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# Introduction

Welcome to another course in the STEP 2000 series, **S**iemens **T**echnical **E**ducation **P**rogram, designed to prepare our distributors to sell Siemens Energy & Automation products more effectively. This course covers **Basics of AC Drives** and related products.

Upon completion of **Basics of AC Drives** you should be able to:

- Explain the concept of force, inertia, speed, and torque
- Explain the difference between work and power
- Describe the construction of a squirrel cage AC motor
- Identify the nameplate information of an AC motor necessary for application to an AC Drive
- Describe the operation of a three-phase rotating magnetic field
- Calculate synchronous speed, slip, and rotor speed
- Describe the relationship between V/Hz, torque, and current
- Describe the basic construction and operation of a PWM type AC drive
- Describe features and operation of the Siemens MICROMASTER and MASTERDRIVE VC
- Describe the characteristics of constant torque, constant horsepower, and variable torque applications

This knowledge will help you better understand customer applications. In addition, you will be able to describe products to customers and determine important differences between products. You should complete **Basics of Electricity** before attempting **Basics of AC Drives**. An understanding of many of the concepts covered in **Basics of Electricity** is required for **Basics of AC Drives**.

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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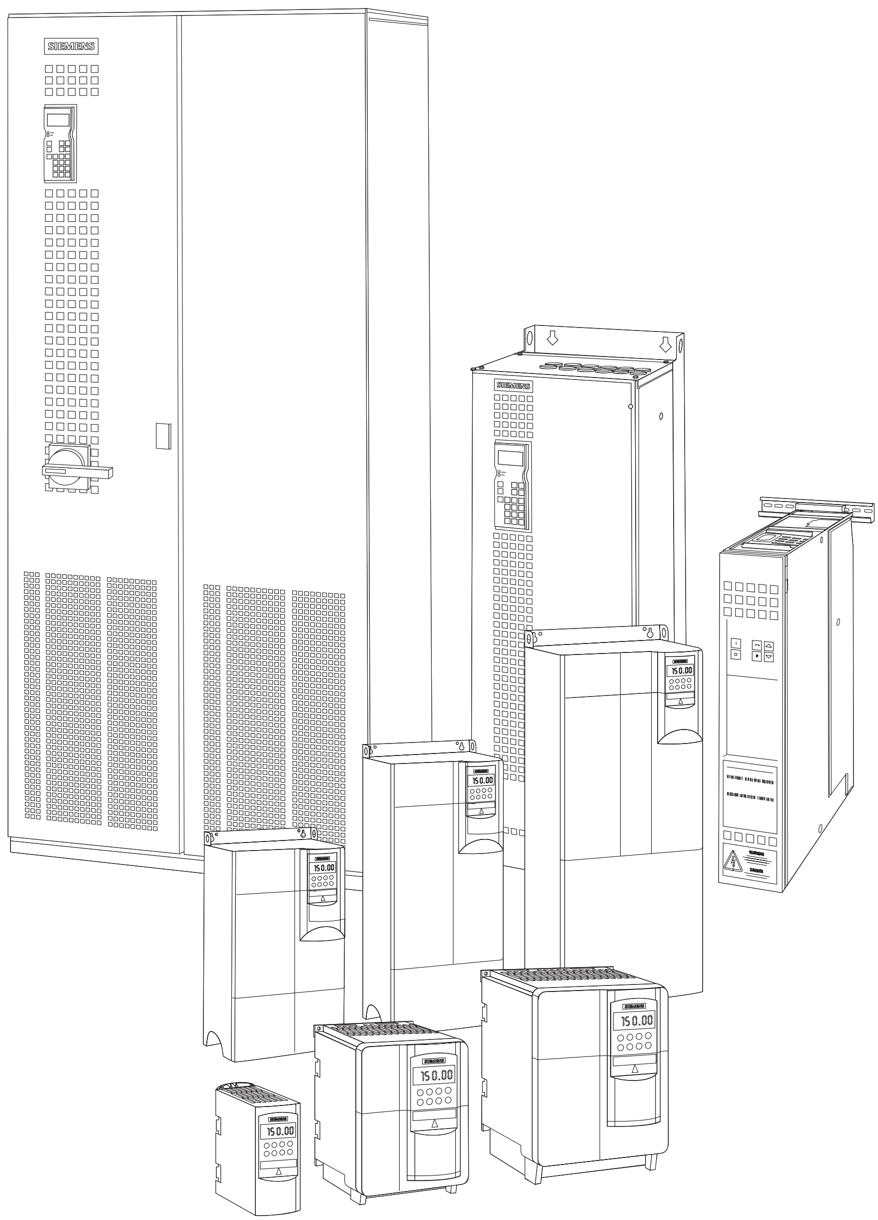
National Electrical Manufacturers Association is located at 2101 L. Street, N.W., Washington, D.C. 20037. The abbreviation “NEMA” is understood to mean National Electrical Manufacturers Association.

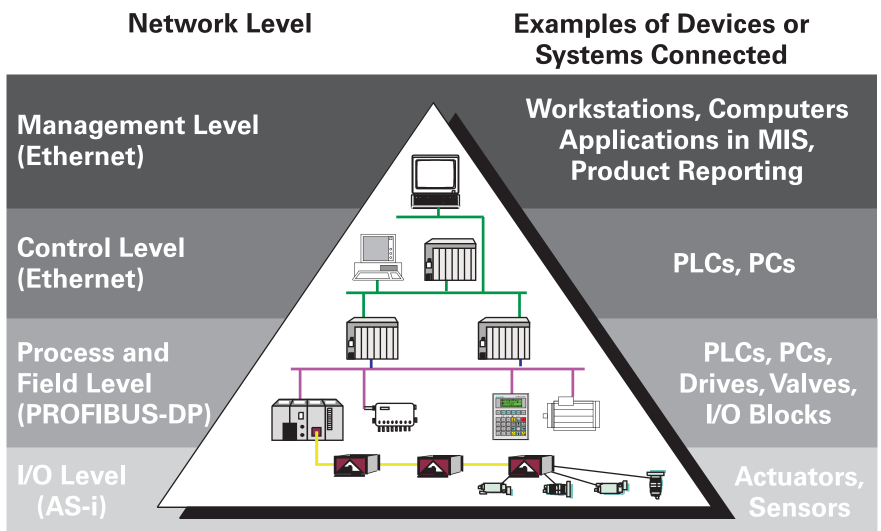
# Siemens AC Drives and Totally Integrated Automation

This course focuses on several Siemens AC drives, which include the MICROMASTER and MASTERDRIVE VC, which are important elements of the TIA strategy.



## Totally Integrated Automation

Totally Integrated Automation (TIA) is more than a concept. TIA is a strategy developed by Siemens that emphasizes the seamless integration of automation products. The TIA strategy incorporates a wide variety of automation products such as programmable controllers, computer numerical controls, Human Machine Interfaces (HMI), and drives which are easily connected via open protocol networks.

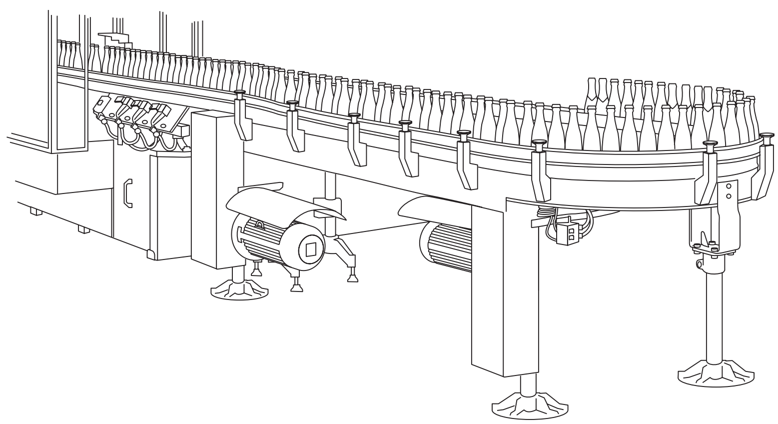



## PROFIBUS DP

An important aspect of TIA is the ability of devices to communicate with each other over various network protocols, such as Ethernet and PROFIBUS DP. PROFIBUS DP is an open bus standard for a wide range of applications in various manufacturing and automation applications. Siemens AC drives can easily communicate with other control devices such as programmable logic controllers (PLCs) and personal computers (PCs) through the PROFIBUS-DP communication system and other various protocols.

