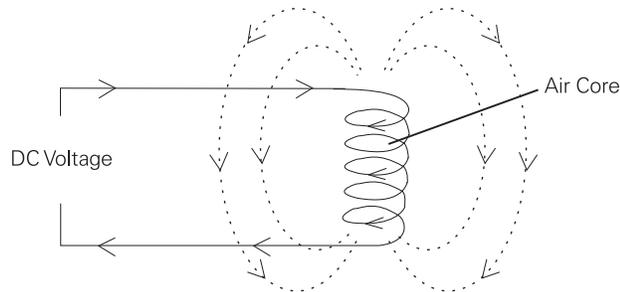
Current Flow  
Away From View



Current Flow  
Toward View

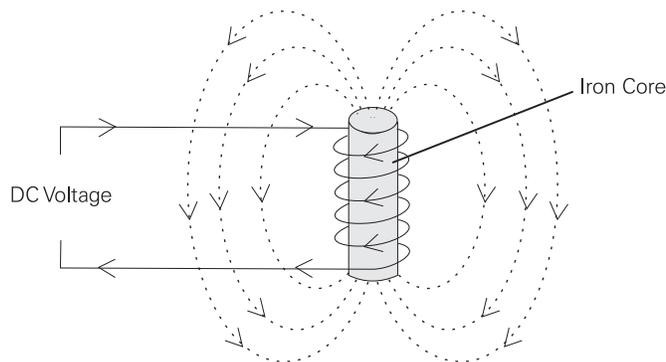
## Electromagnet

An electromagnet can be made by winding the conductor into a coil and applying a DC voltage. The lines of flux, formed by current flow through the conductor, combine to produce a larger and stronger magnetic field. The center of the coil is known as the core. In this simple electromagnet the core is air.



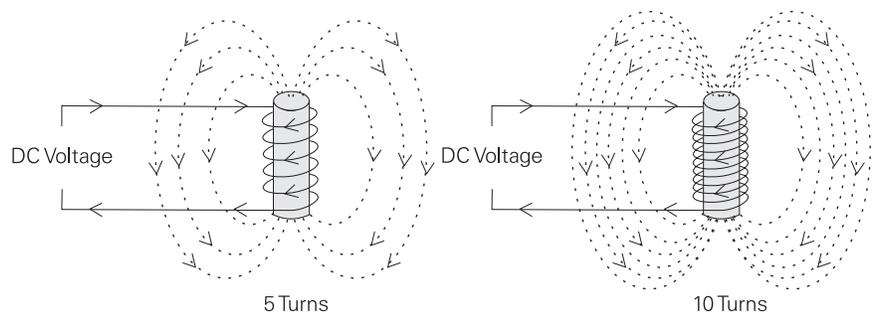
## Adding an Iron Core

Iron is a better conductor of flux than air. The air core of an electromagnet can be replaced by a piece of soft iron. When a piece of iron is placed in the center of the coil more lines of flux can flow and the magnetic field is strengthened.



## Number of Turns

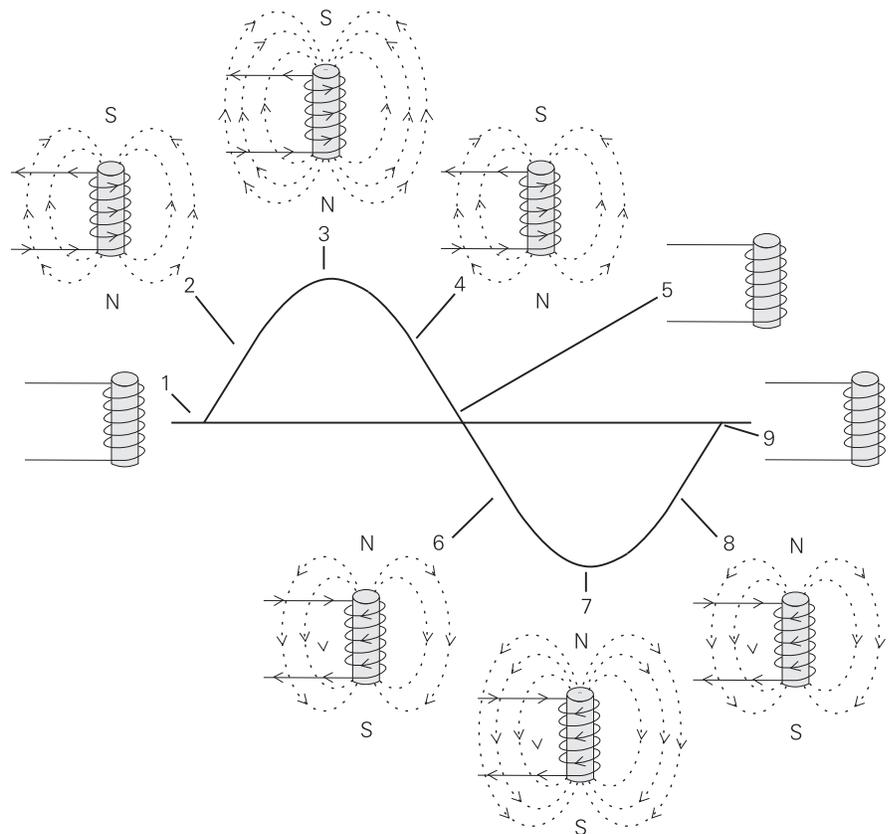
The strength of the magnetic field in the DC electromagnet can be increased by increasing the number of turns in the coil. The greater the number of turns the stronger the magnetic field.



