

SIEMENS

STEP 2000

Basics of AC Drives

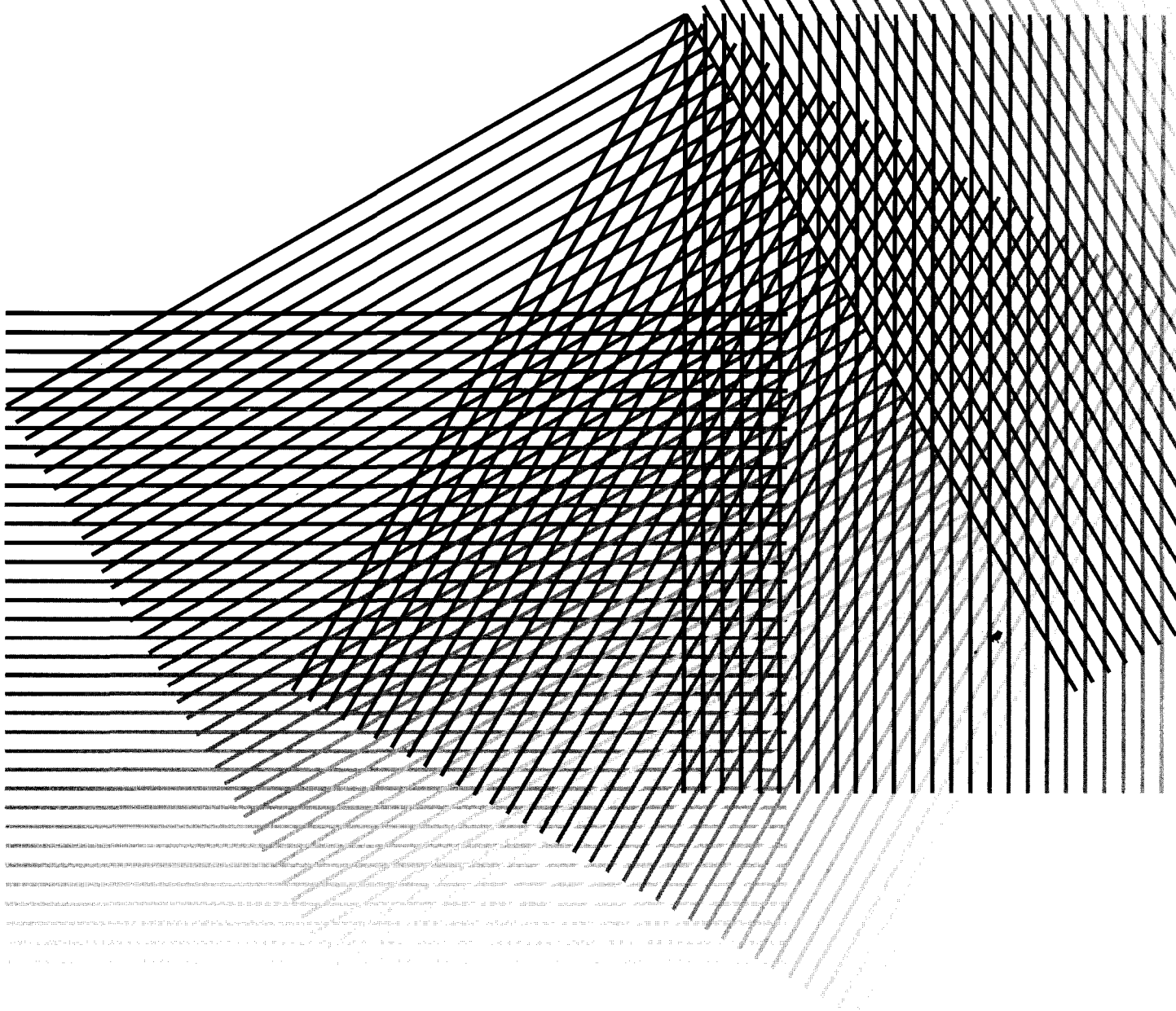


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Introduction

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 **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
- 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**.

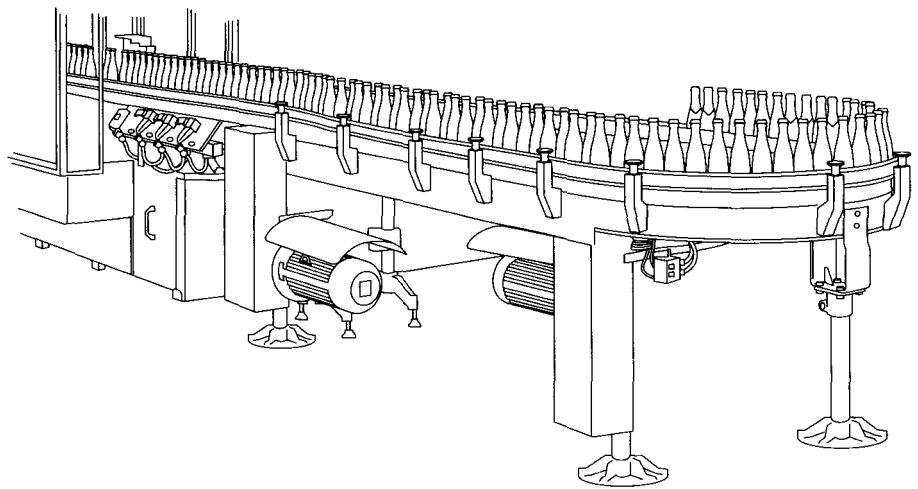
If you are an employee of a Siemens Energy & Automation authorized distributor, fill out the final exam tear-out card and mail in the card. We will mail you a certificate of completion if you score a passing grade. Good luck with your efforts.

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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.

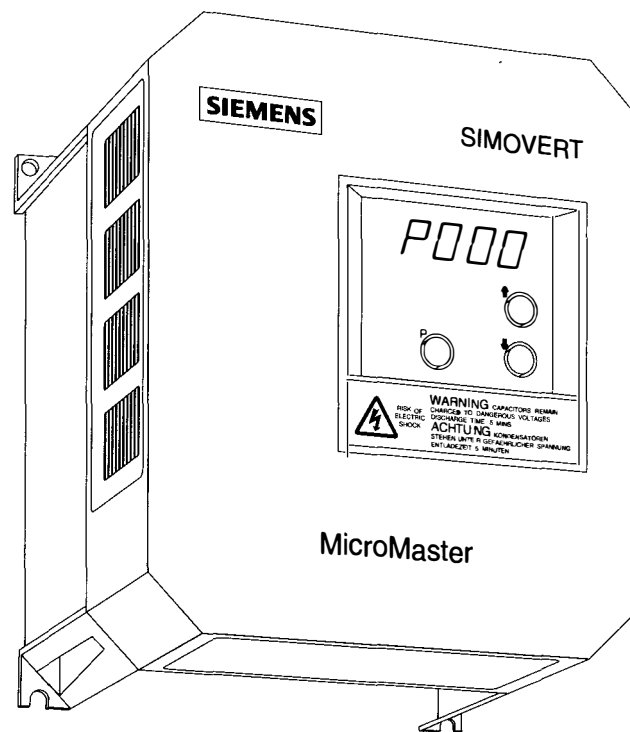
Force and Motion

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.



AC drives

The speed of the 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, like the Siemens MicroMaster, 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.



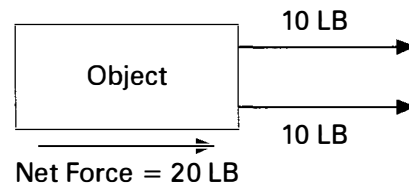
Before discussing AC drives it is necessary to understand some of the basic terminology associated with drive operation. Many of these terms are familiar to us in some other context. Later in the course we will see how these terms apply to AC drives.

Force

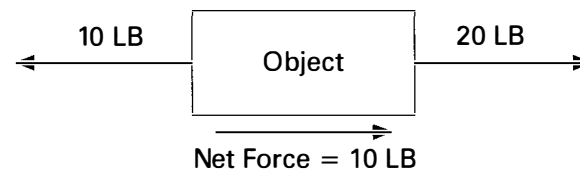
In simple terms, a force is a push or a pull. Force may be caused by electromagnetism, gravity, or a combination of physical means.

Net force

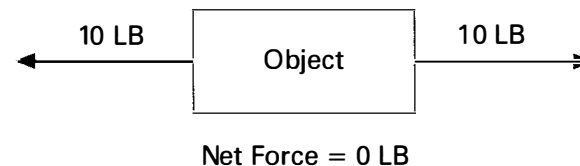
Net force is the vector sum of all forces that act on an object, including friction and gravity. When forces are applied in the same direction they are added. For example, if two 10 pound forces were applied in the same direction the net force would be 20 pounds.



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.

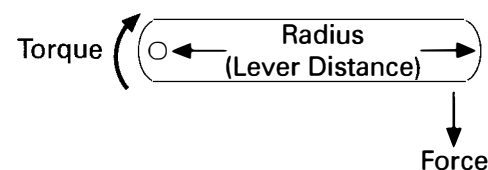


If 10 pounds of force were applied equally in both directions, the net force would be zero and the object would not move.



Torque

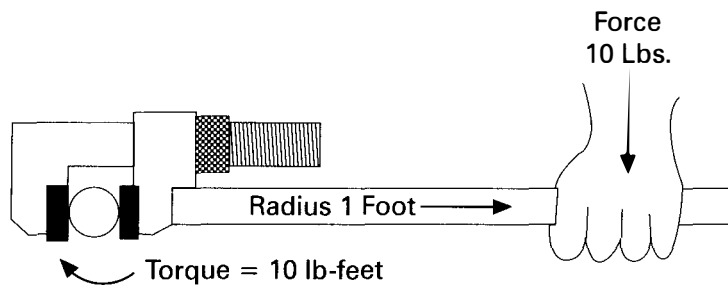
Torque is a twisting or turning force that causes an object to rotate. For example, a force applied to the end of a lever causes a turning effect or torque at the pivot point.



Torque (T) is the product of force and radius (lever distance) and is typically measured in lb-feet.

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

It can be seen that increasing force or increasing the radius increases torque. For example, if 10 pounds of force were applied to a lever 1 foot long there would be 10 lb-feet of torque. Increasing the force to 20 pounds, or the lever to two feet would increase the torque to 20 lb-feet.



Inertia

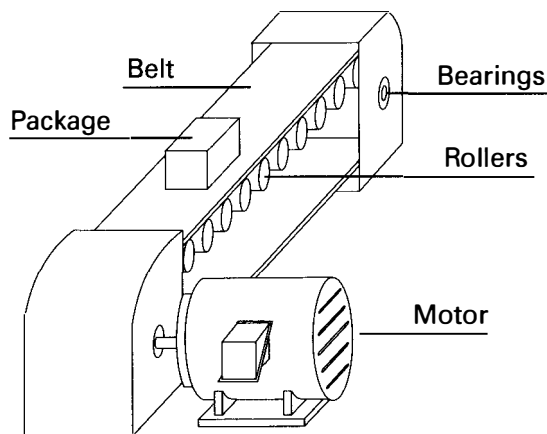
Mechanical systems are subject to the law of inertia. The law of inertia states that an object will tend to remain in its current state of rest or motion unless acted upon by an external force. A soccer ball, for example, remains at rest until a player applies a force by kicking the ball. The ball will remain in motion until another force, such as friction or the goal net, stops it.



Friction

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. In the following illustration, a motor runs a conveyor. A large amount of force is applied to overcome inertia and start the system. Once the system is in motion only the energy required to compensate for various losses need be applied to keep the conveyor in motion. These losses include:

- Friction within motor and conveyor bearings
- Wind losses in the motor and conveyor
- Friction between conveyor belt and rollers

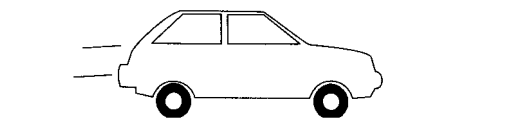


Speed

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.

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

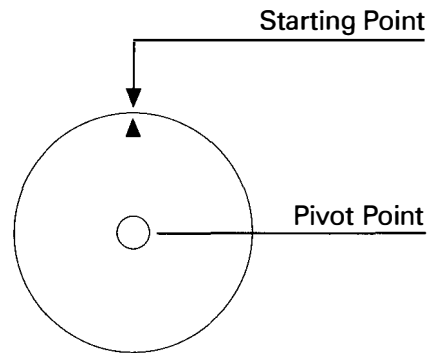
A car, for example, may travel 60 miles in one hour. The speed of the car is 60 miles per hour (MPH).



$$60 \text{ MPH} = \frac{60 \text{ Miles}}{1 \text{ Hour}}$$

Speed of a rotating object

Speed also applies to a rotating object, such as the tire of a car or the shaft of a motor. The speed of a rotating object is a measurement of how long it takes a given point on the rotating object to make one complete revolution from its starting point. Speed of a rotating object is generally given in revolutions per minute (RPM). An object that makes ten complete revolutions in one minute has a speed of 10 RPM.