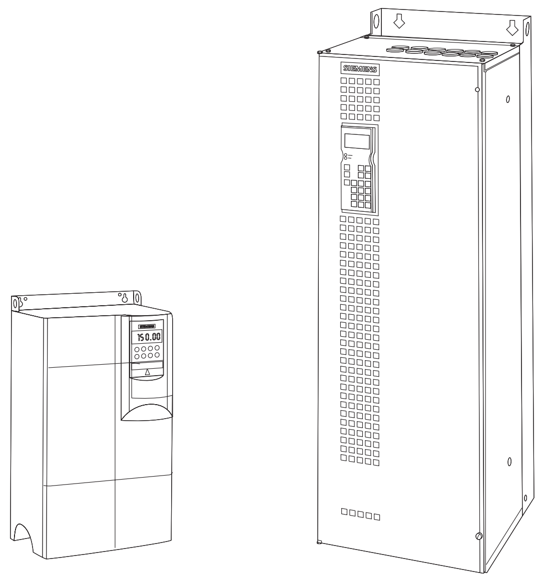
# Mechanical Basics

In many commercial, industrial, and utility applications electric motors are used to transform electrical energy into mechanical energy. Those electric motors may be part of a pump or fan, or they may be connected to some other form of mechanical equipment such as a conveyor or mixer. In many of these applications the speed of the system is determined primarily by its mechanical design and loading. For an increasing number of these applications, however, it is necessary to control the speed of the system by controlling the speed of the motor.



## Variable Speed Drives

The speed of a motor can be controlled by using some type of electronic drive equipment, referred to as variable or adjustable speed drives. Variable speed drives used to control DC motors are called DC drives. Variable speed drives used to control AC motors are called AC drives. The term inverter is also used to describe an AC variable speed drive. The inverter is only one part of an AC drive, however, it is common practice to refer to an AC drive as an inverter.



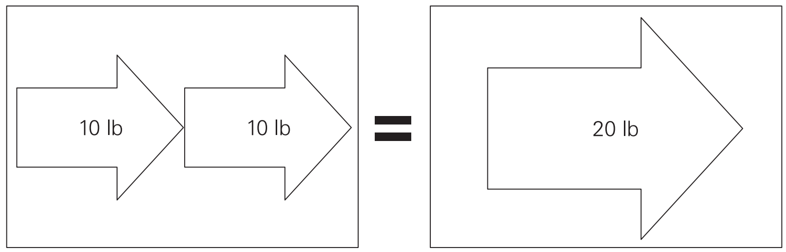
Before discussing AC drives it is necessary to understand some of the basic terminology associated with drive operation. Many of these terms are familiar to us in some other context. Later in the course we will see how these terms apply to AC drives.

**Force**

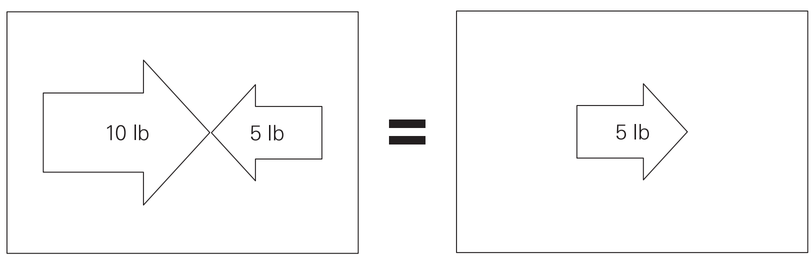
In simple terms, a force is a push or a pull. Force may be caused by electromagnetism, gravity, or a combination of physical means.

**Net Force**

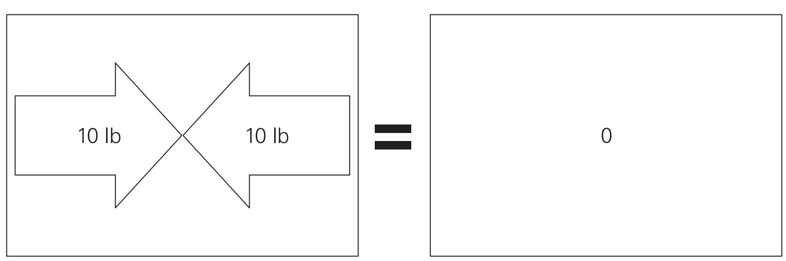
Net force is the vector sum of all forces that act on an object, including friction and gravity. When forces are applied in the same direction they are added. For example, if two 10 lb forces were applied in the same direction the net force would be 20 lb.




If 10 lb of force were applied in one direction and 5 lb of force applied in the opposite direction, the net force would be 5 lb and the object would move in the direction of the greater force.




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



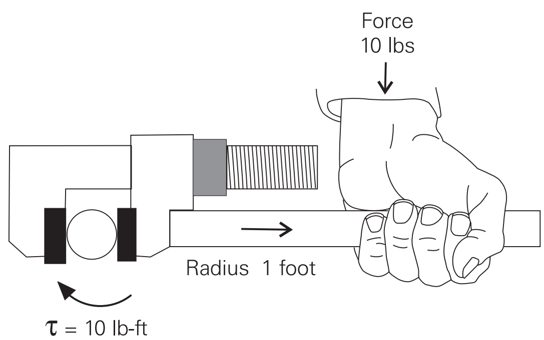
## Torque

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

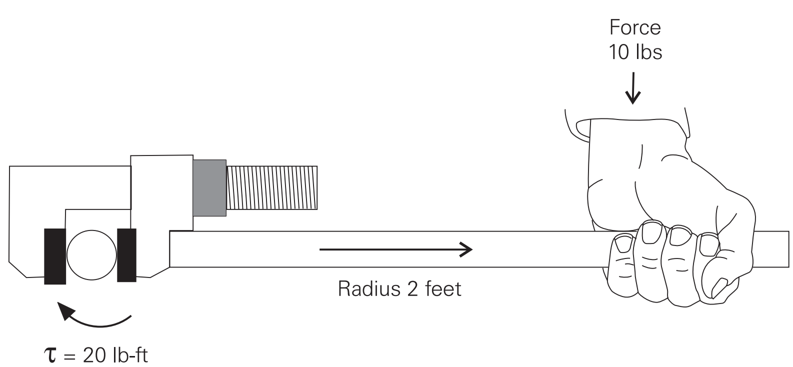
Torque ($\tau$) is the product of force and radius (lever distance).

Torque ($\tau$) = Force x 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 2 feet, for example, results in 20 lb-ft of torque.