## Changing Polarity

The magnetic field of an electromagnet has the same characteristics as a natural magnet, including a north and south pole. However, when the direction of current flow through the electromagnet changes, the polarity of the electromagnet changes. The polarity of an electromagnet connected to an AC source will change at the same frequency as the frequency of the AC source. This can be demonstrated in the following illustration.

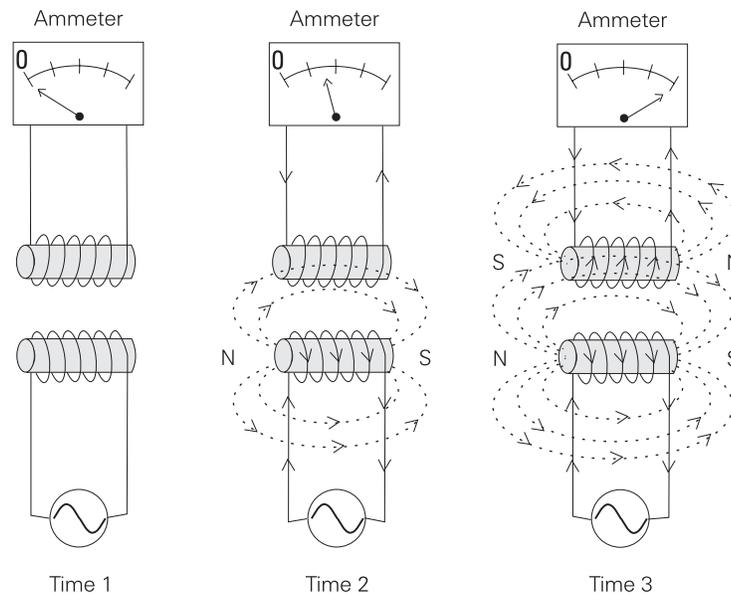
At Time 1 current flow is at zero. There is no magnetic field produced around the electromagnet. At Time 2 current is flowing in a positive direction. A magnetic field builds up around the electromagnet. The electromagnet assumes a polarity with the south pole on the top and the north pole on the bottom. At Time 3 current flow is at its peak positive value. The strength of the electromagnetic field is at its greatest value. At Time 4 current flow decreases and the magnetic field begins to collapse, until Time 5 when current flow and magnetic field are at zero. Current immediately begins to increase in the opposite direction. At Time 6 current is increasing in a negative direction. The polarity of the electromagnetic field has changed. The north pole is now on top and the south pole is on the bottom. The negative half of the cycle continues through Times 7 and 8, returning to zero at Time 9. This process will repeat 60 times a second with a 60 Hz AC power supply.