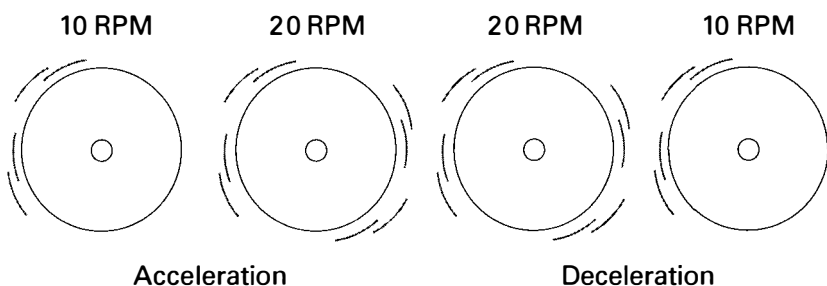


Acceleration

An object can change speed. This change in speed is called acceleration. Acceleration only occurs when there is a change in the force acting upon the object. A car increases speed from 30 MPH to 60 MPH. There has been a change in speed of 30 MPH. An object can also change from a higher to a lower speed. This is known as deceleration (negative acceleration).



Acceleration and deceleration also apply to rotating objects. A rotating object, for example, can accelerate from 10 RPM to 20 RPM, or decelerate from 20 RPM to 10 RPM.



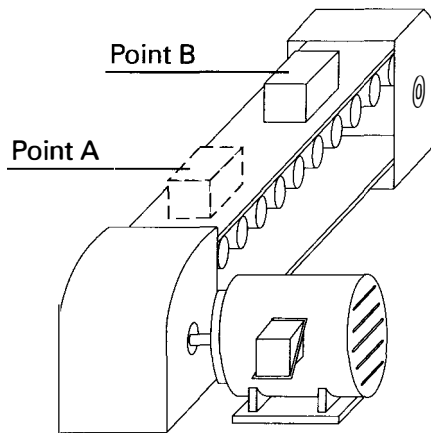
Review 1

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-feet.
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.

Energy

Work

Whenever a force of any kind causes motion, work is accomplished. For example, work is accomplished when a conveyor belt moves a package from point A to point B.



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.

$$W = F \times d$$

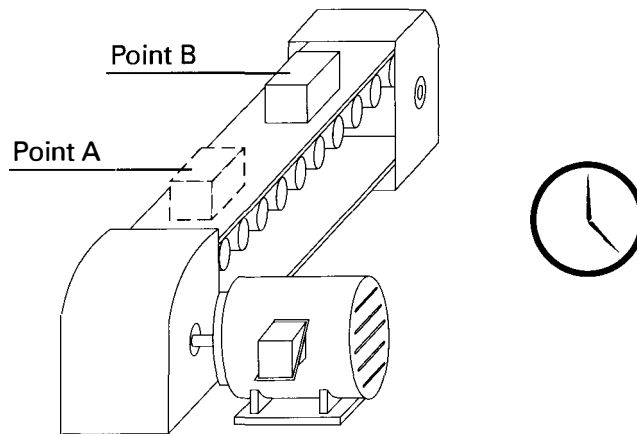
Power

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

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

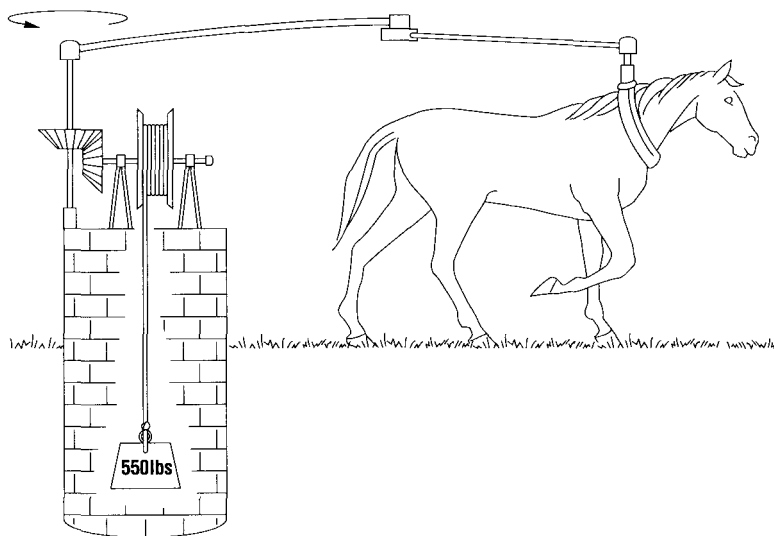
$$\text{Power} = \frac{\text{Work}}{\text{Time}}$$

In other words, power is the amount of work it takes to move the package from point A to point B, 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.

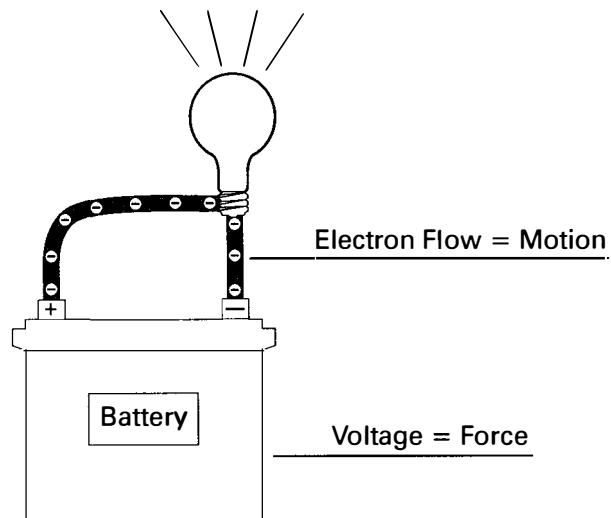


The following formula can be used to calculate horsepower when torque (in lb-ft) and speed are known. An increase of torque, speed, or both will cause an increase in horsepower.

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

Electrical Energy

In an electrical circuit, voltage applied to a conductor will cause electrons to flow. Voltage is the force and electron flow is the motion.



The rate at which work is done is called power and is represented by the symbol "P". Power is measured in watts represented by the symbol "W". The watt is defined as *the rate work is done in a circuit when 1 amp flows with 1 volt applied*.

Power in a DC circuit

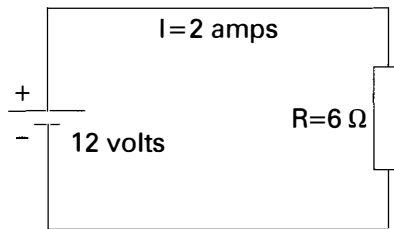
Power consumed in a resistor depends on the amount of current that passes through the resistor for a given voltage. This is expressed as voltage (E) times current (I).

$$P = E \times I$$

or

$$P = EI$$

In the following simple DC circuit power can be calculated.



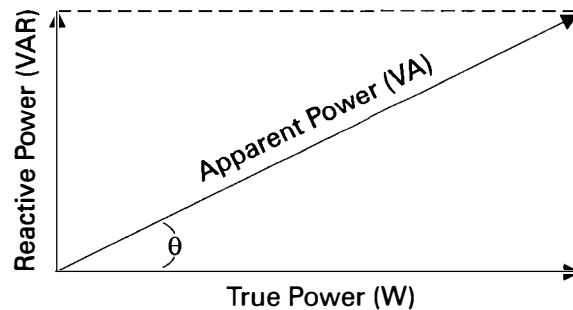
$$P = EI$$

$$P = 12 \text{ volts} \times 2 \text{ amps}$$

$$P = 24 \text{ watts}$$

Power in an AC circuit

Resistance is not the only circuit property that effects power in an AC circuit. Power consumed by a resistor is dissipated in heat and not returned to the source. This power is used to do useful work and is called true power. True power is the rate at which energy is used and is measured in watts (W). Current in an AC circuit rises to peak values and diminishes to zero many times a second. The energy stored in the magnetic field of an inductor or plates of a capacitor is returned to the source when current changes direction. This power is not consumed and is called reactive power. Reactive power is measured in volt-amps reactive (VAR). Power in an AC circuit is the vector sum of true power and reactive power. This is called apparent power. Apparent power is measured in volt-amps (VA).



The formula for apparent power is:

$$P = EI$$

True power is calculated from a trigonometric function, the cosine of the phase angle ($\cos \theta$ as shown on the previous page). The formula for true power is:

$$P = EI \cos \theta$$

Power factor

Power factor is the ratio of true power to apparent power, or a measurement of how much power is consumed and how much power is returned to the source. Power factor is equal to the cosine of the phase angle.

$$PF = \cos \theta$$

In a purely resistive circuit where current and voltage are in phase, there is no angle of displacement between current and voltage. The cosine of a zero degree angle is one. The power factor is one. This means that all energy delivered by the source is consumed by the circuit and dissipated in the form of heat.

Horsepower and kilowatts

AC drives and 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:

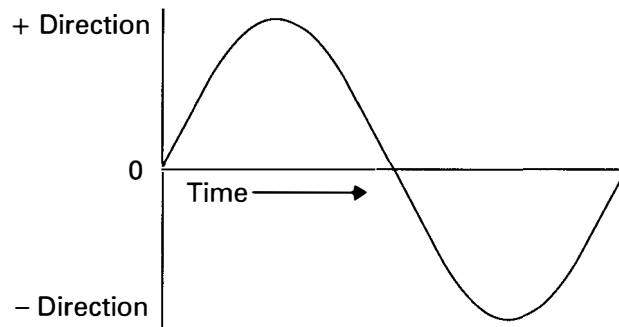
$$KW = \frac{V \times I \times PF}{1000}$$

The power formula for three-phase power is:

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

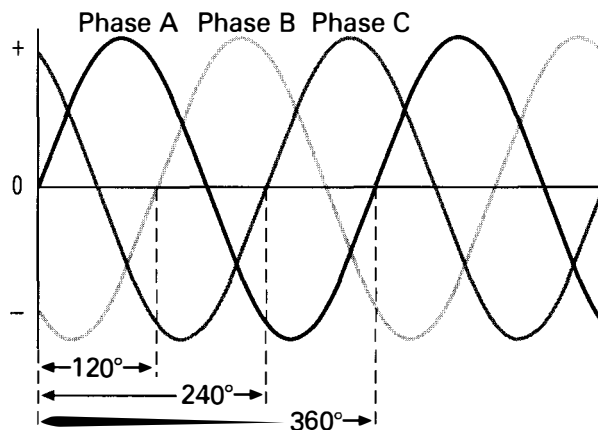
Single-phase power

Power is considered single-phase when it is operated by one voltage source. Single-phase power is used for small electrical demands such as found in the home. Single-phase power can also be found in some light duty commercial and industrial applications.



Three-phase power

Three-phase power is produced by three voltage sources. Three-phase power is a continuous series of three overlapping AC voltages. Each voltage wave represents a phase and is offset by 120 electrical degrees. Three-phase power is used where a large quantity of electrical power is required, such as commercial and industrial applications.

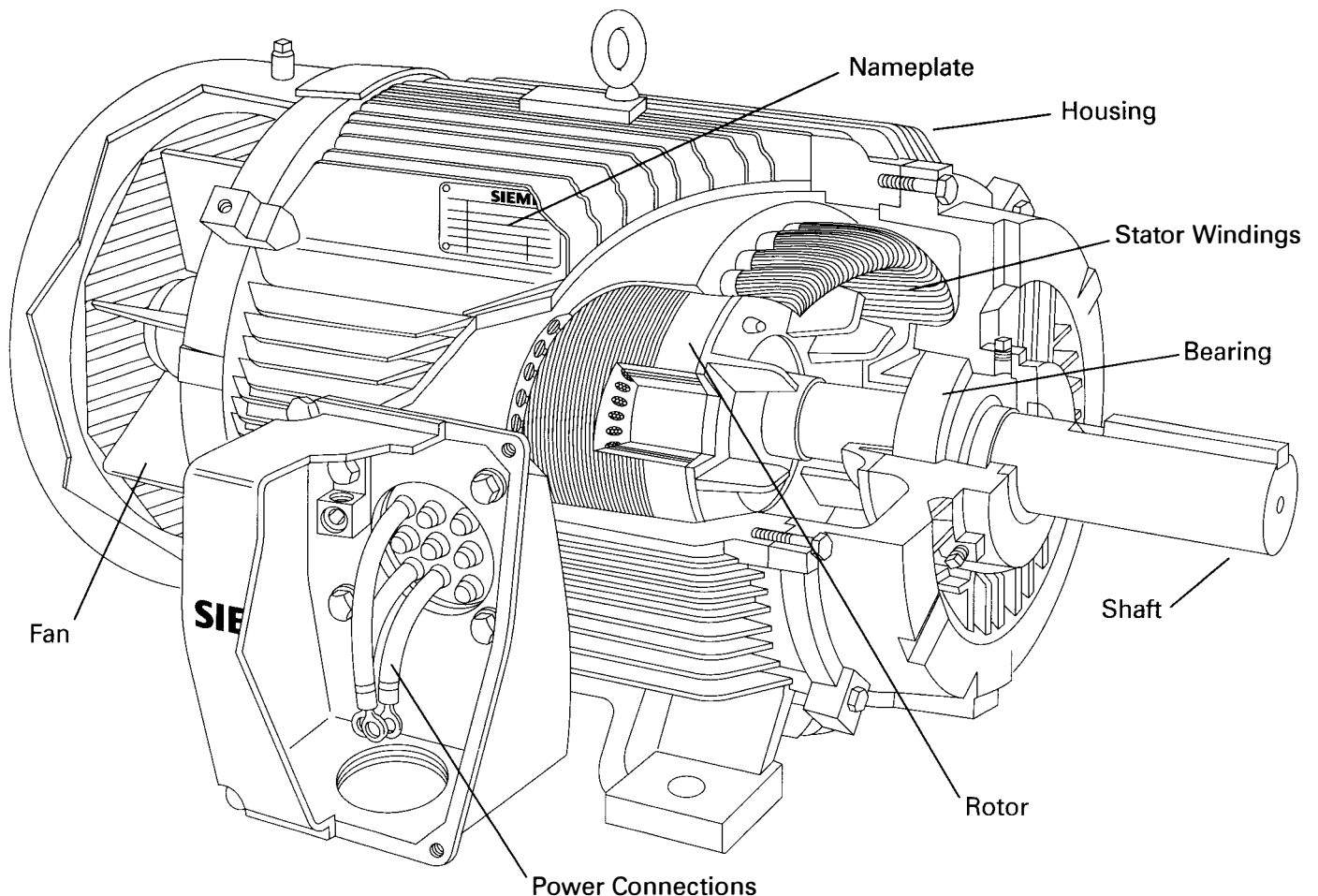


Review 2

1. _____ is accomplished whenever force causes motion.
2. _____ is the rate of doing work.
3. In an electrical circuit the force required to cause electron flow is called _____.
4. Power used to do work is called _____ power.
5. True power is measured in _____ and apparent power is measured in _____.
6. The ratio of true power to apparent power is known as _____.
7. 18 KW is equivalent to _____ HP.