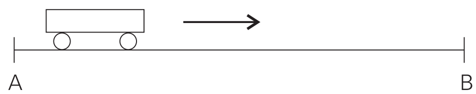

## Speed

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

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

## Linear Speed

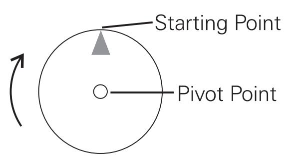
The linear speed of an object is a measure of how long it takes the object to get from point A to point B. Linear speed is usually given in a form such as meters per second (m/s). For example, if the distance between point A and point B were 10 meters, and it took 2 seconds to travel the distance, the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




Linear Motion

## 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.




Rotational Motion

## Acceleration

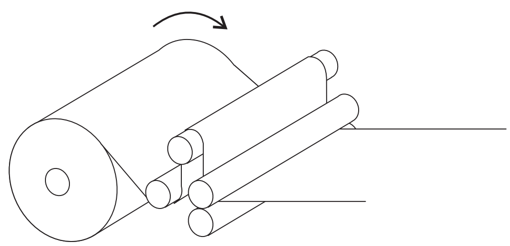
An object can change speed. An increase in speed is called acceleration. Acceleration occurs only when there is a change in the force acting upon the object. An object can also change from a higher to a lower speed. This is known as deceleration (negative acceleration). A rotating object, for example,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


Acceleration Deceleration

**Law of 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 ($lb\text{-}ft^2$).

If we look at a continuous roll of paper, as it unwinds, 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**

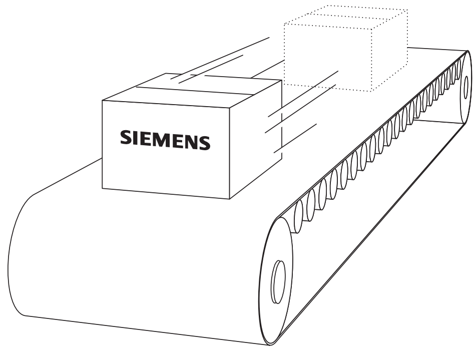
A large amount of force is applied to overcome the inertia of the system at rest to start it moving. Because friction removes energy from a mechanical system, a continual force must be applied to keep an object in motion. The law of inertia is still valid, however, since the force applied is needed only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

- Friction within motor and driven equipment bearings
- Windage 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 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.

$$W = F \times d$$

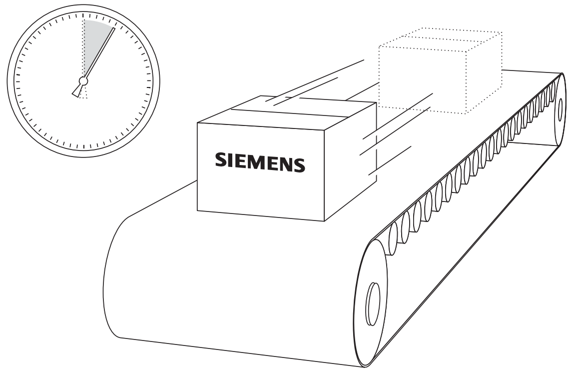
**Power**

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

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

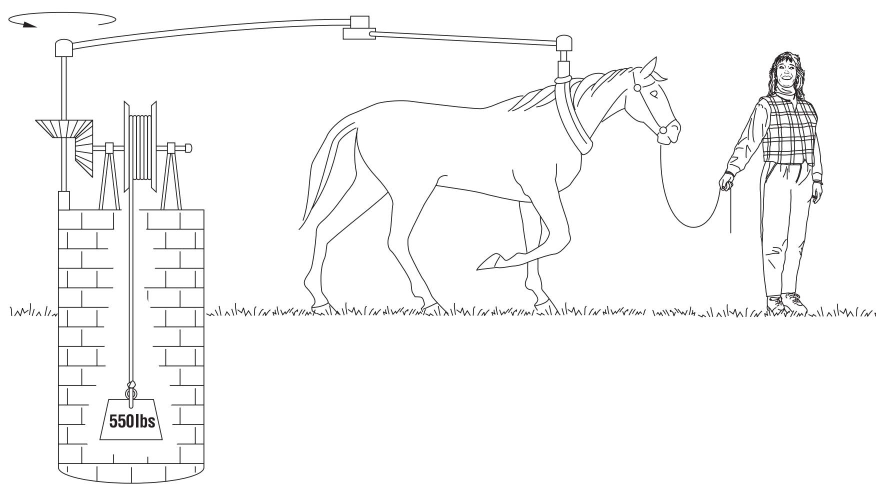
$$\text{Power} = \frac{\text{Work}}{\text{Time}}$$

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 500 foot-pounds per second or 33,000 foot-pounds per minute.




The following formula can be used to calculate horsepower when torque (lb-ft) and speed (RPM) are known. It can be seen from the formula that an increase of torque, speed, or both will cause a corresponding increase in horsepower.