## Induced Voltage

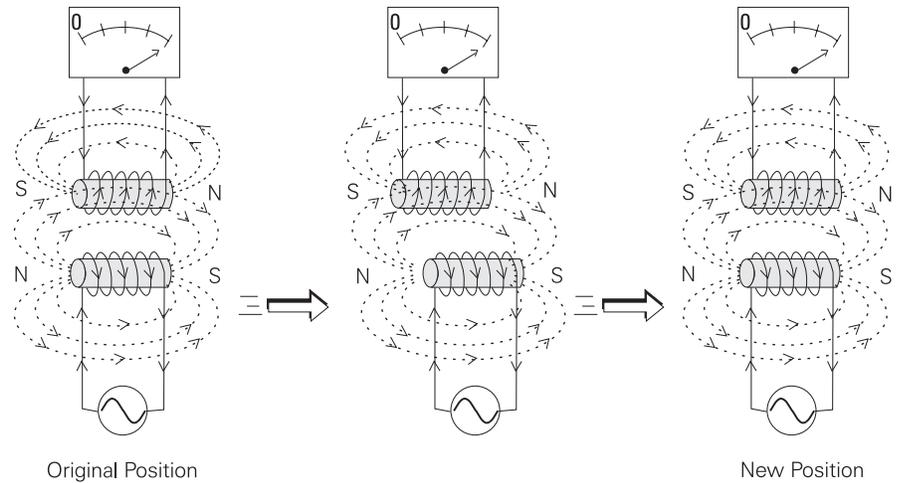
A conductor moving through a magnetic field will have a voltage induced into it. This electrical principle is used in the operation of AC induction motors. In the following illustration an electromagnet is connected to an AC power source. Another electromagnet is placed above it. The second electromagnet is in a separate circuit. There is no physical connection between the two circuits.

At Time 1 voltage and current are zero in both circuits. At Time 2 voltage and current are increasing in the bottom circuit. A magnetic field builds up in the bottom electromagnet. Lines of flux from the magnetic field building up in the bottom electromagnet cut across the top electromagnet. A voltage is induced in the top electromagnet and current flows through it. At Time 3 current flow has reached its peak. Maximum current is flowing in both circuits. The magnetic field around the coil continues to build up and collapse as the alternating current continues to increase and decrease. As the magnetic field moves through space, moving out from the coil as it builds up and back towards the coil as it collapses, lines of flux cut across the top coil. As current flows in the top electromagnet it creates its own magnetic field.



## Electromagnetic Attraction

The polarity of the magnetic field induced in the top electromagnet is opposite the polarity of the magnetic field in the bottom electromagnet. Since opposite poles attract, the top electromagnet will follow the bottom electromagnet when it is moved.



## Review 3

- Magnetic lines of flux leave the \_\_\_\_\_ pole of a magnet and enter the \_\_\_\_\_ pole.
- In the following illustration, which magnets will attract each other and which magnets will repel each other?
  - |   |   |
|---|---|
| N | S |
|---|---|

N	S
---	---

 \_\_\_\_\_
  - |   |   |
|---|---|
| N | S |
|---|---|

S	N
---	---

 \_\_\_\_\_
  - |   |   |
|---|---|
| S | N |
|---|---|

N	S
---	---

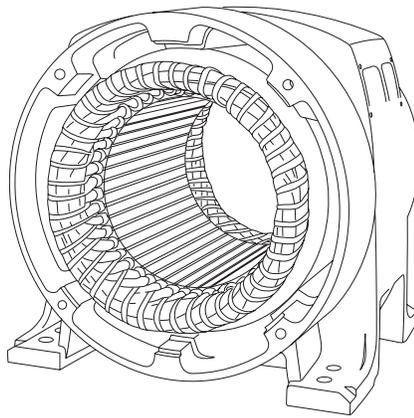
 \_\_\_\_\_
  - |   |   |
|---|---|
| S | N |
|---|---|

S	N
---	---

 \_\_\_\_\_
- A \_\_\_\_\_ is produced around a conductor when current is flowing through it.
- Which of the following will not increase the strength of the magnetic field?
  - Increase the current flow
  - Increase the number of turns in a coil
  - Add an iron core to a coil
  - Increase AC power supply frequency

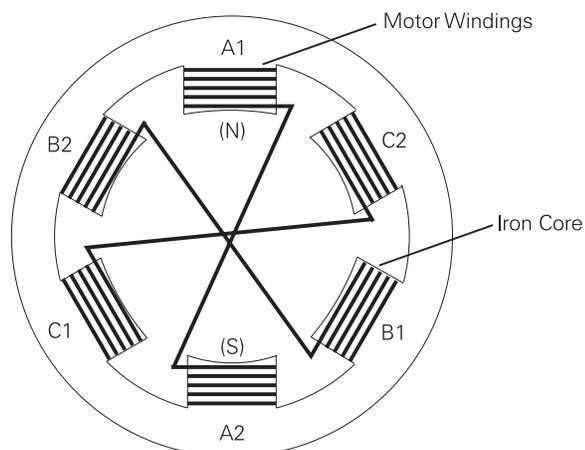
# Developing a Rotating Magnetic Field

The principles of electromagnetism explain the shaft rotation of an AC motor. Recall that the stator of an AC motor is a hollow cylinder in which coils of insulated wire are inserted.