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.



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.

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%.

Kilowatts and power factor

Motor manufacturers may also use kilowatts (KW) instead of horsepower and power factor (Cos. Θ) instead of efficiency. For example, a motor may be rated at 18 KW, 460 Volts, 30.5 Amps with a power factor of 0.83. To properly setup an AC drive it may be necessary to convert KW to horsepower and calculate efficiency.

To convert KW to HP use the following equation:

$$HP = 1.341 \times KW$$

$$HP = 24$$

Efficiency can be calculated with the following formula:

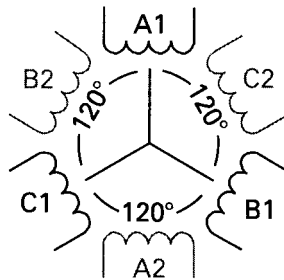
$$3\text{-Phase Efficiency} = \frac{746 \times HP}{1.732 \times V \times I \times PF}$$

$$3\text{-Phase Efficiency} = \frac{746 \times 24}{1.732 \times 460 \times 30.5 \times .83}$$

$$3\text{-Phase Efficiency} = 88.7\%$$

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.



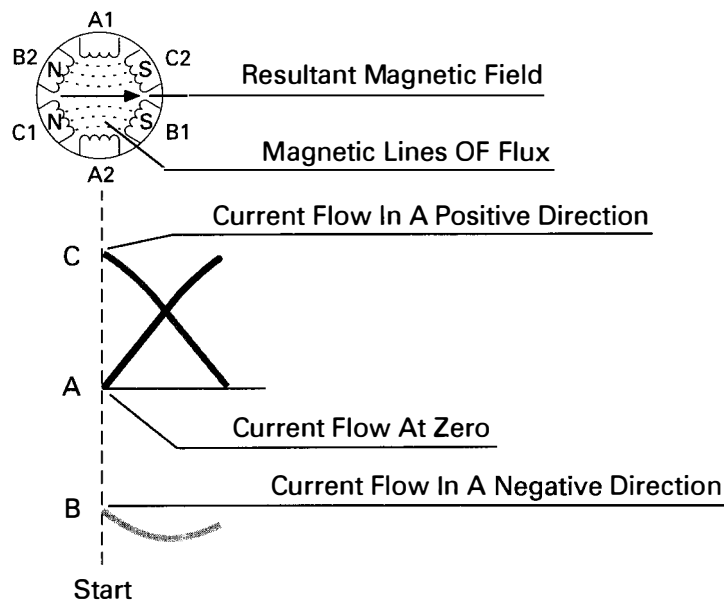
2-Pole Stator Winding

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

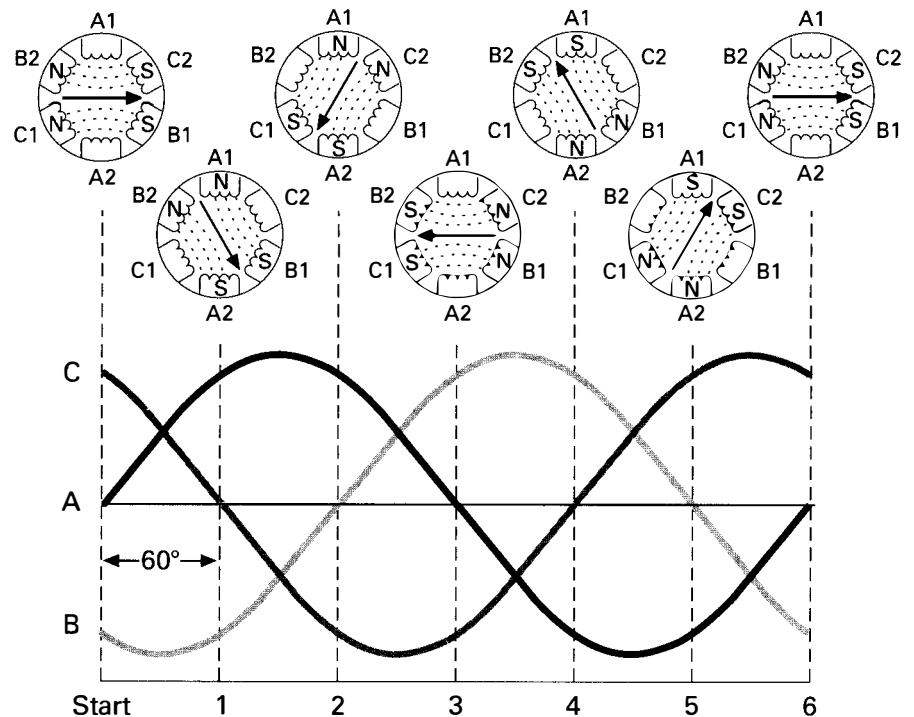
It is easier to visualize a magnetic field if a time is picked when no current is flowing through one phase. In the following illustration, for example, a time has been selected during which phase A has no current flow, phase B has current flow in a negative direction and phase C has current flow in 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 at 60° intervals from the starting point, at point 1, it can be seen that the field will rotate 60°. At point 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. 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 (N_s). Synchronous speed is equal to 120 times the frequency (F), divided by the number of poles (P).

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

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

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

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

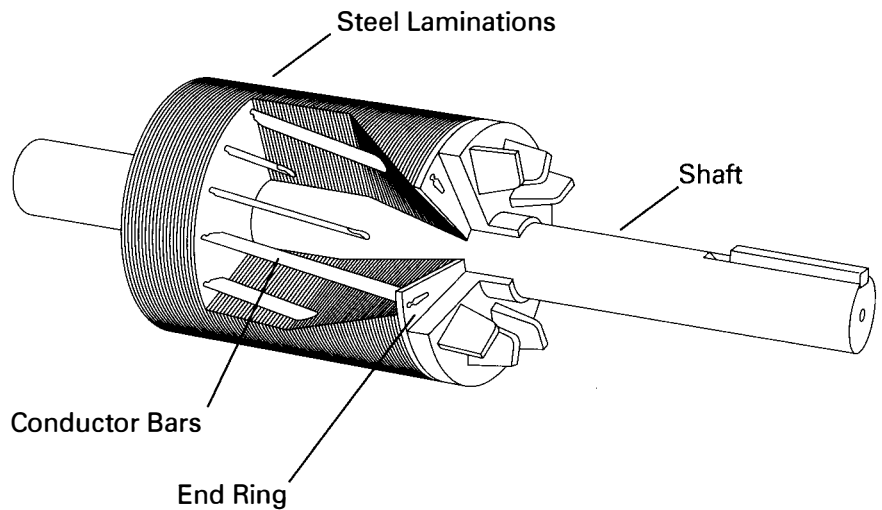
Review 3

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. An increase of stator voltage in a 3-phase AC motor will cause the magnetic lines of flux to _____.
7. An increase of stator frequency in a 3-phase AC motor will cause the magnetic lines of flux to _____.

Rotor Construction

Rotor construction

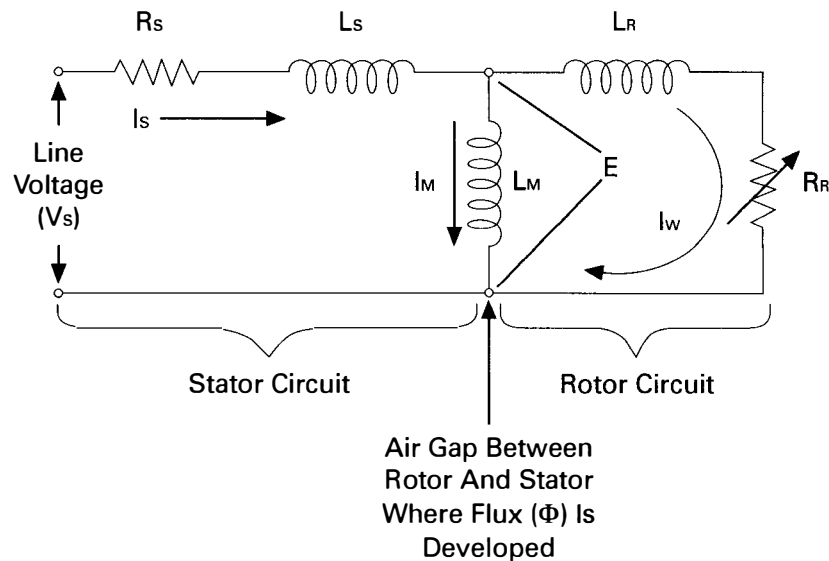
The most common type of rotor is the “squirrel cage” rotor. The construction of the squirrel cage rotor is reminiscent of rotating exercise wheels found in cages of pet rodents. The rotor consists of a stack of steel laminations with evenly spaced conductor bars around the circumference. The conductor 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.



Electrical Components Of A Motor

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 (Φ), 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).

$$I_s = \sqrt{I_M^2 + I_w^2}$$

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.

Note: Most NEMA terms and concepts apply to motors operated from 60 Hz power lines, not variable speed drive operation.

Definitions

Locked rotor torque is also referred to as starting torque. This 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 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 is the torque developed during acceleration from start to the point breakdown torque occurs.

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

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

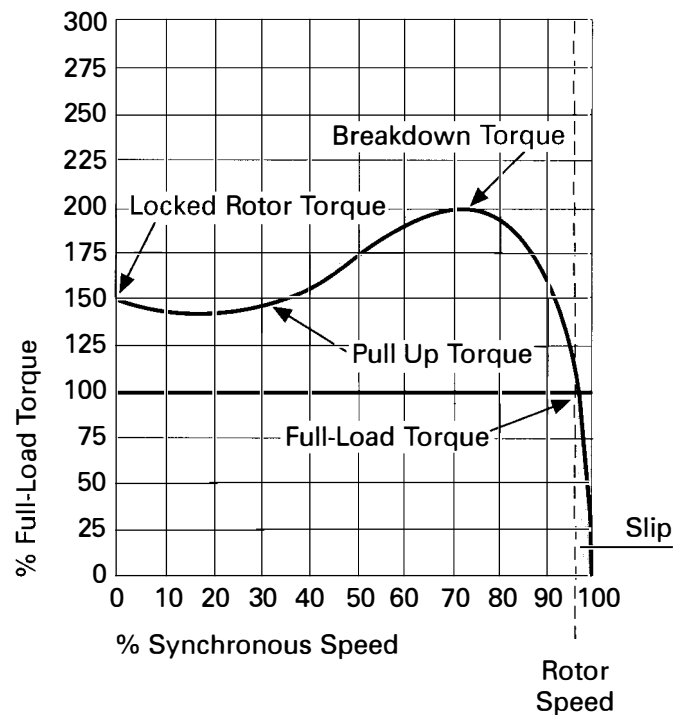
Full-load current is the current taken from the supply line at rated voltage, frequency and load.

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/torque curve

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.



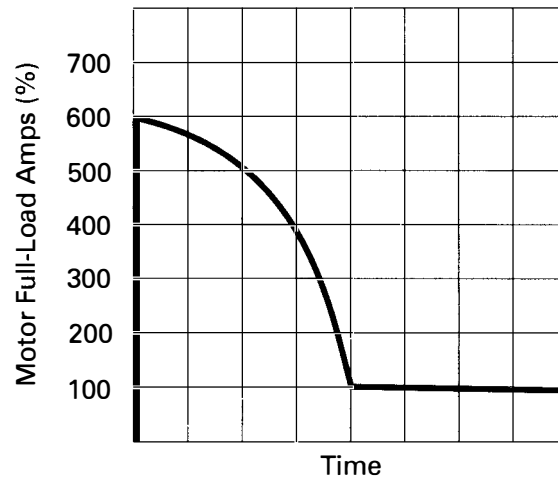
Torque

Torque (T) is equal to certain mechanical constants of the motor (k) times flux (Φ) times working current (I_w). An increase in flux or an increase in load will cause an increase in torque.

$$T = k\Phi I_w$$

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.