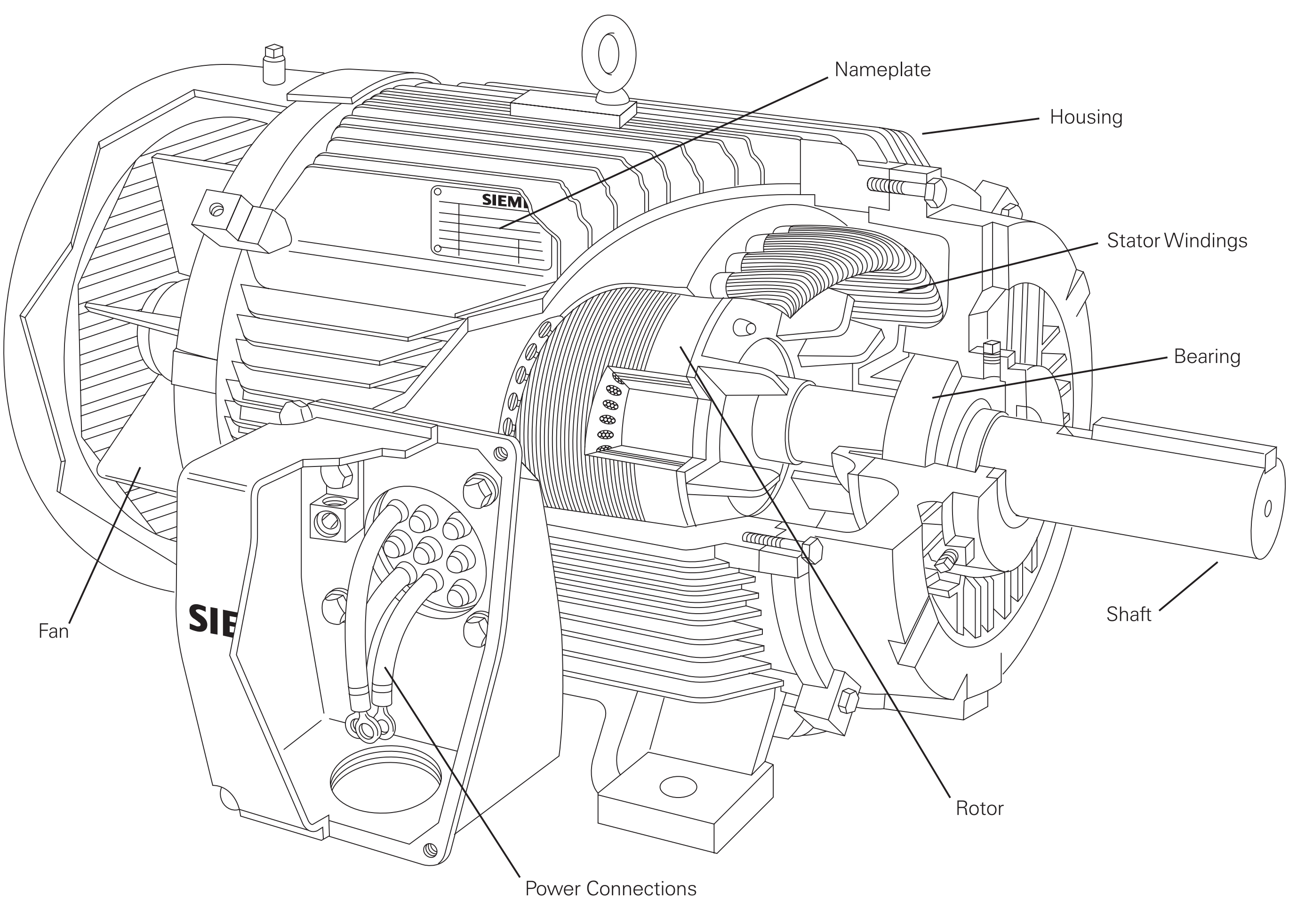
$$HP = \frac{T \times RPM}{5250}$$

**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 ____________ .

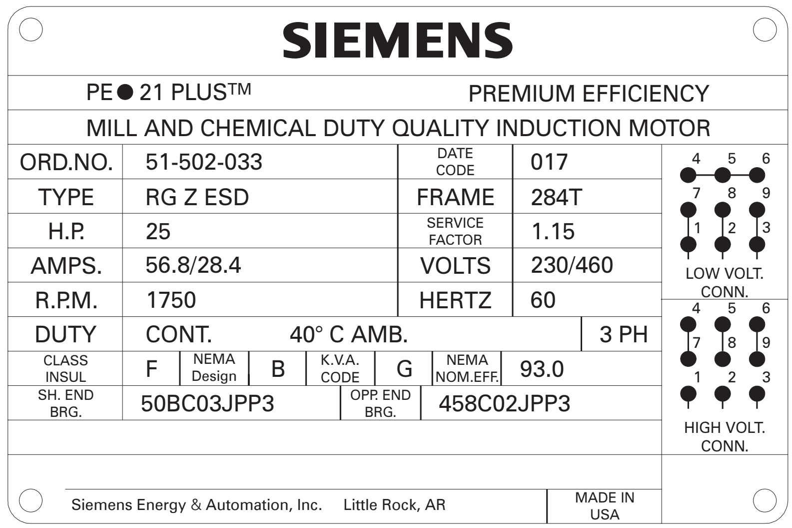
# AC Motor Construction

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. Electromagnetic stator windings are mounted in a housing. Power connections, attached to the stator windings, are brought out to be attached to a three-phase power supply. On three-phase, dual-voltage motors nine leads are supplied for power connections. Three power connection leads are shown in the following illustration for simplicity. A rotor is mounted on a shaft and supported by bearings. On self-cooled motors, like the one shown, a fan is mounted on the shaft to force cooling air over the motor.



**Nameplate**

The nameplate of a motor provides important information necessary when applying a motor to an AC drive. The following drawing illustrates the nameplate of a sample 25 horsepower AC motor.




**Connections**

This motor can be used on 230 VAC or 460 VAC systems. A wiring diagram indicates the proper connection for the input power leads. The low voltage connection is intended for use on 230 VAC with a maximum full load current of 56.8 Amps. The high voltage connection is intended for use on 460 VAC with a maximum full load current of 28.4 Amps.

**Base Speed**

Base speed is the nameplate speed, given in RPM, where the motor develops rated horsepower at rated voltage and frequency. It is an indication of how fast the output shaft will turn the connected equipment when fully loaded and proper voltage is applied at 60 hertz. The base speed of this motor is 1750 RPM at 60 Hz. If the connected equipment is operating at less than full load, the output speed will be slightly greater than base speed.

It should be noted that with European and Asian motors and many special motors, such as those used in the textile industry, base speed, frequency and voltage may be different than standard American motors. This is not a problem, however, because the voltage and frequency supplied to a variable speed drive does not have to be the same as the motor. The supply voltage to a variable speed drive has nothing to do with motor voltage, speed or frequency. A variable speed drive can be set up to work with any motor within a reasonable size range and rating.

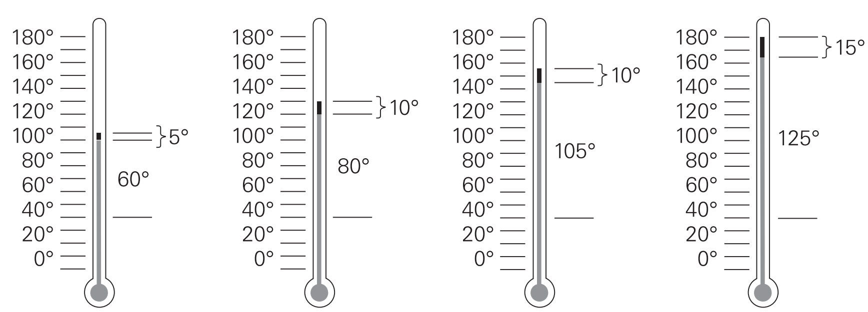
**Service Factor**

A motor designed to operate at its nameplate horsepower rating has a service factor of 1.0. Some applications may require a motor to exceed the rated horsepower. In these cases a motor with a service factor of 1.15 can be specified. The service factor is a multiplier that may be applied to the rated power. A 1.15 service factor motor can be operated 15% higher than the motor's nameplate horsepower. Motors with a service factor of 1.15 are recommended for use with AC drives. It is important to note, however, that even though a motor has a service factor of 1.15 the values for current and horsepower at the 1.0 service factor are used to program a variable speed drive.

**Insulation Class**

The National Electrical Manufacturers Association (NEMA) has established insulation classes to meet motor temperature requirements found in different operating environments. The four insulation classes are A, B, F, and H. Class F is commonly used. Class A is seldom used. Before a motor is started, its windings are at the temperature of the surrounding air. This is known as ambient temperature. NEMA has standardized on an ambient temperature of 40° C, or 104° F for all motor classes.

Temperature rises in the motor as soon as it is started. The combination of ambient temperature and allowed temperature rise equals the maximum winding temperature in a motor. A motor with Class F insulation, for example, has a maximum temperature rise of 105° C. The maximum winding temperature is 145° C (40° ambient plus 105° rise). A margin is allowed for a point at the center of the motor's windings where temperature is higher. This is referred to as the motor's hot spot.




Class A
60° C Rise
5° C Hot Spot

Class B
80° C Rise
10° C Hot Spot

Class F
105° C Rise
10° C Hot Spot

Class H
125° C Rise
15° C Hot Spot

The operating temperature of a motor is important to efficient operation and long life. Operating a motor above the limits of the insulation class reduces the motor's life expectancy. A 10° C increase in the operating temperature can decrease the life expectancy of a motor as much as 50%.

**NEMA Design**

The National Electrical Manufacturers Association (NEMA) has established standards for motor construction and performance. The nameplate on page 20 is for a motor designed to NEMA B specifications. NEMA B motors are commonly used with AC drives. Any NEMA design (A, B, C, or D) AC motor will work perfectly well with a properly sized variable speed drive.

**Efficiency**

AC motor efficiency is expressed as a percentage. It is an indication of how much input electrical energy is converted to output mechanical energy. The nominal efficiency of this motor is 93.0%.

**Converting KW to HP**

Motor manufacturers may also use kilowatts (KW) instead of horsepower.

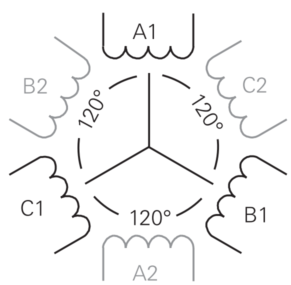
To convert KW to HP use the following equation:

$$HP = 1.341 \times KW$$

$$HP = 24$$

# Developing A Rotating Magnetic Field

A rotating magnetic field must be developed in the stator of an AC motor in order to produce mechanical rotation of the rotor. Wire is coiled into loops and placed in slots in the motor housing. These loops of wire are referred to as the stator windings. The following drawing illustrates a three-phase stator. Phase windings (A, B, and C) are placed 120° 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.