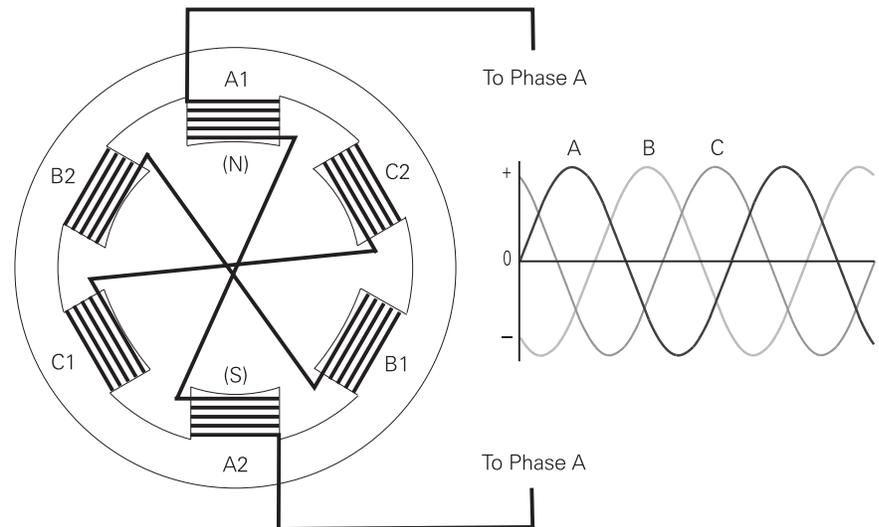
## Stator Coil Arrangement

The following schematic illustrates the relationship of the coils. In this example six coils are used, two coils for each of the three phases. The coils operate in pairs. The coils are wrapped around the soft iron core material of the stator. These coils are referred to as motor windings. Each motor winding becomes a separate electromagnet. The coils are wound in such a way that when current flows in them one coil is a north pole and its pair is a south pole. For example, if A1 were a north pole then A2 would be a south pole. When current reverses direction the polarity of the poles would also reverse.

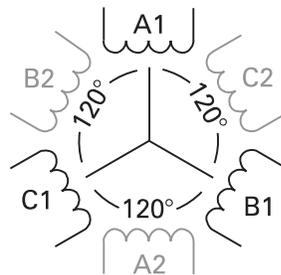


## Power Supply

The stator is connected to a 3-phase AC power supply. In the following illustration phase A is connected to phase A of the power supply. Phase B and C would also be connected to phases B and C of the power supply respectively.



Phase windings (A, B, and C) are placed  $120^\circ$  apart. In this example, a second set of three-phase windings is installed. The number of poles is determined by how many times a phase winding appears. In this example, each phase winding appears two times. This is a two-pole stator. If each phase winding appeared four times it would be a four-pole stator.



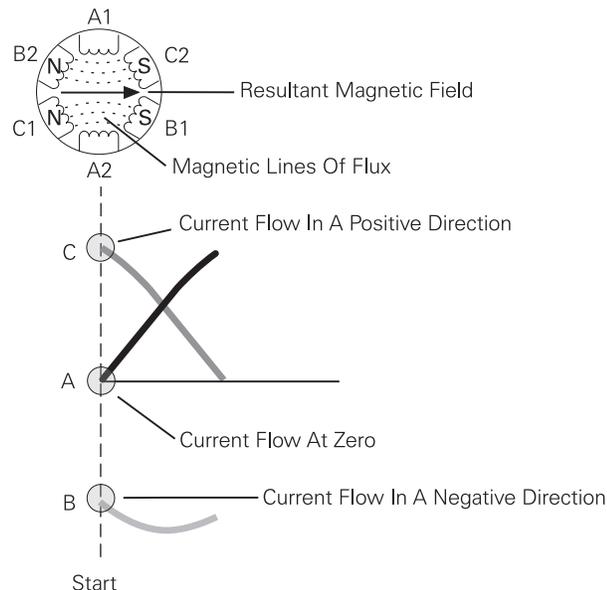
2-Pole Stator Winding

When AC voltage is applied to the stator, current flows through the windings. The magnetic field developed in a phase winding depends on the direction of current flow through that winding. The following chart is used here for explanation only. It will be used in the next few illustrations to demonstrate how a rotating magnetic field is developed. It assumes that a positive current flow in the A1, B1 and C1 windings result in a north pole.