Review 4

1. The _____ is the most common type of rotor in AC motors.
2. The difference in stator speed and rotor speed is known as _____.
3. A two-pole motor operating on 60 Hz power at 3450 RPM has _____ % slip.
4. An increase in load will cause an _____ in working current (I_w) and slip.
5. Current that actually produces torque to turn the rotor is known as _____ current.
6. Stator current is the vector sum of _____ current and _____.
7. Starting torque of a NEMA B motor is approximately _____ % of full load torque, and starting current is approximately _____ % of full load current.

Voltage And Frequency

Up to this point, the operation of an AC motor with rated voltage and frequency applied has been examined. Many applications require the speed of an AC motor to vary. The easiest way to vary the speed of an AC induction motor is to use an AC drive to vary the applied frequency. Operating a motor at other than the rated frequency has an effect on motor current and torque.

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 (Φ), 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.

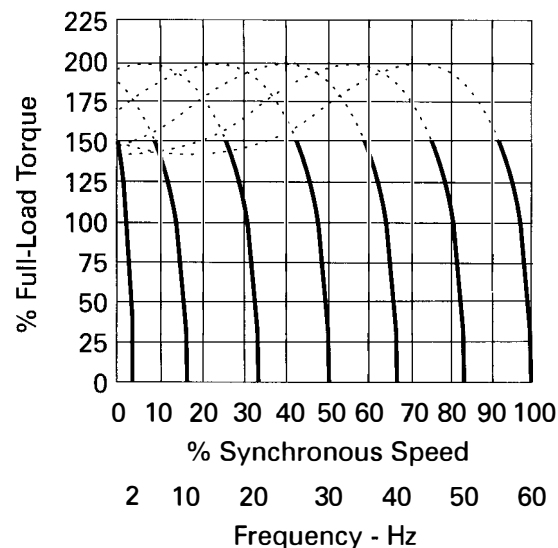
$$\Phi \approx \frac{E}{F}$$

$$T = k\Phi/w$$

$$I_M = \frac{E}{2\pi FL_M}$$

Reduced voltage and frequency starting

A NEMA B motor that is started by connecting it to the power supply at full voltage and full frequency will develop approximately 150% starting torque and 600% starting current. AC drives start at reduced voltage and frequency. The motor will start with approximately 150% torque and 150% current at reduced frequency and voltage. 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. An AC drive, properly sized to a motor, is capable of delivering 150% torque at any speed up to speed corresponding to the incoming line voltage. The only limitations on starting torque are peak drive current and peak motor torque, whichever is less.

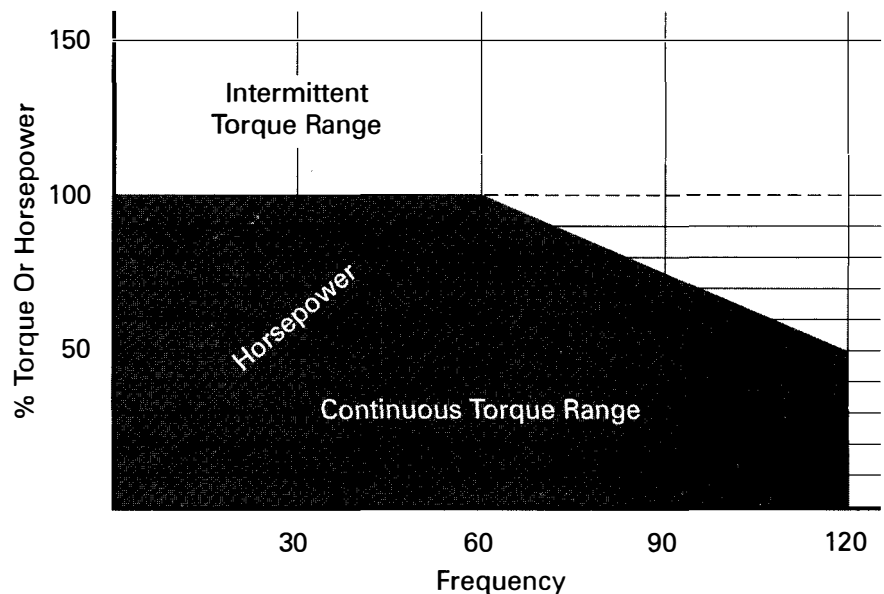


Some applications require higher than 150% starting torque. A conveyor, for example, may require 200% rated torque for starting. If a motor is capable of 200% torque at 200% current, and the drive is capable of 200% current, then 200% motor torque is possible. Typically drives are capable of producing 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.

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 50% 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 70% torque intermittently.

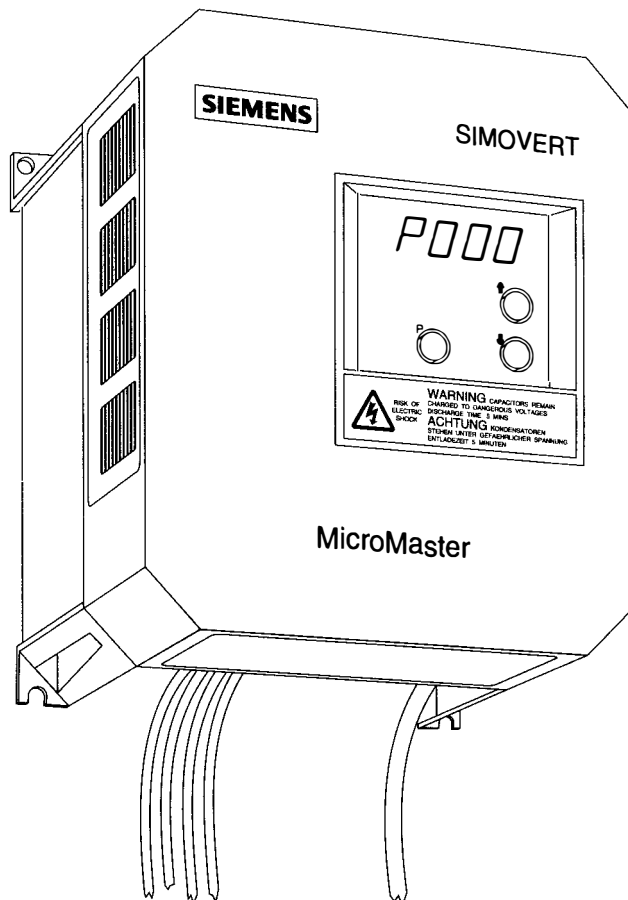


The sample motor described above is capable of operating at 100% rated torque continuously at low frequencies. Many motors are not capable of operating continuously at 100% continuous torque at low frequencies. Each motor must be evaluated before selecting it for use on an AC drive.

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

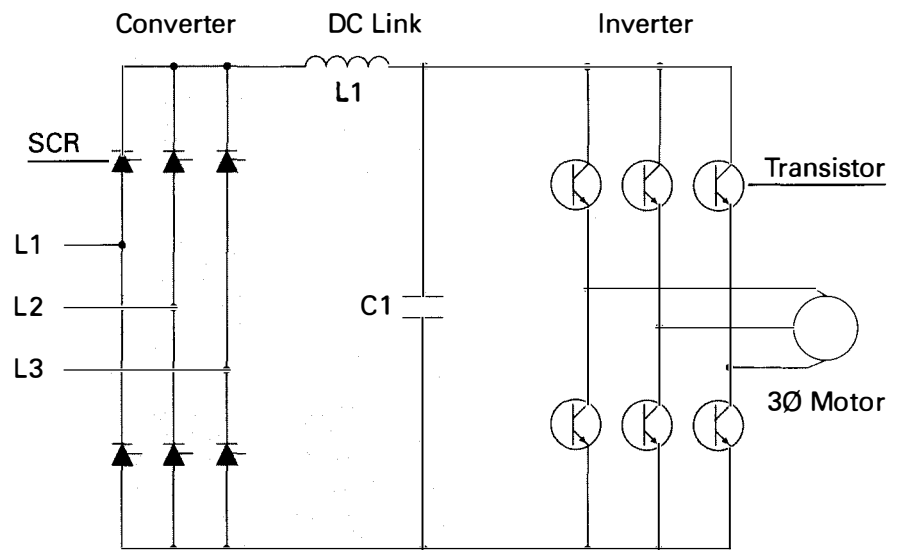
Basic AC Drives

AC drives, inverters, and adjustable frequency drives are all terms that are used to refer to equipment designed to control the speed of an AC motor. The term **SIMOVERT** is used by Siemens to identify a **Siemens MOtor inVERTer** (AC drive). AC drives, like the Siemens MicroMaster, receive AC power and convert it to an adjustable frequency, adjustable voltage output for controlling motor operation. A typical inverter receives 480 VAC, three-phase, 60 Hz input power and provides power to the motor which can be steplessly adjusted through the speed range. The three common inverter types are the variable voltage inverter (VVI), current source inverter (CSI), and pulse width modulation (PWM). All AC drives convert AC to DC, and then through various switching techniques invert the DC into a variable voltage, variable frequency output.

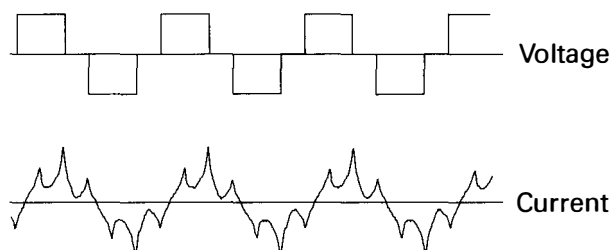


Variable voltage inverter (VVI)

The variable voltage inverter (VVI) uses an SCR converter bridge to convert the incoming AC voltage into DC. The SCRs provide a means of controlling the value of the rectified DC voltage from 0 to approximately 600 VDC. The L1 choke and C1 capacitor(s) make up the DC link section and smooth the converted DC voltage. The inverter section consists of six switching devices. Various devices can be used such as thyristors, bipolar transistors, MOSFETs, and IGBTs. The following schematic shows an inverter that utilizes bipolar transistors. Control logic (not shown) uses a microprocessor to switch the transistors on and off providing a variable voltage and frequency to the motor.

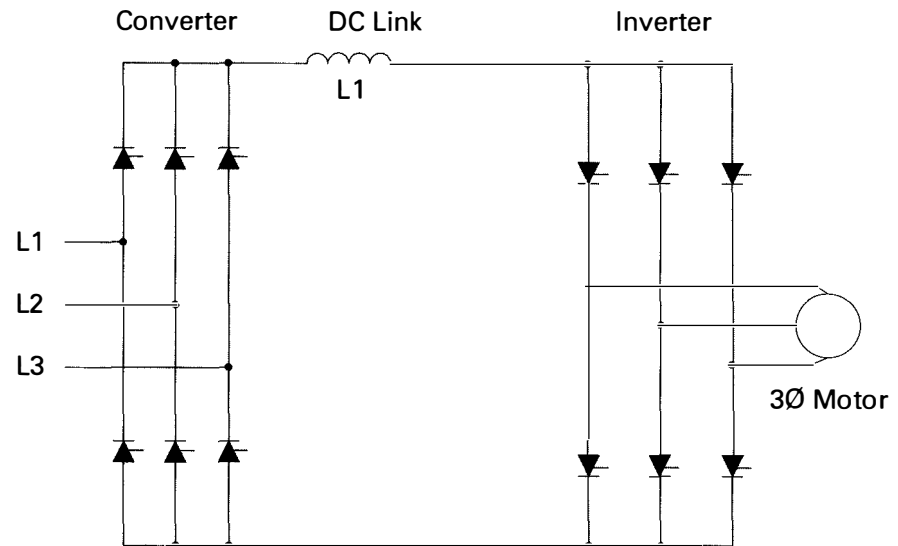


This type of switching is often referred to as six-step because it takes six 60° steps to complete one 360° cycle. Although the motor prefers a smooth sine wave, a six-step output can be satisfactorily used. The main disadvantage is torque pulsation which occurs each time a switching device, such as a bipolar transistor, is switched. The pulsations can be noticeable at low speeds as speed variations in the motor. These speed variations are sometimes referred to as cogging. The non-sinusoidal current waveform causes extra heating in the motor requiring a motor derating.

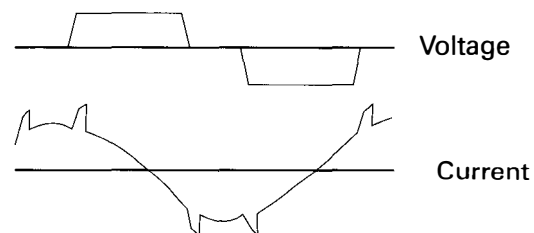


Current source inverter (CSI)

The current source inverter (CSI) uses an SCR input to produce a variable voltage DC link. The inverter section also uses SCRs for switching the output to the motor. The current source inverter controls the current in the motor. The motor must be carefully matched to the drive.