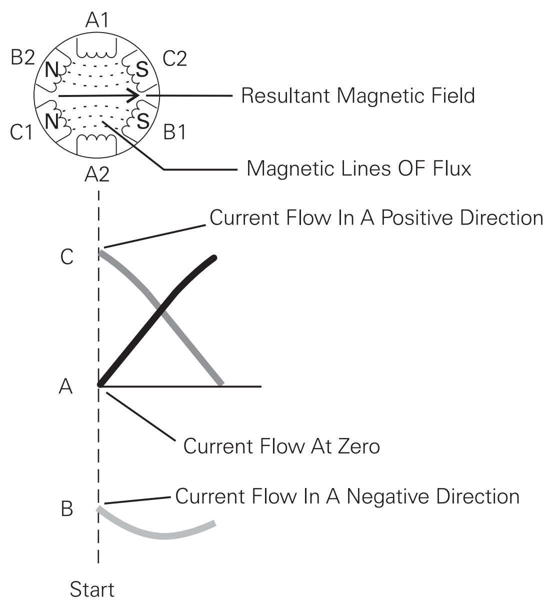

2-Pole Stator Winding

## Magnetic Field

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 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 |

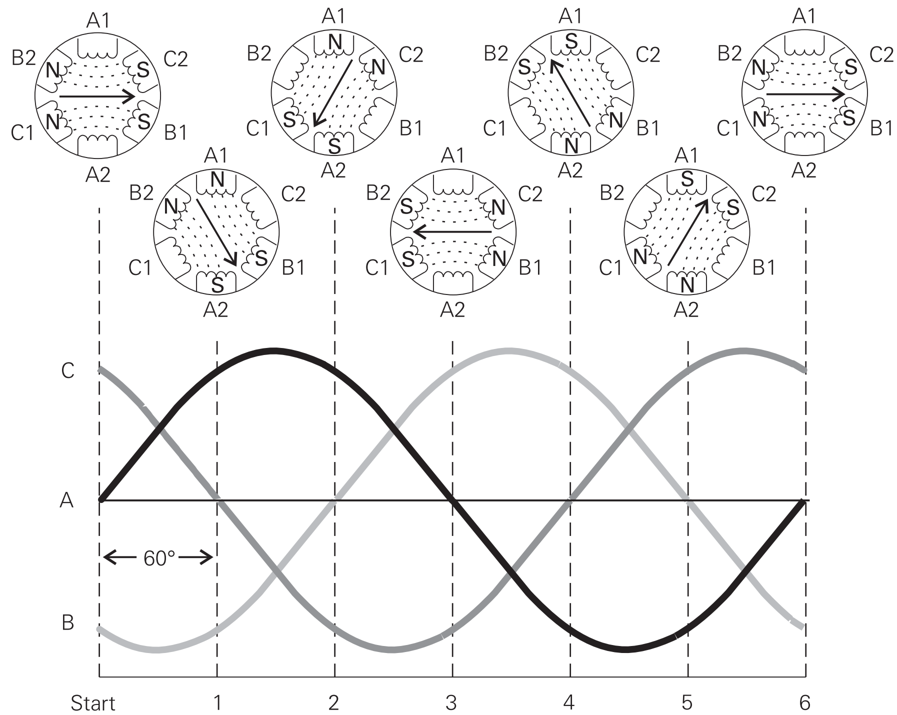
It is easier to visualize a magnetic field if a time is picked when no current is flowing through one phase. In the following illustration, for example, a time has been selected during which phase A has no current flow, phase B has current flow in a negative direction and phase C has current flow in 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 indicated by the arrow.




The amount of flux lines (Φ) the magnetic field produces is proportional to the voltage (E) divided by the frequency (F). Increasing the supply voltage increases the flux of the magnetic field. Decreasing the frequency increases the flux.

$$\Phi \approx \frac{E}{F}$$

If the field is evaluated in 60° intervals from the starting point, it can be seen that at point 1 the field has rotated 60°. 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. At the end of six such intervals the magnetic field will have rotated one full revolution or 360°.




**Synchronous Speed**

The speed of the rotating magnetic field is referred to as synchronous speed (NS). Synchronous speed is equal to 120 times the frequency (F), divided by the number of poles (P).

$$NS = \frac{120F}{P}$$

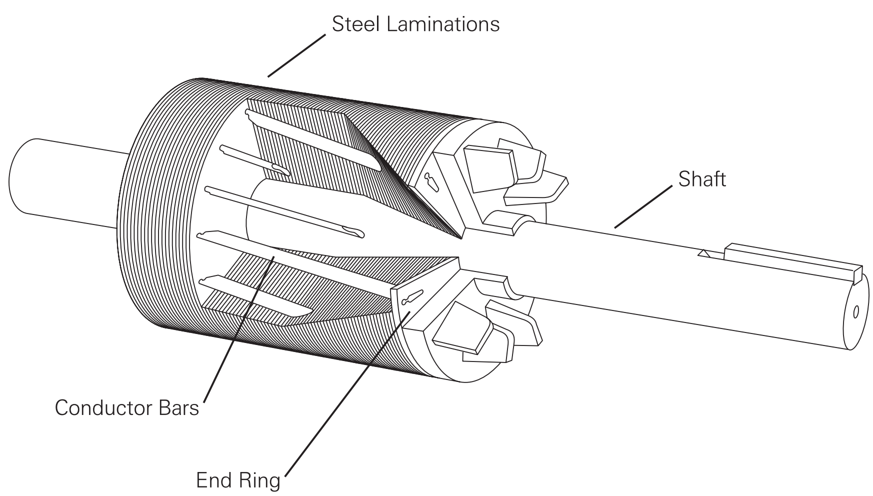
If the applied frequency of the two-pole stator used in the previous example is 60 hertz, synchronous speed is 3600 RPM.

$$NS = \frac{120 \times 60}{2}$$

$$NS = 3600 \text{ RPM}$$

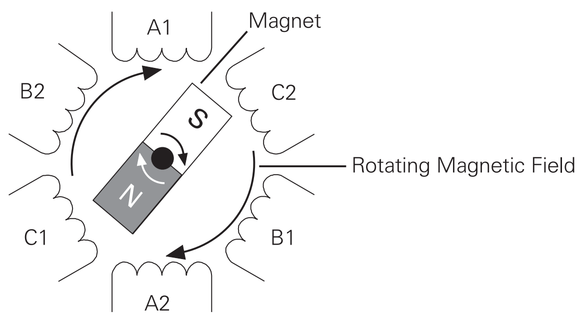
# Rotor Construction

The most common type of rotor is the “squirrel cage” rotor. 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 conductor bars are mechanically and electrically connected with end rings. A slight skewing of the bars helps to reduce audible hum. The rotor and shaft are an integral part.



**Rotating Magnet**

There is no direct electrical connection between the stator and the rotor or the power supply and the rotor of an induction motor. To see how a rotor works, a magnet mounted on the 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 type of design is used on some motors and is referred to as a permanent magnet synchronous motor.

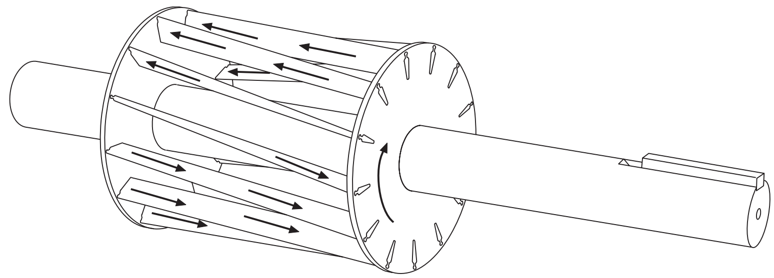



**Rotation of a Squirrel Cage Rotor**

The squirrel cage rotor of an AC motor acts essentially the same as the magnet. When a conductor, such as the conductor bars of the rotor, passes through a magnetic field a voltage (emf) is induced in the conductor. The induced voltage causes current flow in the conductor. The amount of induced voltage (E) depends on the amount of flux ($\Phi$) and the speed (N) at which the conductor cuts through the lines of flux. The more lines of flux, or the faster they are cut, the more voltage is induced. Certain motor constants (k), determined by construction also affect induced voltage. These constants, such as rotor bar shape and construction, do not change with speed or load.

$$E = k\Phi N$$

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. The squirrel cage rotor becomes an electromagnet with alternating north and south poles. The magnetic fields of the rotor interact with the magnetic fields of the stator. It must be remembered that the current and magnetic fields of the stator and rotor are constantly changing. As the stator magnetic field rotates, the rotor and shaft follow.