Winding	Current Flow Direction	
	Positive	Negative
A1	North	South
A2	South	North
B1	North	South
B2	South	North
C1	North	South
C2	South	North

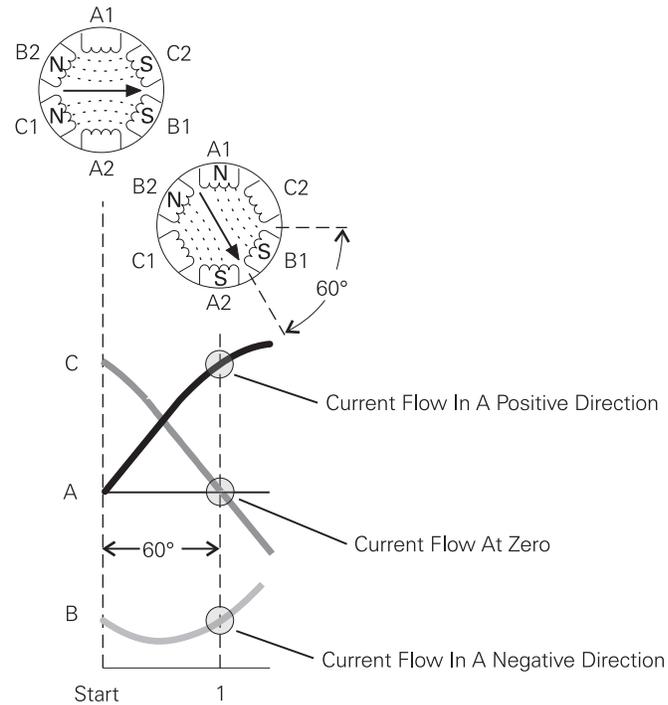
## Start

It is easier to visualize a magnetic field if a start time is picked when no current is flowing through one phase. In the following illustration, for example, a start time has been selected during which phase A has no current flow, phase B has current flow in a negative direction and phase C has current flow in a positive direction. Based on the above chart, B1 and C2 are south poles and B2 and C1 are north poles. Magnetic lines of flux leave the B2 north pole and enter the nearest south pole, C2. Magnetic lines of flux also leave the C1 north pole and enter the nearest south pole, B1. A magnetic field results, as indicated by the arrow.



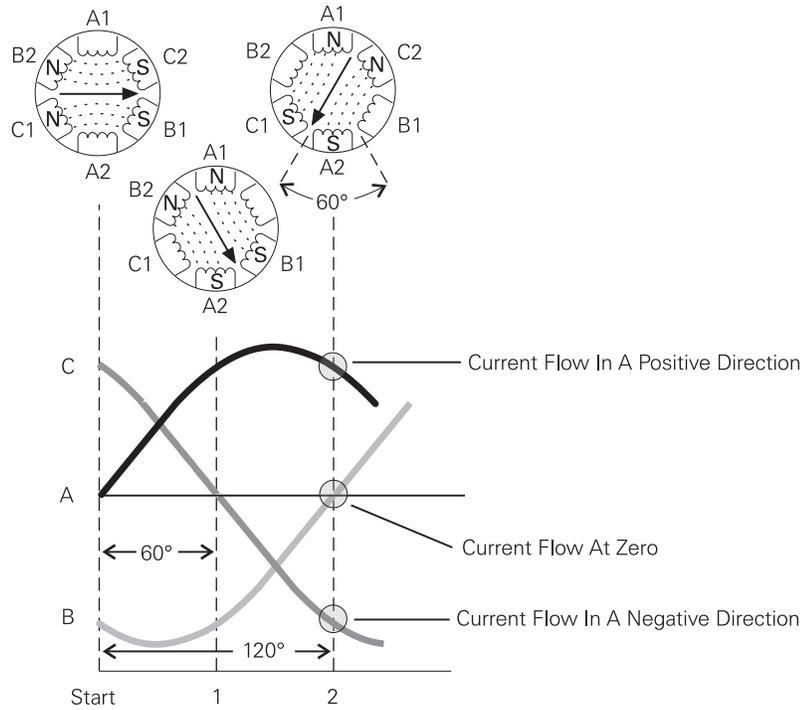
## Time 1

If the field is evaluated at  $60^\circ$  intervals from the starting point, at Time 1, it can be seen that the field will rotate  $60^\circ$ . At Time 1 phase C has no current flow, phase A has current flow in a positive direction and phase B has current flow in a negative direction. Following the same logic as used for the starting point, windings A1 and B2 are north poles and windings A2 and B1 are south poles.