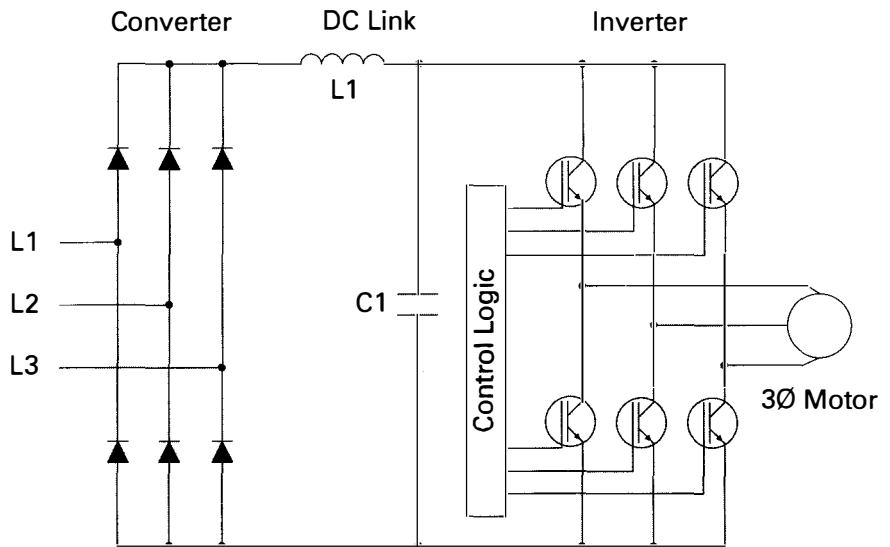


Current spikes, caused by switching, can be seen in the output. At low speeds current pulses can cause the motor to cog.



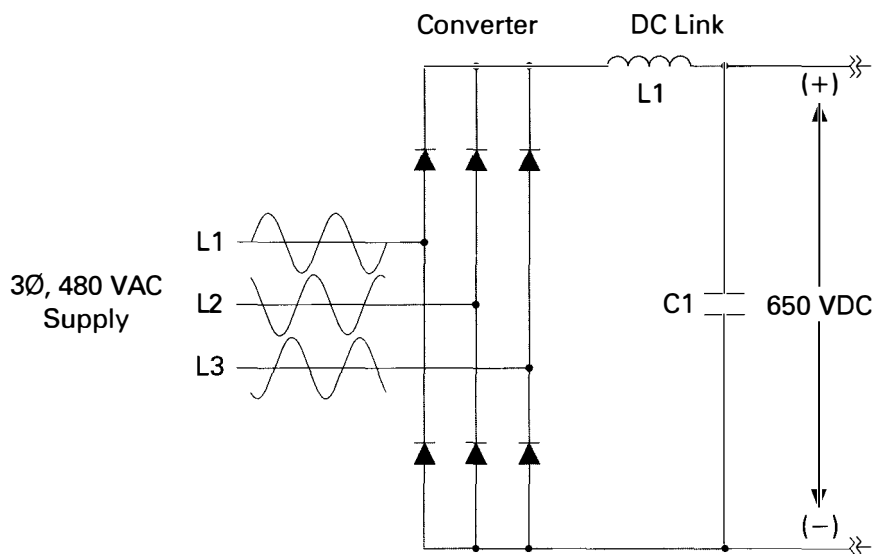
Pulse width modulation

Pulse width modulation (PWM) drives, like the Siemens MicroMaster, provide a more sinusoidal current output to control frequency and voltage supplied to an AC motor. PWM drives are more efficient and typically provide higher levels of performance. A basic PWM drive consists of a converter, DC link, control logic and an inverter.



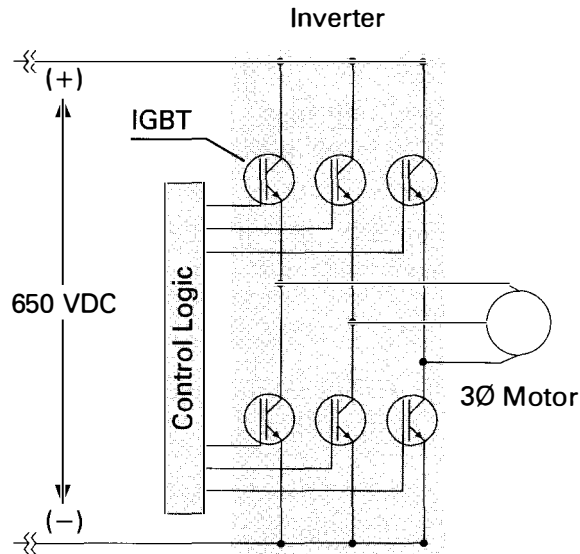
Converter and DC link

The converter section consists of a fixed diode bridge rectifier which converts the three-phase power supply to a DC voltage. The L1 choke and C1 capacitor(s) smooth the converted DC voltage. The rectified DC value is approximately 1.35 times the line-to-line value of the supply voltage. The rectified DC value is approximately 650 VDC for a 480 VAC supply.



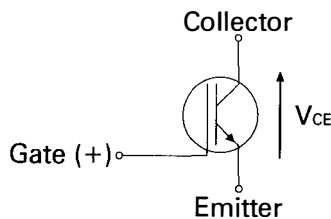
Control logic and inverter

Output voltage and frequency to the motor are controlled by the control logic and inverter section. The inverter section consists of six switching devices. Various devices can be used such as thyristors, bipolar transistors, MOSFETs and IGBTs. The following schematic shows an inverter that utilizes IGBTs. The control logic uses a microprocessor to switch the IGBTs on and off providing a variable voltage and frequency to the motor.



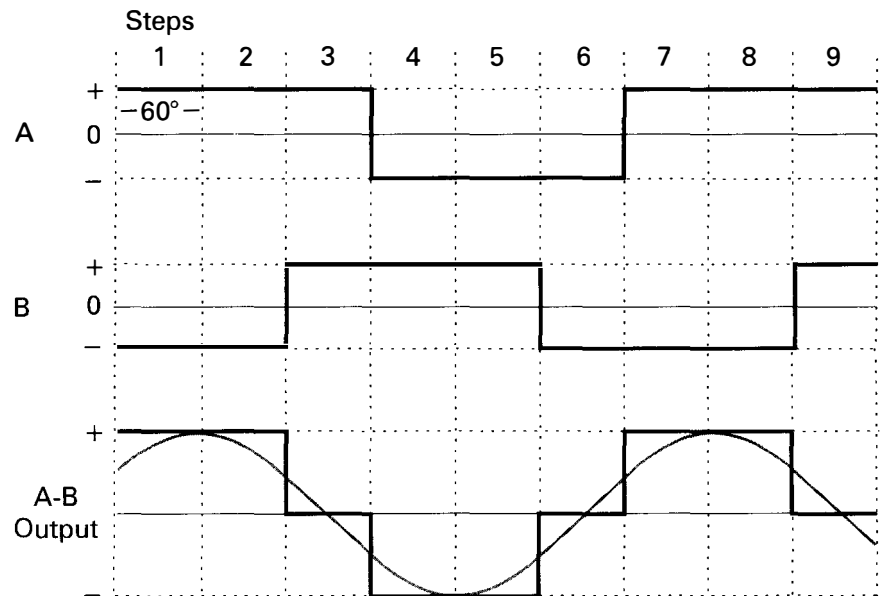
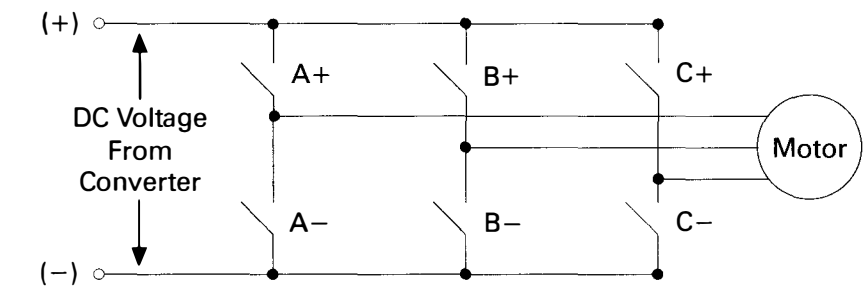
IGBTs

IGBTs (insulated gate bipolar transistor), like those used in the Siemens MicroMaster, provide a high switching speed necessary for PWM inverter operation. IGBTs are capable of switching on and off several thousand times a second. An IGBT can turn on in less than 400 nanoseconds and off in approximately 500 nanoseconds. An IGBT consists of a gate, collector and an emitter. When a positive voltage (typically +15 VDC) is applied to the gate the IGBT will turn on. This is similar to closing a switch. Current will flow between the collector and emitter. An IGBT is turned off by removing the positive voltage from the gate. During the off state the IGBT gate voltage is normally held at a small negative voltage (-15 VDC) to prevent the device from turning on.



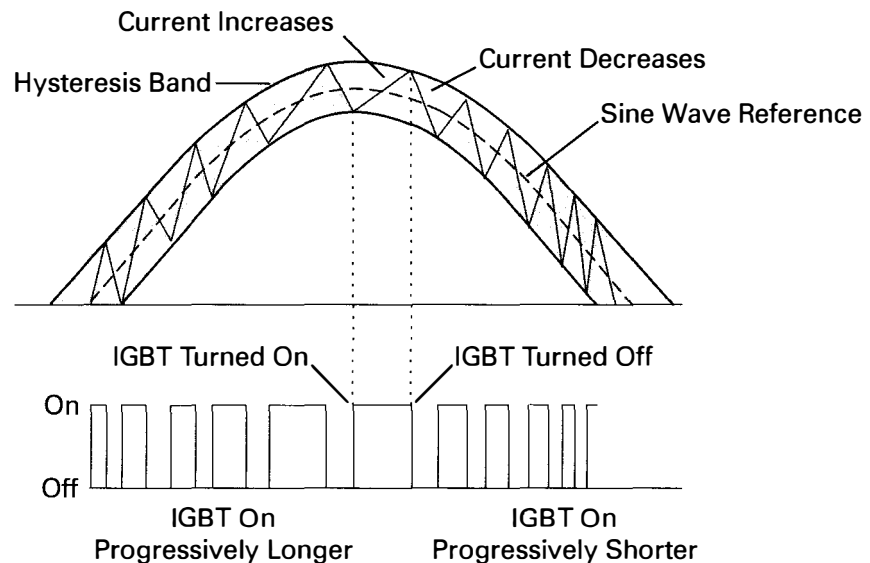
Using switching devices to develop a basic AC output

In the following example, one phase of a three-phase output is used to show how an AC voltage can be developed. Switches replace the IGBTs. A voltage that alternates between positive and negative is developed by opening and closing switches in a specific sequence. For example, during steps one and two A+ and B- are closed. The output voltage between A and B is positive. During step three A+ and B+ are closed. The difference of potential from A to B is zero. The output voltage is zero. During step four A- and B+ are closed. The output voltage from A to B is negative. The voltage is dependent on the value of the DC voltage and the frequency is dependent on the speed of the switching. An AC sine wave has been added to the output (A-B) to show how AC is simulated.



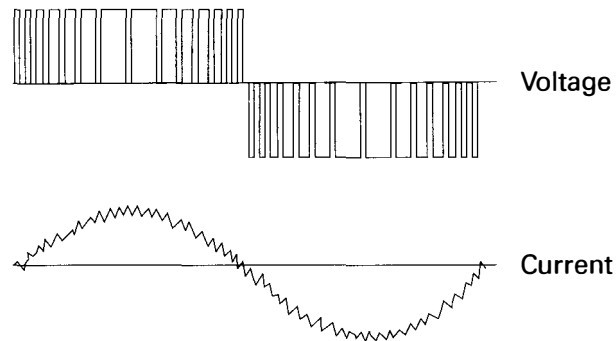
Generating a PWM output

There are several PWM modulation techniques. It is beyond the scope of this book to describe them all in detail. The following text and illustrations describe a typical pulse width modulation method. An IGBT (or other type switching device) can be switched on connecting the motor to the positive value of DC voltage (650 VDC from the converter). Current flows in the motor. The IGBT is switched on for a short period of time, allowing only a small amount of current to build up in the motor and then switched off. The IGBT is switched on and left on for progressively longer periods of time, allowing current to build up to higher levels until current in the motor reaches a peak. The IGBT is then switched on for progressively shorter periods of time, decreasing current build up in the motor. The negative half of the sine wave is generated by switching an IGBT connected to the negative value of the converted DC voltage.

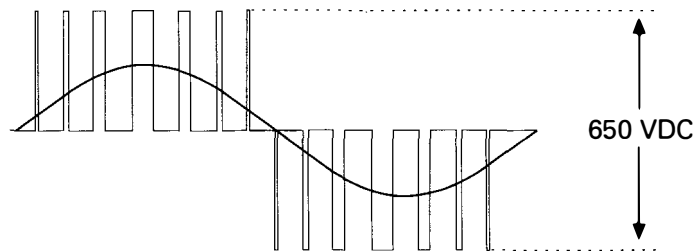


PWM voltage and current waveforms

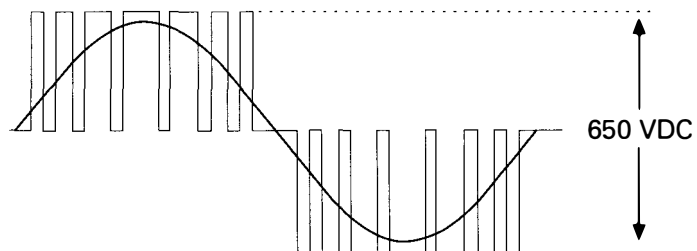
The more sinusoidal current output produced by the PWM reduces the torque pulsations, low speed motor cogging, and motor losses noticeable when using a six-step output.