**Slip**

There must be a relative difference in speed between the rotor and the rotating magnetic field. The difference in speed of the rotating magnetic field, expressed in RPM, and the rotor, expressed in RPM, is known as slip.

Slip is necessary to produce torque. 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. 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.

$$\% \text{ Slip} = \frac{NS - NR}{NS} \times 100$$

For example, a four-pole motor operated at 60 Hz has a synchronous speed of 1800 RPM. If the rotor speed at full load were 1750 RPM, the slip is 2.8%.

$$\% \text{ Slip} = \frac{1800 - 1750}{1800} \times 100$$

$$\% \text{ Slip} = 2.8\%$$

**Review 2**

1. Given an AC motor with the following: a nameplate amps of 10/5, and volts of 230/460, the full load amps at 460 volts is ____________ amps.

2. A motor which is permitted to exceed the rated horsepower by 15% has a service factor of ____________.

3. A motor with a rating of 37 KW would have an equivalent horsepower rating of ____________ HP.

4. Stator windings in a three-phase, two-pole motor are placed ____________ degrees apart.

5. The synchronous speed of a four-pole stator with 60 Hertz applied is ____________ RPM.

   The synchronous speed of a four-pole stator with 50 Hertz applied is ____________ RPM.

6. ____________ is the relative difference in speed between the rotor and the rotating magnetic field.

# NEMA Rotor Characteristics

The National Electrical Manufacturers Association (NEMA) classifies motors according to locked rotor torque and current, pull up torque, breakdown torque and percent slip. In addition, full-load torque and current must be considered when evaluating an application.

Most NEMA terms and concepts apply to motors operated from 60 Hz power lines, not variable speed drive operation. In following sections we will see how an AC variable speed drive can improve the starting and operation of an AC motor.

**Locked Rotor Torque**

Locked rotor torque, also referred to as starting torque, is developed when the rotor is held at rest with rated voltage and frequency applied. This condition occurs each time a motor is started. When rated voltage and frequency are applied to the stator there is a brief amount of time before the rotor turns.

**Locked Rotor Current**

Locked rotor current is also referred to as starting current. This is the current taken from the supply line at rated voltage and frequency with the rotor at rest.

**Pull Up Torque**

Pull up torque is the torque developed during acceleration from start to the point breakdown torque occurs.

**Breakdown Torque**

Breakdown torque is the maximum torque a motor develops at rated voltage and speed without an abrupt loss of speed.

**Full-Load Torque**

Full-load torque is the torque developed when the motor is operating with rated voltage, frequency and load.

**Full-Load Current**

Full-load current is the current taken from the supply line at rated voltage, frequency and load.

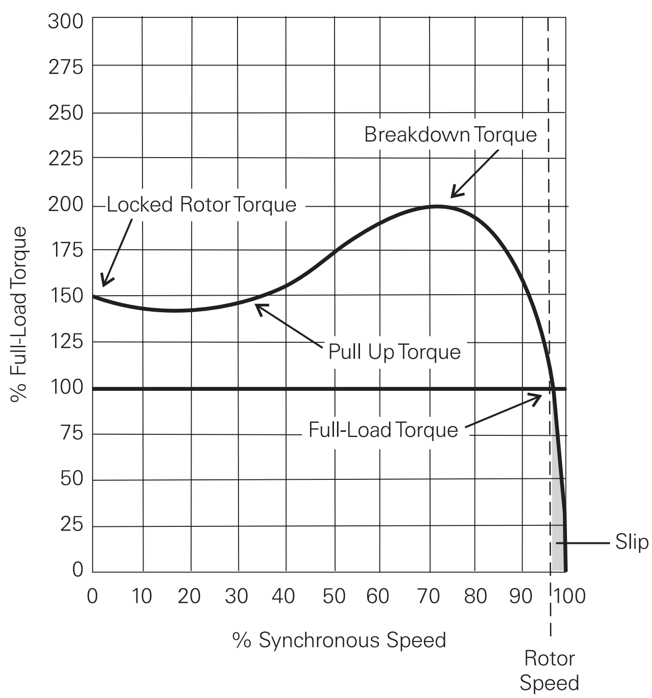
**NEMA Classifications**

Three-phase AC motors are classified by NEMA as NEMA A, B, C and D. NEMA specifies certain operating characteristics for motors when started by applying rated voltage and frequency (across the line starting). A NEMA B motor, for example, typically requires 600% starting current and 150% starting torque. These considerations do not apply to motors started with an AC drive. NEMA B design motors are the most common and most suitable for use on AC drives.

**NEMA B Speed and Torque**

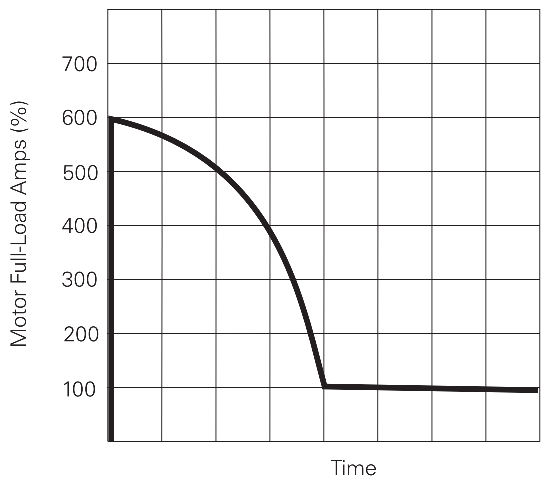
A graph similar to the one illustrated below is used to show the relationship between motor speed and torque of a NEMA B motor. When rated voltage and frequency are applied to the motor, synchronous speed goes to 100% immediately. The rotor must perform a certain amount of work to overcome the mechanical inertia of itself and the connected load.

Typically a NEMA B motor will develop 150% torque to start the rotor and load. As the rotor accelerates the relative difference in speed between synchronous speed and rotor speed decreases until the rotor reaches its operating speed. The operating speed of a NEMA B motor with rated voltage, frequency and load is approximately 97% (3% slip) of synchronous speed. The amount of slip and torque is a function of load. With an increase in load there is a corresponding increase in slip and torque. With a decrease in load there is a corresponding decrease in slip and torque.



**Starting Current**

When a motor is started, it must perform work to overcome the inertia of the rotor and attached load. The starting current measured on the incoming line ($I_S$) is typically 600% of full-load current when rated voltage and frequency is first applied to a NEMA B motor. Stator current decreases to its rated value as the rotor comes up to speed. The following graph applies to "across the line" operation, not variable speed drive operation.