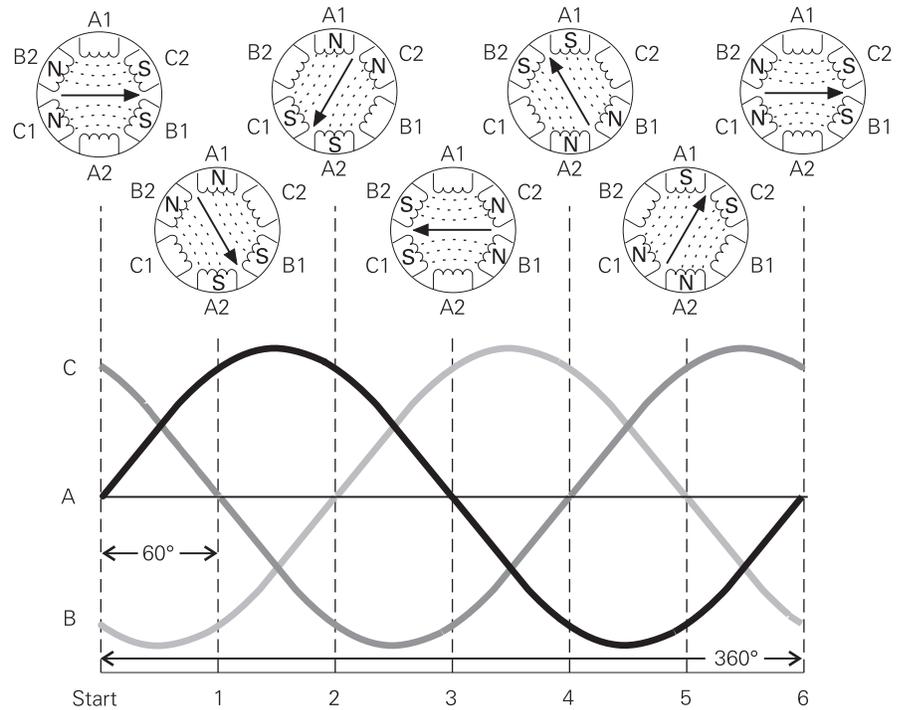
## Time 2

At Time 2 the magnetic field has rotated  $60^\circ$ . Phase B has no current flow. Although current is decreasing in phase A it is still flowing in a positive direction. Phase C is now flowing in a negative direction. At start it was flowing in a positive direction. Current flow has changed directions in the phase C windings and the magnetic poles have reversed polarity.



### 360° Rotation

At the end of six such time intervals the magnetic field will have rotated one full revolution or 360°. This process will repeat 60 times a second on a 60 Hz power supply.



### Synchronous Speed

The speed of the rotating magnetic field is referred to as synchronous speed ( $N_s$ ). Synchronous speed is equal to 120 times the frequency ( $F$ ), divided by the number of poles ( $P$ ). The synchronous speed for a two-pole motor operated at 60 Hz, for example, is 3600 RPM.

$$N_s = \frac{120F}{P} \implies N_s = \frac{120 \times 60}{2} \implies N_s = 3600 \text{ RPM}$$

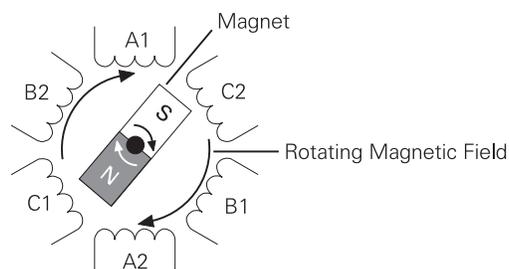
Synchronous speed decreases as the number of poles increase. The following table shows the synchronous speed at 60 Hz for the corresponding number of poles.