The voltage and frequency is controlled electronically by circuitry within the AC drive. The fixed DC voltage (650 VDC) is modulated or clipped with this method to provide a variable voltage and frequency. At low output frequencies a low output voltage is required. The switching devices are turned on for shorter periods of time. Voltage and current build up in the motor is low. At high output frequencies a high voltage is required. The switching devices are turned on for longer periods of time. Voltage and current build up in the motor increases.



Shorter "On" Duration, Lower Voltage



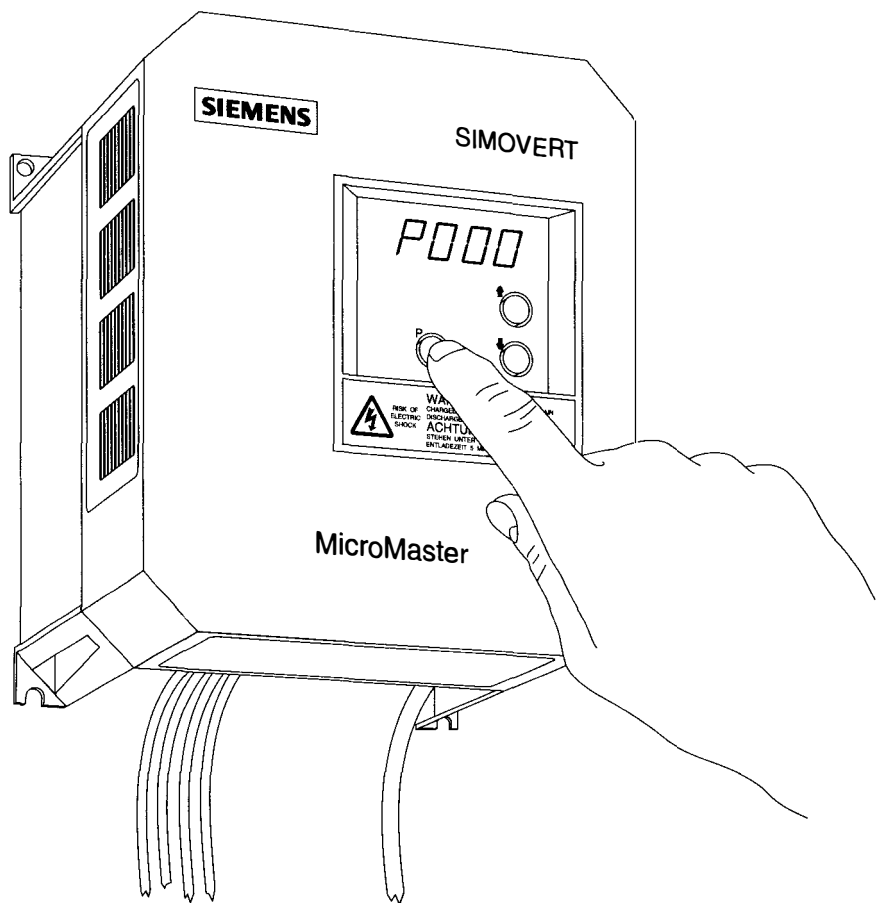
Longer "On" Duration, Higher Voltage

Review 5

1. The volts per hertz ratio of a 460 Volt, 60 Hz motor is _____.
2. An increase in voltage will cause flux (Φ) to _____, and torque (T) capability to _____.
3. A motor operated within a speed range that allows a constant volts per hertz ratio is said to be constant _____.
 - a. horsepower
 - b. torque
4. If torque decreases proportional to speed (RPM) increasing, then _____ is constant.
5. Siemens uses the term _____ to identify a Siemens inverter (AC drive).
6. On a PWM drive with a 480 VAC supply, the approximate voltage after being converted to DC is _____ VDC.
7. IGBTs are capable of being switched several _____ a second.
 - a. times
 - b. hundred times
 - c. thousand times
 - d. million times
8. A PWM output, like that used on the Siemens MicroMaster is preferred to a six-step output because _____.
 - a. PWM provides a more sinusoidal output
 - b. Cogging is more noticeable on a six-step
 - c. The non-sinusoidal waveform of a six-step increases motor heat
 - d. a, b, and c
9. To obtain a lower voltage and frequency output on a PWM inverter, control circuitry will switch IGBTs on for _____ periods of time.
 - a. shorter
 - b. longer

Siemens MicroMaster

Siemens offers a broad range of AC drives. At the low end of the horsepower range is the Siemens MicroMaster. For information on other AC drive products contact your Siemens representative. The Siemens MicroMaster is an adjustable frequency AC drive that uses a built-in microprocessor to control the operation of the drive. A keypad allows the mode of operation to be adjusted for practically any application requirement. The MicroMaster is available from ¼ HP to 3 HP for 230 VAC motors, and 2 HP to 7½ HP for 460 VAC motors.



Enclosure	The National Electrical Manufacturers Association (NEMA) has specified standards for equipment enclosures. The MicroMaster is supplied in a NEMA 1 enclosure. This is a general purpose, indoor enclosure. Other enclosures, such as NEMA 12, can be provided. NEMA 12 is an industrial, dusttight and driptight enclosure intended for indoor use. Contact your Siemens sales representative for more information.
Ambient temperature	The MicroMaster is rated for operation in an ambient temperature of 0 to 40° C with the cover on, or 0 to 50° C with the cover off.
Elevation	The MicroMaster is rated for operation below 3300 feet. At higher elevations the air is thinner, consequently the drive can't dissipate heat as effectively. Above 3300 feet the drive must be derated.
Distance between drive and motor	Distance from the drive to the motor must also be taken into consideration. All motor cables have line-to-line and line-to-ground capacitance. The longer the cable, the greater the capacitance. Some types of cables, shielded cable for example, have greater capacitance. Spikes occur on the output of all PWM drives because of the charging current of the cable capacitance. Higher voltage (460 VAC) and higher capacitance (long cables) result in higher current spikes. Voltage spikes caused by long cable lengths can potentially shorten the life of the inverter and the motor. The maximum distance between a motor and the MicroMaster is 50 meters (164 feet). If shielded cable is used, the maximum distance is 25 meters (82 feet). When considering an application where distance may be a problem, contact your local Siemens representative.
230 Volt models	Input voltage is single-phase 208 to 230 VAC. In addition there is a -10%/+15% (187 VAC to 264 VAC) tolerance for voltage fluxuations. The acceptable input frequency ranges from 47 Hz to 63 Hz. The output voltage is 0 to 200/230 VAC, three-phase. The maximum value depends on the input voltage.
380 - 500 Volt models	Input voltage is three-phase 380 to 500 VAC. In addition there is a -10% (342 VAC) to +10% (550 VAC) tolerance for voltage fluxuations. The acceptable input frequency ranges from 47 Hz to 63 Hz. The output voltage is 0 to 400/500 VAC, three-phase. The maximum value depends on the input voltage.

Output frequency

Output frequency is adjustable from 0 to 650 Hz. Consideration must be given to the motor and application, which may not be capable of operating at 650 Hz. The 6SE30 is capable of being set to a minimum and maximum speed appropriate for the application. If the minimum speed required is 10 Hz, and the maximum speed required is 60 Hz, then the 6SE30 can be programmed for a speed range of 10 to 60 Hz.

Catalog numbers

The following catalog numbers reflect models available at the time this book was printed. A MicroMaster may also be referred to by its model series, 6SE30.

230 VAC

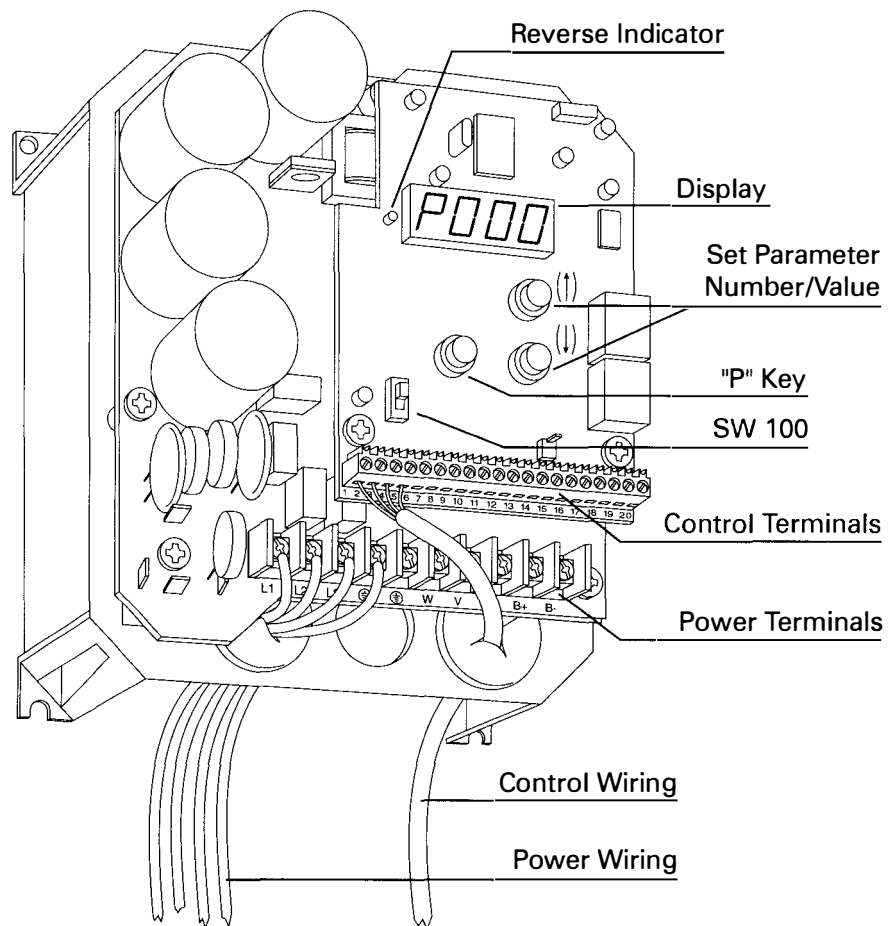
HP	KW	Rated Current	Model Number
¼	.25	1.6	6SE3011-5BA00
½	.37	2.3	6SE3012-0BA00
¾	.55	3.3	6SE3012-6BA00
1	.75	3.9	6SE3013-4BA00
1½	1.1	5.5	6SE3014-8BC00
2	1.5	7.1	6SE3016-4BC00
3	2.2	10.4	6SE3018-8BC00

380 - 500 VAC

HP	KW	Rated Current	Model Number
2	1.5	4.0	6SE3014-0DC00
3	2.2	5.9	6SE3015-8DC00
5	3.0	7.7	6SE3017-7DC00
	4.0	10.2	6SE3021-0DC00
7.5	5.5	13.2	6SE3021-3DC00

Interior of a MicroMaster

The following drawing illustrates a MicroMaster with the cover removed. A 4-digit, 7-segment display is selectable to indicate output frequency, frequency setpoint, motor current, DC-link voltage or motor torque. In addition, the display will show the value of any parameter. Parameters can be accessed and adjusted using the up and down parameter buttons. The "P" key toggles between a parameter number and a parameter value. Another LED indicates if the drive is running the motor in the reverse direction. SW 100 is a switch that lets an operator select current or voltage as a speed reference source. Control wiring, such as speed reference, is connected to the control terminals. Power wiring, such as the AC supply, is connected to the power terminals.

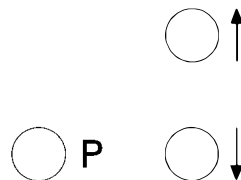


Parameter

A parameter is a variable that is given a constant value. For example, ramp up time is parameter number P002. Ramp up time can be set for any value from 0 to 650 seconds. When setting up the drive a value of 10 seconds might be selected. When given a start command it would take 10 seconds for the drive to ramp up to full speed. Parameter adjustment on the MicroMaster is simple. Standard applications require no special settings, however, parameters can be easily modified for special applications.

Parameterization panel

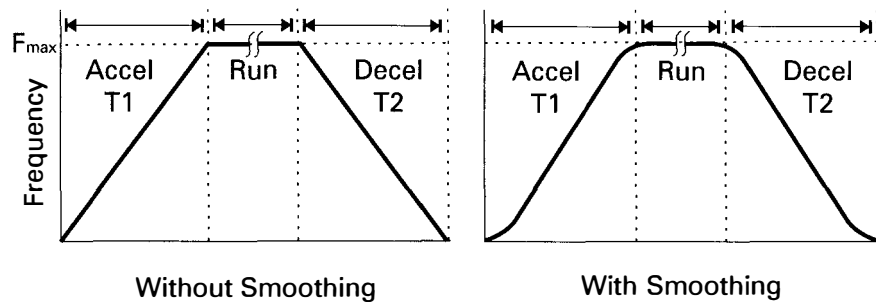
Programming is done on the MicroMaster parameterization panel using three push buttons and a 4-digit LED display. Parameters, such as ramp times, minimum and maximum frequencies, and modes of operation are easily set. The "P" key toggles the display between a parameter number and the value of the parameter. The up and down pushbuttons scroll through parameters and are used to set a parameter value. In the event of a failure the inverter switches off and a fault code appears in the display.



The MicroMaster has various parameters for proper drive and motor operation. It is beyond the scope of this book to describe in detail every parameter available. Some of the key parameters are described in the following text.