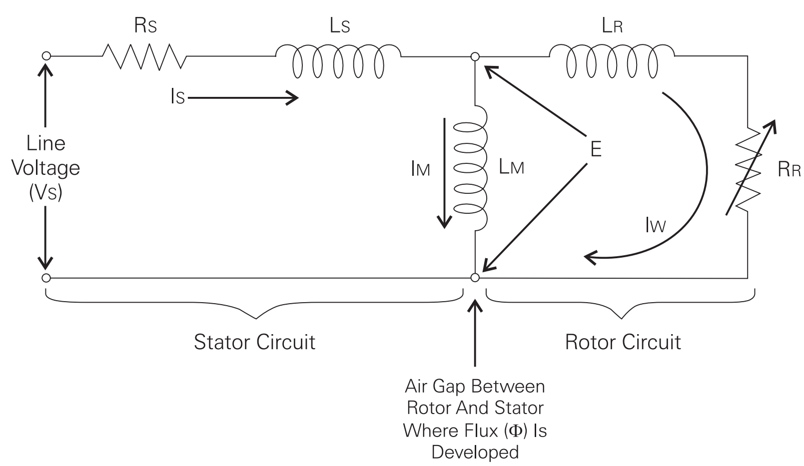


# Electrical Components Of A Motor

Up to this point we have examined the operation of an AC motor with rated voltage and frequency applied. Many applications require the speed of an AC motor to vary, which is easily accomplished with an AC drive. However, operating a motor at other than rated voltage and frequency has an effect on motor current and torque. In order to understand how a motor's characteristics can change we need a better understanding of both AC motors and AC drives.

The following diagram represents a simplified equivalent circuit of an AC motor. An understanding of this diagram is important in the understanding of how an AC motor is applied to an AC drive.

| | |
|---|---|
| $V_S$ | Line voltage applied to stator power leads |
| $R_S$ | Stator resistance |
| $L_S$ | Stator leakage inductance |
| $I_S$ | Stator current |
| $E$ | Air gap or magnetizing voltage |
| $L_M$ | Magnetizing inductance |
| $I_M$ | Magnetizing current |
| $R_R$ | Rotor resistance (varies with temperature) |
| $L_R$ | Rotor leakage inductance |
| $I_W$ | Working or torque producing current |



**Line Voltage**

Voltage ($V_S$) is applied to the stator power leads from the AC power supply. Voltage drops occur due to stator resistance ($R_S$). The resultant voltage (E) represents force (cemf) available to produce magnetizing flux and torque.

**Magnetizing Current**

Magnetizing current ($I_M$) is responsible for producing magnetic lines of flux which magnetically link with the rotor circuit. Magnetizing current is typically about 30% of rated current. Magnetizing current, like flux ($\Phi$), is proportional to voltage (E) and frequency (F).

$$I_M = \frac{E}{2\pi F L_M}$$

**Working Current**

The current that flows in the rotor circuit and produces torque is referred to as working current ($I_W$). Working current is a function of the load. An increase in load causes the rotor circuit to work harder increasing working current ($I_W$). A decrease in load decreases the work the rotor circuit does decreasing working current ($I_W$).

**Stator Current**

Stator current ($I_S$) is the current that flows in the stator circuit. Stator current can be measured on the supply line and is also referred to as line current. A clamp-on ammeter, for example, is frequently used to measure stator current. The full-load ampere rating on the nameplate of a motor refers to stator current at rated voltage, frequency and load. It is the maximum current the motor can carry without damage. Stator current is the vector sum of working current ($I_W$) and magnetizing current ($I_M$). Typically magnetizing current ($I_M$) remains constant. Working current ($I_W$) will vary with the applied load which causes a corresponding change in stator current ($I_S$).

$$I_S = \sqrt{I_M^2 + I_W^2}$$

# Voltage And Frequency

**Volts per Hertz**

A ratio exists between voltage and frequency. This ratio is referred to as volts per hertz (V/Hz). A typical AC motor manufactured for use in the United States is rated for 460 VAC and 60 Hz. The ratio is 7.67 volts per hertz. Not every motor has a 7.67 V/Hz ratio. A 230 Volt, 60 Hz motor, for example, has a 3.8 V/Hz ratio.

$$\frac{460}{60} = 7.67 \text{ V/Hz} \qquad \frac{230}{60} = 3.8 \text{ V/Hz}$$

Flux ($\Phi$), magnetizing current ($I_M$), and torque are all dependent on this ratio. Increasing frequency (F) without increasing voltage (E), for example, will cause a corresponding increase in speed. Flux, however, will decrease causing motor torque to decrease. Magnetizing current ($I_M$) will also decrease. A decrease in magnetizing current will cause a corresponding decrease in stator or line ($I_S$) current. These decreases are all related and greatly affect the motor's ability to handle a given load.

$$\Phi \approx \frac{E}{F}$$

$$T = k\Phi I_W$$

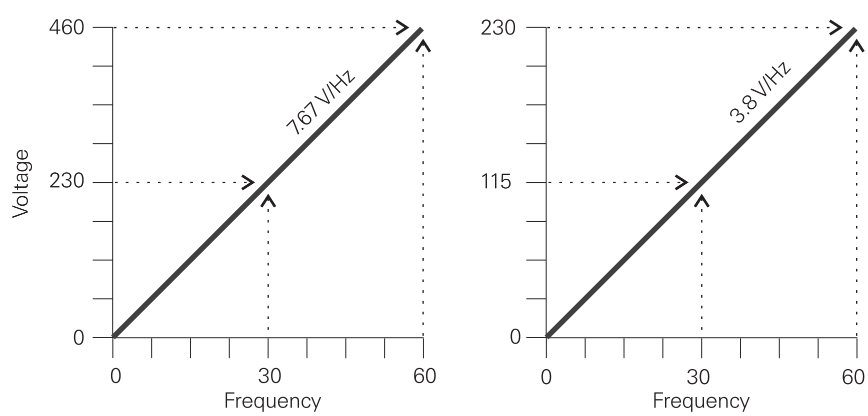
$$I_M = \frac{E}{2\pi F L_M}$$

## Constant Torque

AC motors running on an AC line operate with a constant flux (Φ) because voltage and frequency are constant. Motors operated with constant flux are said to have constant torque. Actual torque produced, however, is determined by the demand of the load.

$$T = k\Phi I w$$

An AC drive is capable of operating a motor with constant flux (Φ) from approximately zero (0) to the motor's rated nameplate frequency (typically 60 Hz). This is the constant torque range. As long as a constant volts per hertz ratio is maintained the motor will have constant torque characteristics. AC drives change frequency to vary the speed of a motor and voltage proportionately to maintain constant flux. The following graphs illustrate the volts per hertz ratio of a 460 volt, 60 hertz motor and a 230 volt, 60 Hz motor. To operate the 460 volt motor at 50% speed with the correct ratio, the applied voltage and frequency would be 230 volts, 30 Hz. To operate the 230 volt motor at 50% speed with the correct ratio, the applied voltage and frequency would be 115 volts, 30 Hz. The voltage and frequency ratio can be maintained for any speed up to 60 Hz. This usually defines the upper limits of the constant torque range.




$$\frac{460}{60} = 7.67 \text{ V/Hz} \qquad \frac{230}{60} = 3.8 \text{ V/Hz}$$

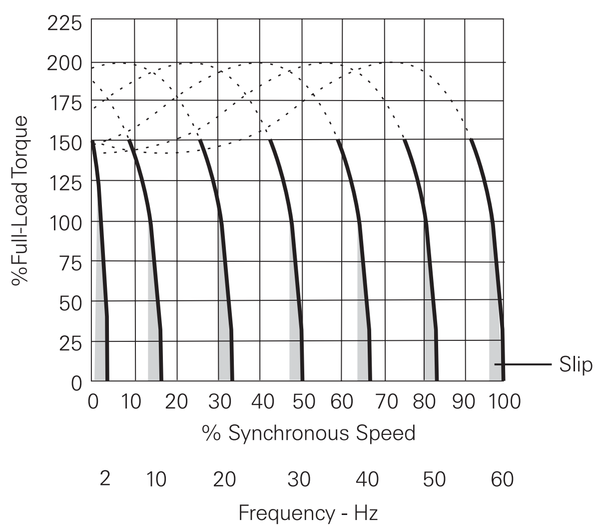
$$\frac{230}{30} = 7.67 \text{ V/Hz} \qquad \frac{115}{30} = 3.8 \text{ V/Hz}$$

## Reduced Voltage and Frequency Starting

You will recall that a NEMA B motor started by connecting it to the power supply at full voltage and frequency will develop approximately 150% starting torque and 600% starting current. An advantage of using AC drives to start a motor is the ability to develop 150% torque with a starting current of 150% or less. This is possible because an AC drive is capable of maintaining a constant volts per hertz ratio from approximately zero speed to base speed, thereby keeping flux ($\Phi$) constant. Torque is proportional to the square of flux developed in the motor.

$$T \approx \Phi^2$$

The torque/speed curve shifts to the right as frequency and voltage are increased. The dotted lines on the torque/speed curve illustrated below represent the portion of the curve not used by the drive. The drive starts and accelerates the motor smoothly as frequency and voltage are gradually increased to the desired speed. Slip, in RPM, remains constant throughout the speed range. An AC drive, properly sized to a motor, is capable of delivering 150% torque at any speed up to the speed corresponding to the incoming line voltage. The only limitations on starting torque are peak drive current and peak motor torque, whichever is less.