No. of Poles	Synchronous Speed
2	3600
4	1800
6	1200
8	900
10	720

# Rotor Rotation

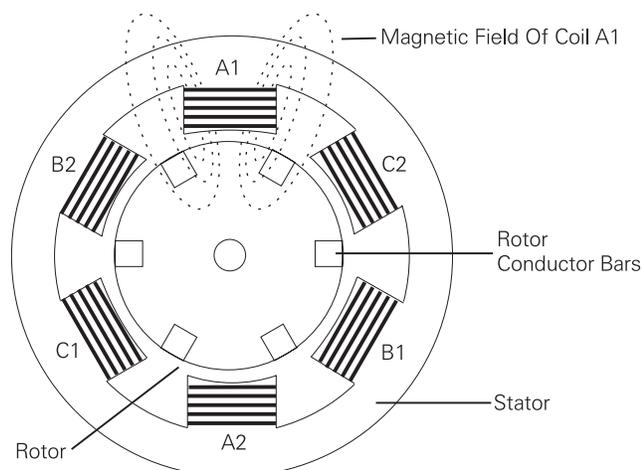
## Permanent Magnet

To see how a rotor works, a magnet mounted on a shaft can be substituted for the squirrel cage rotor. When the stator windings are energized a rotating magnetic field is established. The magnet has its own magnetic field that interacts with the rotating magnetic field of the stator. The north pole of the rotating magnetic field attracts the south pole of the magnet, and the south pole of the rotating magnetic field attracts the north pole of the magnet. As the rotating magnetic field rotates, it pulls the magnet along causing it to rotate. This design, used on some motors, is referred to as a permanent magnet synchronous motor.

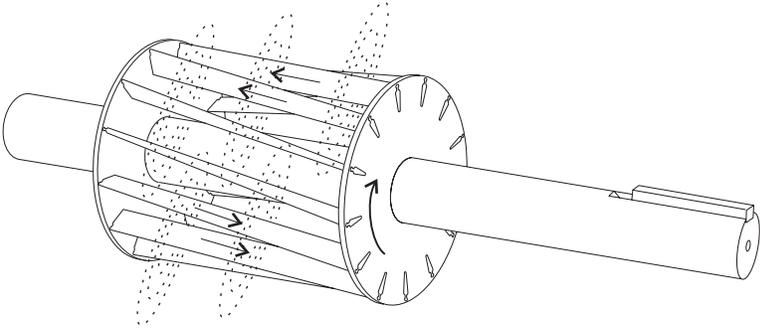


## Induced Voltage Electromagnet

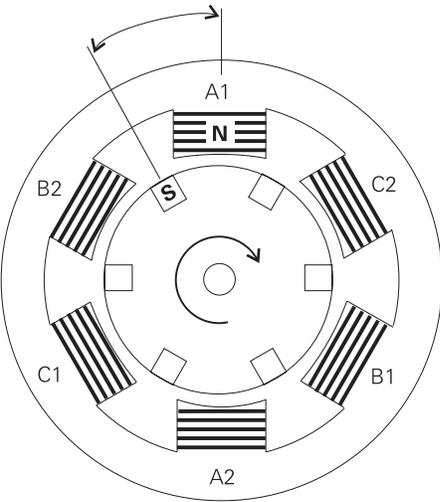
The squirrel cage rotor acts essentially the same as the magnet. When power is applied to the stator, current flows through the winding, causing an expanding electromagnetic field which cuts across the rotor bars.



When a conductor, such as a rotor bar, passes through a magnetic field a voltage (emf) is induced in the conductor. The induced voltage causes a current flow in the conductor. Current flows through the rotor bars and around the end ring. The current flow in the conductor bars produces magnetic fields around each rotor bar. Recall that in an AC circuit current continuously changes direction and amplitude. The resultant magnetic field of the stator and rotor continuously change. The squirrel cage rotor becomes an electromagnet with alternating north and south poles.



The following drawing illustrates one instant in time during which current flow through winding A1 produces a north pole. The expanding field cuts across an adjacent rotor bar, inducing a voltage. The resultant magnetic field in the rotor tooth produces a south pole. As the stator magnetic field rotates the rotor follows.