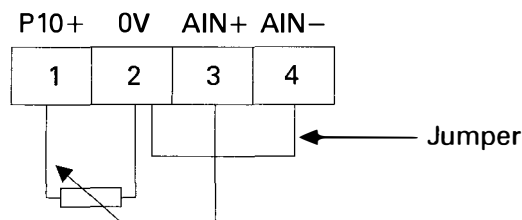
Ramp function

A feature of AC drives is the ability to increase or decrease the voltage and frequency to a motor gradually. This accelerates the motor smoothly with less stress on the motor and connected load. Parameters P002, P003 and P004 are used to set a ramp function. Acceleration and deceleration are separately programmable from 0 to 650 seconds. Acceleration, for example, could be set for 10 seconds and deceleration could be set for 60 seconds. Smoothing is a feature of the MicroMaster that can be added to the acceleration/deceleration curve. This feature smooths the transition between starting and finishing a ramp. Minimum and maximum speed are set by parameters P012 and P013.



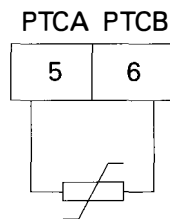
Analog inputs

Parameter P006 is used to select either an analog or digital reference, or fixed frequency. Terminals one (1) through four (4) are used to provide an analog reference that controls the speed of the motor from 0 to 100%. Terminal one (1) is a +10 VDC power supply that is internal to the drive. Terminal two (2) is the return path, or ground, for the 10 Volt supply. An adjustable resistor can be connected between terminals one and two. Terminal three (3) is the positive (+) analog input to the drive. A positive voltage will control the speed of the motor in the forward direction. The wiper arm of the adjustable resistor is connected to terminal three. Terminal four (4) is a negative (-) analog input. A negative voltage will control the speed of the motor in the reverse direction. The drive can also be programmed to accept 0 to 20 mA, or 4 to 20 mA speed reference signal. These signals are typically supplied to the drive by other equipment such as a programmable logic controller (PLC). Note that a jumper has been connected between terminals two and four. An analog input cannot be left floating (open). If an analog input will not be used it must be connected to terminal two (0 Volts).



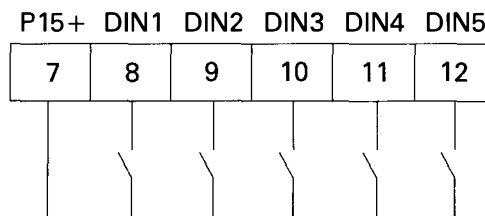
Thermistor

Some motors have a built in thermistor. If a motor becomes overheated the thermistor acts to interrupt the power supply to the motor. A thermistor can be connected to terminals five (5) and six (6). If the motor gets to a preset temperature as measured by the thermistor, the MicroMaster will interrupt power to the motor. The motor will coast to a stop. The display will indicate a fault has occurred. Parameter P087 will tell the drive if a thermistor is used.



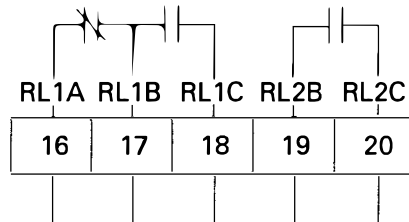
Digital inputs

An input that is either "high" or "low" is referred to as a digital input. The MicroMaster has five digital inputs (DIN). A switch or a contact is connected between +15 VDC (P15+) and a digital input (DIN1 - DIN5). Digital inputs are controlled by parameters P051 through P052 and can be programmed for various functions. Digital input 1 (DIN1), for example, may be used to start and stop the drive. When the switch between P15+ is open the drive is stopped. When the switch between P15+ is closed the drive supplies power to the motor. Other inputs can be used for forward/reverse, preset speeds, jogging or other functions.



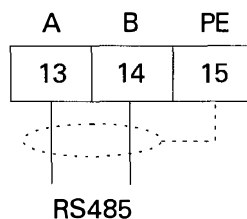
Relay outputs

There are two programmable relay outputs for indication of system status. These are controlled by parameters P061 and P062. One output (terminals 16, 17, 18) can be used for one normally closed (NC) or one normally open (NO) output. The other output (terminals 19, 20) can be used for a normally open output. The relays can be programmed to indicate various conditions such as the drive is running, a failure has occurred, converter frequency is at 0 or converter frequency is at minimum.



Serial interface

The MicroMaster has an RS485 serial interface that allows communication with computers (PCs) or programmable logic controllers (PLCs). The bus address is entered with parameter P091. Other parameters necessary for proper RS485 operation are P092-P094. Up to 31 MicroMaster AC drives can be interconnected for control of multi-drive applications. The standard RS485 protocol is called USS protocol and is programmable up to 19.2 K baud. Siemens PROFIBUS protocol is also available. It is programmable up to 1.5 M baud. Contact your Siemens Sales Representative for information on USS and PROFIBUS protocol.



Current limit and motor overload

A MicroMaster is capable of delivering up to 150% of drive rated current for one minute. The MicroMaster also has sophisticated and useful speed/time/current dependent overload functions to protect the motor. The monitoring and protection functions include a drive overcurrent fault, a motor overload fault, a calculated motor overtemperature warning, and a measured motor overtemperature fault (requires a device inside the motor).

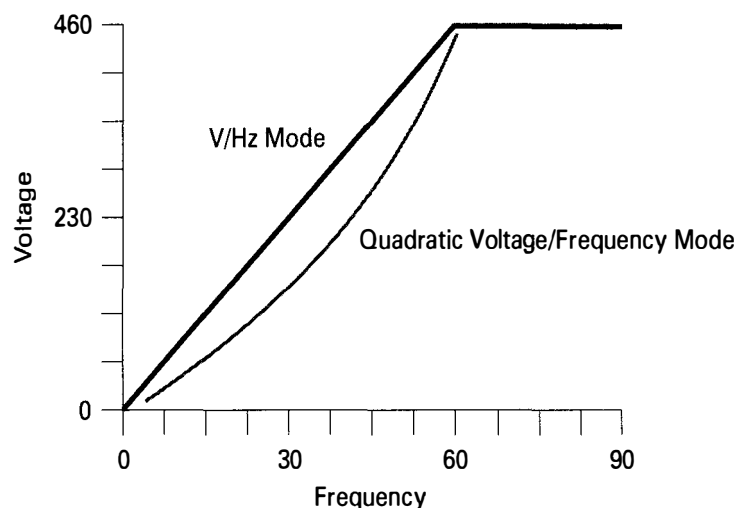
Low speed and starting boost

Low speed boost can be adjusted high for applications requiring high torque at low speeds. Low speed boost can be adjusted low for smooth, cool, and quiet operation at low speed. An additional starting boost is available for applications requiring high starting torque.

Modes of operation

There are three modes of operation, selected by parameter P077. The MicroMaster can operate utilizing a standard V/Hz curve. Using a 460 VAC, 60 Hz motor as an example, constant volts per hertz is supplied to the motor at any frequency between 0 and 60 Hz. This is the simplest type of control and is suitable for general purpose applications.

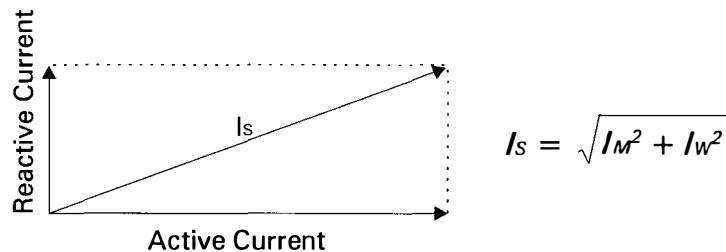
A second mode of operation is referred to as a quadratic voltage/frequency curve. This mode provides a V/Hz curve that matches the torque requirements of simple fan and pump applications.



Flux current control (FCC)

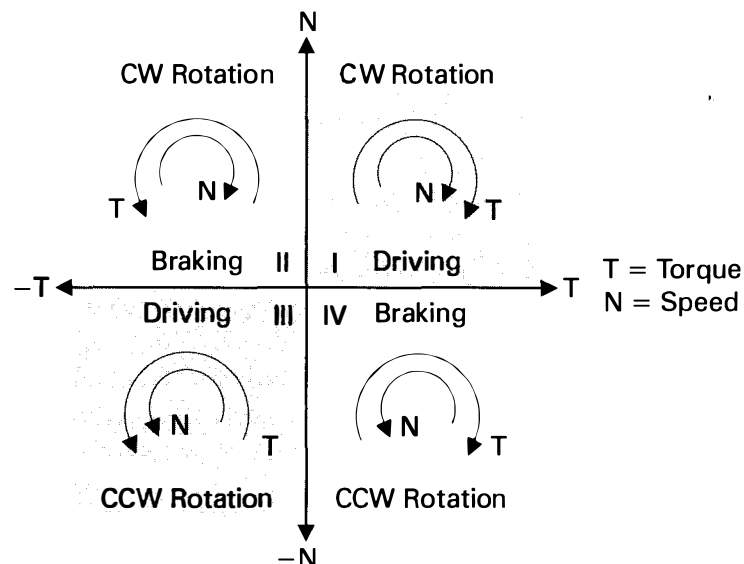
The third mode of operation, flux current control (FCC), is the most complex. Stator current (I_s) is made up of active and reactive current. The reactive current component of stator current produces the rotating magnetic field. The active current produces work. Motor nameplate data is entered into the MicroMaster. The MicroMaster estimates motor magnetic flux based on the measured reactive stator current and the entered nameplate data. Proprietary internal computer algorithms attempt to keep the estimated magnetic flux constant.

If the motor nameplate information has been correctly entered and the drive properly set up, the flux current control mode will usually provide better dynamic performance than simple V/Hz control. Flux current control automatically adapts the drive output to the load. The motor is always operated at optimum efficiency. Speed remains reliably constant even under varying load conditions.



Single-quadrant operation

In the speed-torque chart there are four quadrants according to direction of rotation and direction of torque. A single-quadrant drive operates only in quadrants I or III (shaded area). Quadrant I is forward motoring or driving (CW). Quadrant III is reverse motoring or driving (CCW). Reverse motoring is achieved by reversing the direction of the rotating magnetic field. Motor torque is developed in the positive direction to drive the connected load at a desired speed (N). This is similar to driving a car forward on a flat surface from standstill to a desired speed. It takes more forward or motoring torque to accelerate the car from zero to the desired speed. Once the car has reached the desired speed your foot can be let off the accelerator a little. When the car comes to an incline a little more gas, controlled by the accelerator, maintains speed.



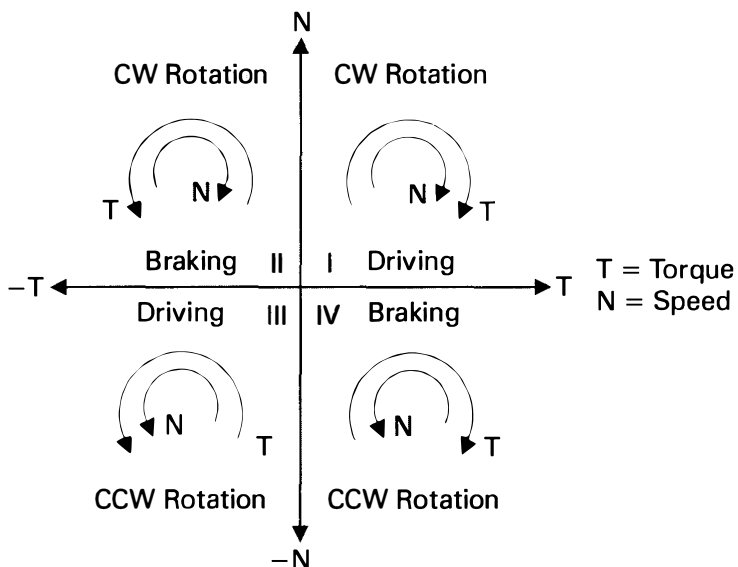
To stop an AC motor in single-quadrant operation voltage and frequency can simply be removed and the motor allowed to coast to a stop. This is similar to putting a car in neutral, turning off the ignition and allowing the car to coast to a stop. Another way is to use a controlled deceleration. Voltage and frequency are reduced gradually until the motor is at stop. This would be similar to slowly removing your foot from the accelerator of a car. The amount of time required to stop a motor depends on the inertia of the motor and connected load. The more inertia the longer it will take to stop.

DC Injection braking

The MicroMaster offers a third method of stopping in single-quadrant operation. DC injection braking is standard in the Siemens MicroMaster. This braking mode stops the rotating magnetic field and applies DC voltage to the motor windings, helping stop the motor. Up to 250% of the motor's rated current can be applied. This is similar to removing your foot from the accelerator and applying the brakes to bring the car to a stop quickly.

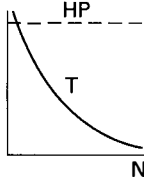
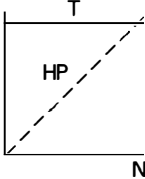
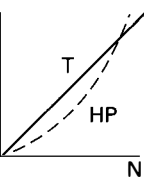
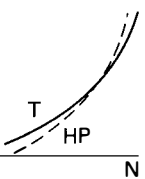
Four-quadrant operation

The dynamics of certain loads may require four-quadrant operation. When equipped with an optional braking resistor the Siemens MicroMaster is capable of four-quadrant operation. Torque will always act to cause the rotor to run towards synchronous speed. If the synchronous speed is suddenly reduced, negative torque is developed in the motor. The motor acts like a generator by converting mechanical power from the shaft into electrical power which is returned to the AC drive. This is similar to driving a car downhill. The car's engine will act as a brake. Braking occurs in quadrants II and IV.