Some applications require higher than 150% starting torque. A conveyor, for example, may require 200% starting torque. If a motor is capable of 200% torque at 200% current, and the drive is capable of 200% current, then 200% motor torque is possible. Typically drives are capable of producing 150% of drive nameplate rated current for one (1) minute. A drive with a larger current rating would be required. It is appropriate to supply a drive with a higher continuous horsepower rating than the motor when high peak torque is required.

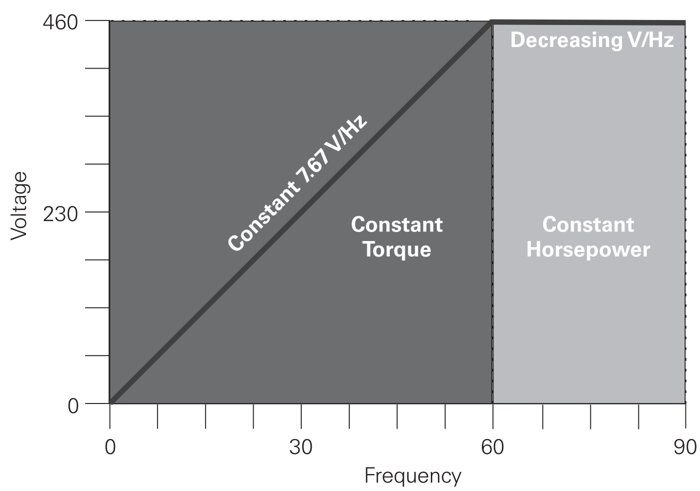
## Constant Horsepower

Some applications require the motor to be operated above base speed. The nature of these applications requires less torque at higher speeds. Voltage, however, cannot be higher than the available supply voltage. This can be illustrated using a 460 volt, 60 Hz motor. Voltage will remain at 460 volts for any speed above 60 Hz. A motor operated above its rated frequency is operating in a region known as a constant horsepower. Constant volts per hertz and torque is maintained to 60 Hz. Above 60 Hz the volts per hertz ratio decreases.

| Frequency | V/Hz |
|---|---|
| 30 Hz | 7.67 |
| 60 Hz | 7.67 |
| 70 Hz | 6.6 |
| 90 Hz | 5.1 |

Flux (Φ) and torque (T) decrease:

$$\Phi \approx \frac{E}{F} \qquad T = k\Phi I_W$$



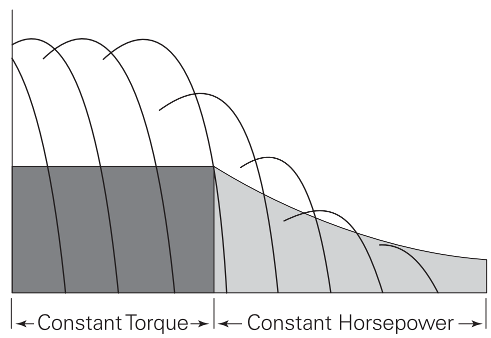

Horsepower remains constant as speed (N) increases and torque (T) decreases in proportion. The following formula applies to speed in revolutions per minute (RPM).

$$\text{HP (remains constant)} = \frac{\text{T (decreases)} \times \text{N (increases)}}{5250}$$

## Field Weakening

Motors operated above base frequency can also be said to be in field weakening. Field weakening occurs whenever there is an increase in frequency without a corresponding increase in voltage. Although an AC drive could be setup for field weakening at any speed, it typically only occurs beyond base frequency.

We have seen that below base speed, in the constant torque region, a motor can develop rated torque at any speed. However, above base speed, in the constant horsepower region, the maximum permissible torque is greatly reduced.




## Field Weakening Factor

A field weakening factor ($F_{FW}$) can be used to calculate the amount of torque reduction necessary for a given extended frequency.

$$F_{FW} = \left( \frac{\text{Rated Frequency}}{\text{Extended Frequency}} \right)^2$$

For example, a 60 Hz motor can only develop 44% rated torque at 90 Hz and 25% rated torque at 120 Hz.

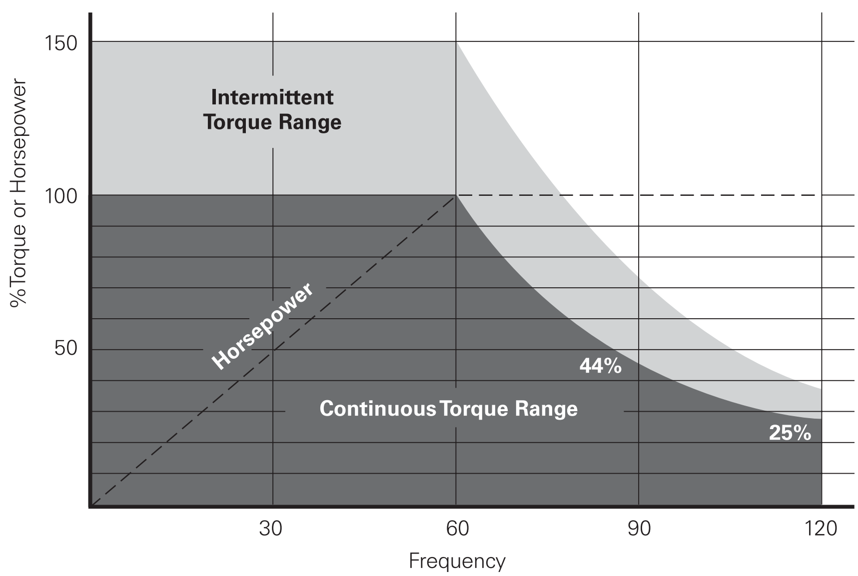
$$F_{FW} = \left( \frac{60}{90} \right)^2 = 44\%$$

$$F_{FW} = \left( \frac{60}{120} \right)^2 = 25\%$$

**Selecting a Motor**

AC drives often have more capability than the motor. Drives can run at higher frequencies than may be suitable for an application. In addition, drives can run at low speeds. Self-cooled motors may not develop enough air flow for cooling at reduced speeds and full load. Consideration must be given to the motor.

The following graph indicates the speed and torque range of a sample motor. Each motor must be evaluated according to its own capability. The sample motor can be operated continuously at 100% torque up to 60 Hz. Above 60 Hz the V/Hz ratio decreases and the motor cannot develop 100% torque. This motor can be operated continuously at 25% torque at 120 Hz. The motor is also capable of operating above rated torque intermittently. The motor can develop as much as 150%* torque for starting, accelerating or load transients, if the drive can supply the current. At 120 Hz the motor can develop 37.5% torque intermittently.




The sample motor described above is capable of operating at 100% rated torque continuously at low frequencies. Many motors are <u>not</u> capable of operating continuously at 100% continuous torque at low frequencies. Each motor must be evaluated before selecting it for use on an AC drive.

* Torque may be higher than 150% if the drive is capable of higher current.