## Slip

There must be a relative difference in speed between the rotor and the rotating magnetic field. If the rotor and the rotating magnetic field were turning at the same speed no relative motion would exist between the two, therefore no lines of flux would be cut, and no voltage would be induced in the rotor. The difference in speed is called slip. Slip is necessary to produce torque. Slip is dependent on load. An increase in load will cause the rotor to slow down or increase slip. A decrease in load will cause the rotor to speed up or decrease slip. Slip is expressed as a percentage and can be determined with the following formula.

$$\% \text{ Slip} = \frac{N_s - N_R}{N_s} \times 100$$

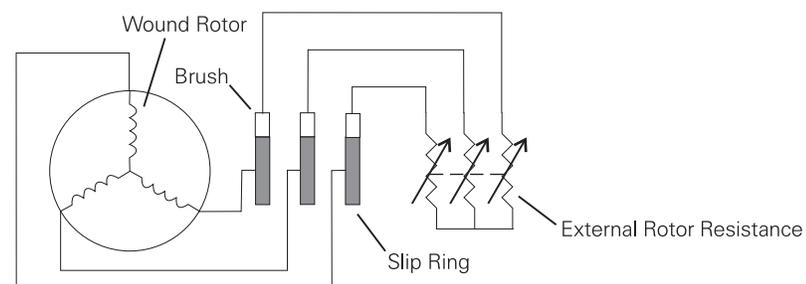
For example, a four-pole motor operated at 60 Hz has a synchronous speed ( $N_s$ ) of 1800 RPM. If the rotor speed at full load is 1765 RPM ( $N_R$ ), then slip is 1.9%.

$$\% \text{ Slip} = \frac{1800 - 1765}{1800} \times 100$$

$$\% \text{ Slip} = 1.9\%$$

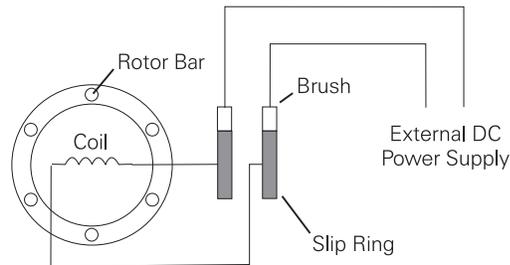
## Wound Rotor Motor

The discussion to this point has been centered on the more common squirrel cage rotor. Another type is the wound rotor. A major difference between the wound rotor motor and the squirrel cage rotor is the conductors of the wound rotor consist of wound coils instead of bars. These coils are connected through slip rings and brushes to external variable resistors. The rotating magnetic field induces a voltage in the rotor windings. Increasing the resistance of the rotor windings causes less current flow in the rotor windings, decreasing speed. Decreasing the resistance allows more current flow, speeding the motor up.



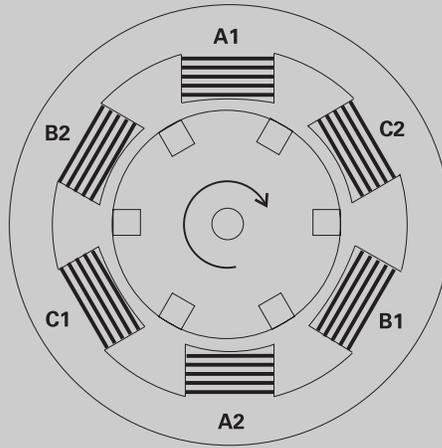
## Synchronous Motor

Another type of AC motor is the synchronous motor. The synchronous motor is not an induction motor. One type of synchronous motor is constructed somewhat like a squirrel cage rotor. In addition to rotor bars coil windings are added. The coil windings are connected to an external DC power supply by slip rings and brushes. On start AC is applied to the stator and the synchronous motor starts like a squirrel cage rotor. DC is applied to the rotor coils after the motor reaches maximum speed. This produces a strong constant magnetic field in the rotor which locks in step with the rotating magnetic field. The rotor turns at the same speed as synchronous speed (speed of the rotating magnetic field). There is no slip. Variations of synchronous motors include a permanent magnet rotor. The rotor is a permanent magnet and an external DC source is not required. These are found on small horsepower synchronous motors.



## Review 4

1. The following illustration represents a \_\_\_\_\_ pole motor. If winding A1 is a south pole then winding A2 is a \_\_\_\_\_ pole.



2. The speed of the rotating magnetic field is referred to as \_\_\_\_\_ speed.
3. The synchronous speed of a 60 Hz 4-pole motor is \_\_\_\_\_ RPM.
4. The difference in speed between the rotor and synchronous speed is \_\_\_\_\_ .
5. A 2-pole motor is operating on a 60 Hz power supply. The rotor is turning at 3450 RPM. Slip is \_\_\_\_\_ %.