Applications

When applying an AC drive and motor to an application it is necessary to know the horsepower, torque, and speed characteristics of the load. The following chart shows characteristics of various loads.

$T \approx \frac{1}{N}$	$T = \text{Constant}$	$T \approx N$	$T \approx N^2$
HP = Constant	HP $\approx N$	HP $\approx N^2$	HP $\approx N^3$
			
Winders Facing lathes Rotary cutting machines	Hoisting gear Belt conveyors Process machines involving forming Rolling mills Planers	Calenders with viscous friction Eddy-current brakes	Pumps Fans Centrifuges

Loads generally fall into one of three categories:

Constant torque

The load is essentially the same throughout the speed range. Hoisting gear and belt conveyors are examples.

Variable torque

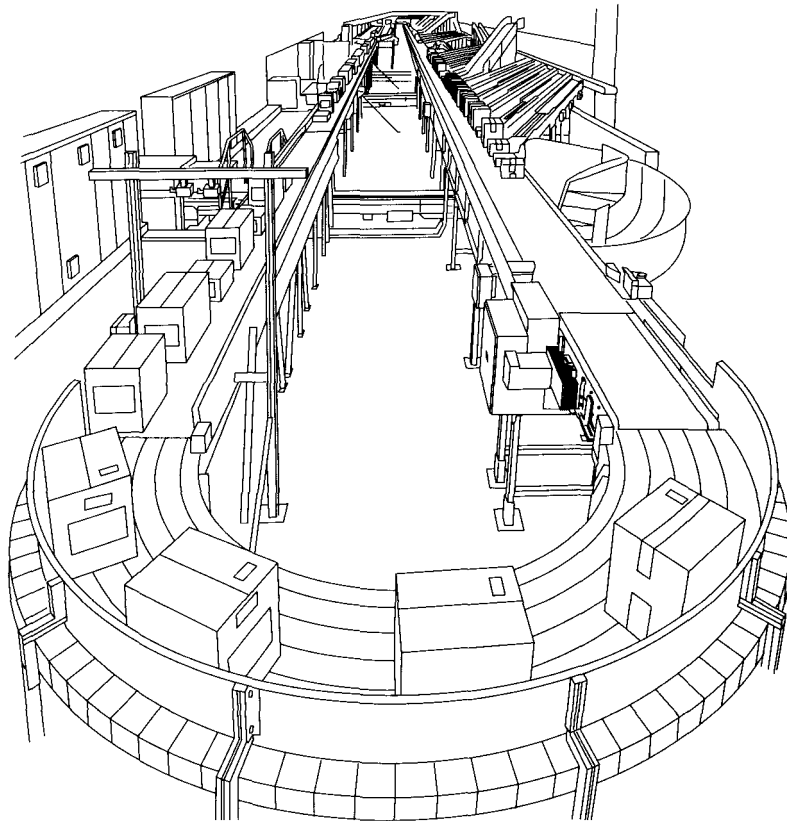
The load increases as speed increases. Pumps and fans are examples.

Constant horsepower

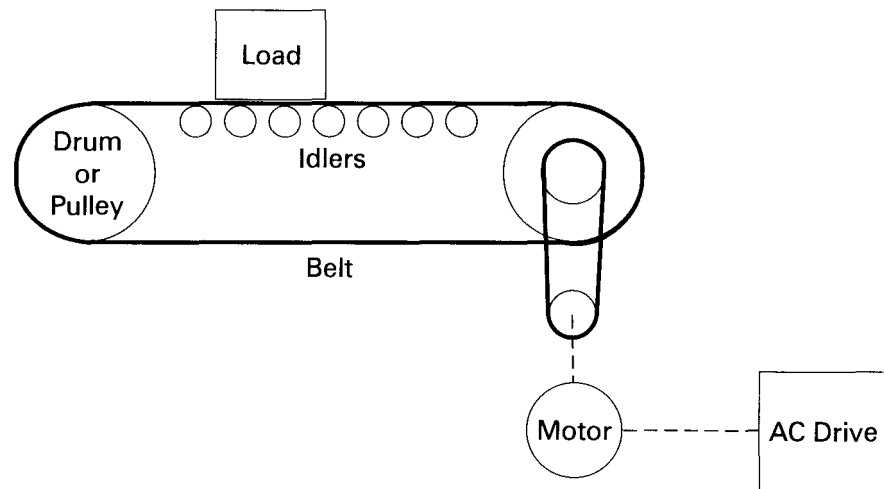
The load decreases as speed increases. Winders and rotary cutting machines are examples.

Constant Torque Applications

A constant torque load implies that the torque required to keep the load running is the same throughout the speed range. It must be remembered that constant torque refers to the motor's ability to maintain constant flux (Φ). Torque produced will vary with the required load. One example of a constant torque load is a conveyor similar to the one shown below. Conveyors can be found in all sorts of applications and environments, and can take many styles and shapes. Although the particular conveyor pictured below may require a larger drive than available in the MicoMaster line, there are many opportunities to apply MicroMasters to smaller conveyor applications. In addition, Siemens manufactures other AC drives capable of handling larger systems.



Conveyors are made up of belts to support the load, various pulleys to support the belt, maintain tension, and change belt direction, and idlers to support the belt and load.



Determining motor speed

The speed and horsepower of an application must be known when selecting a motor and drive. Given the velocity in feet per minute (FPM) of the conveyor belt, the diameter in inches of the driven pulley, and the gear ratio (G) between the motor and driven pulley, the speed of the motor can be determined. The following formula is used to calculate conveyor speed.

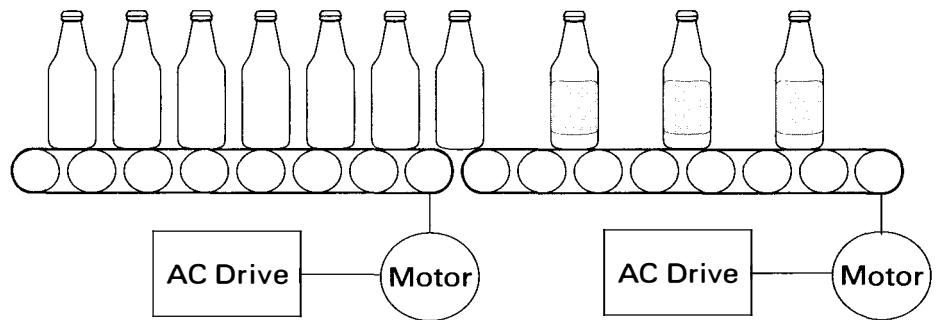
$$\text{Motor RPM} = \frac{\text{Conveyor Velocity (FPM)} \times G}{\pi \times \left(\frac{\text{Diameter in Inches}}{12} \right)}$$

If, for example, the maximum desired speed of a conveyor is 750 FPM, the driven pulley is 18" in diameter, and the gear ratio between the motor and driven pulley is 4:1, the maximum speed of the motor is 638.3 RPM. It would be difficult to find a motor that would operate at exactly this speed. An AC drive can be used with an eight-pole motor (900 RPM). This would allow the conveyor to be operated at any speed between zero and the desired maximum speed of 750 FPM.

$$\text{Motor RPM} = \frac{750 \times 4}{3.14 \times \left(\frac{18}{12} \right)}$$

$$\text{Motor RPM} = 637 \text{ RPM}$$

Another advantage to using AC drives on a conveyor is the ability to run different sections of the conveyor at different speeds. A bottle machine, for example, may have bottles bunched close together for filling and then spread out for labeling. Two motors and two drives would be required. One motor would run the filling section at a given speed and a second motor would run the labeling section slightly faster spreading the bottles out.



Horsepower

Calculating motor horsepower is complicated with many variables, which is beyond the scope of this course. Someone with knowledge of, and experience with conveyor operation would be required to accurately calculate the required horsepower. The horsepower required to drive a conveyor is the effective tension (T_e) times the velocity (V) of the belt in feet per minute, divided by 33,000.

$$HP = \frac{T_e \times V}{33,000}$$

Effective tension (T_e) is determined by several forces:

- Gravitational weight of the load
- Length and weight of belt
- Friction of material on the conveyor
- Friction of all drive components and accessories
 - pulley inertia
 - belt/chain weight
 - motor inertia
 - friction of plows
 - friction of idlers
- Acceleration force when new material is added to conveyor

If the effective tension of a conveyor were calculated to be 2000 pounds and the maximum speed is 750 FPM, then the required horsepower is 45.5.

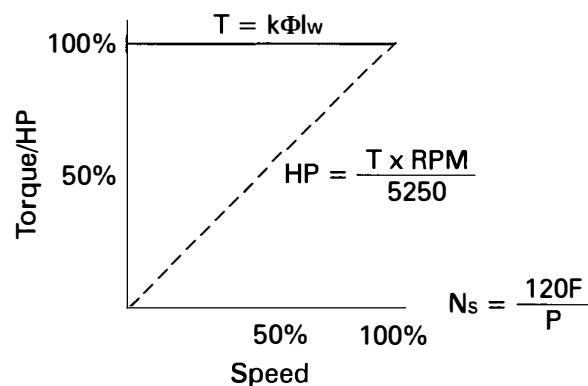
$$HP = \frac{2000 \times 750}{33,000}$$

$$HP = 45.5$$

Starting torque of a conveyor can be 1.5 to 2 times full load torque. A motor capable of driving a fully loaded conveyor may not be able to start and accelerate the conveyor up to speed. AC drives can typically supply 1.5 times full load torque for starting. An engineer may need to choose a larger motor and drive in order to start and accelerate the conveyor.

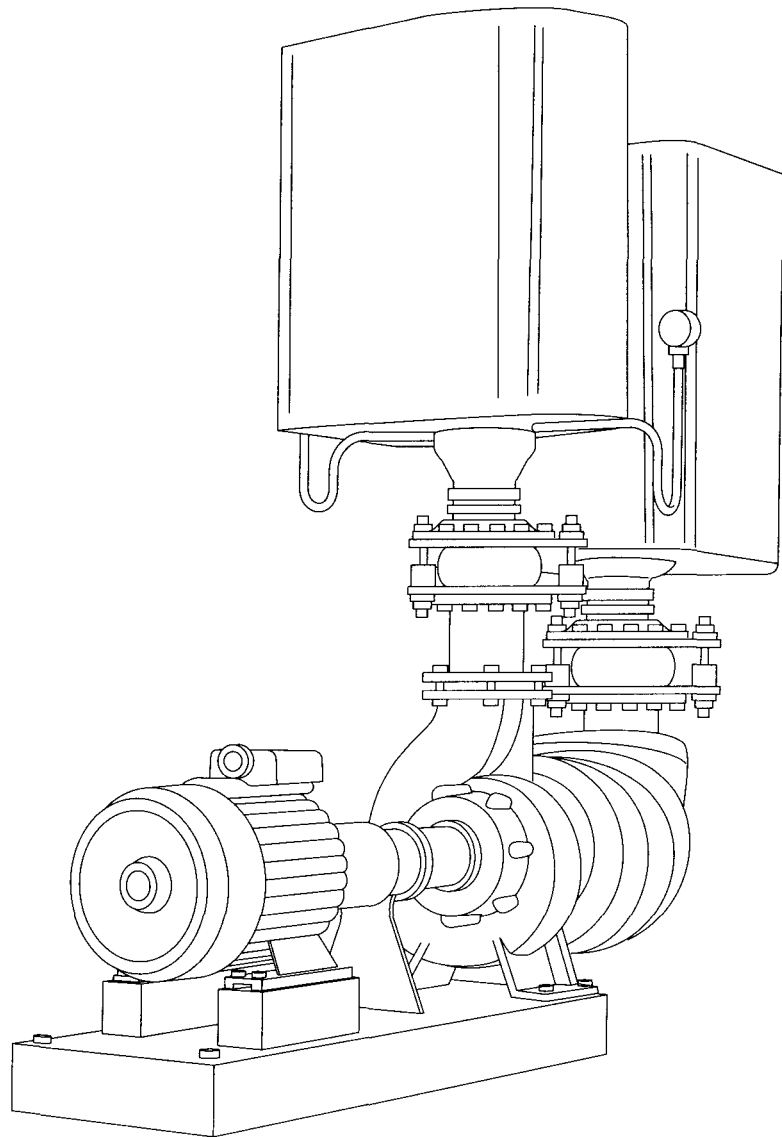
Torque/HP and speed

The speed on a conveyor is increased by increasing the AC drive frequency (F) to the motor. Torque (T) is affected by flux (Φ) and working current (I_w). The drive will maintain constant flux by keeping the voltage and frequency ratio constant. To do this the drive increases voltage and frequency in proportion. During acceleration working current will increase, however, causing a corresponding increase in torque. Once at its new speed the working current and torque will be the same as its old speed. The conveyor cannot be operated above the rated frequency of the motor (60 Hz) because the drive will no longer be able to provide constant flux. As a result, the motor will be unable to supply rated torque. Horsepower (HP) is affected by torque and speed. There will be a corresponding increase in horsepower as speed (RPM) increases.



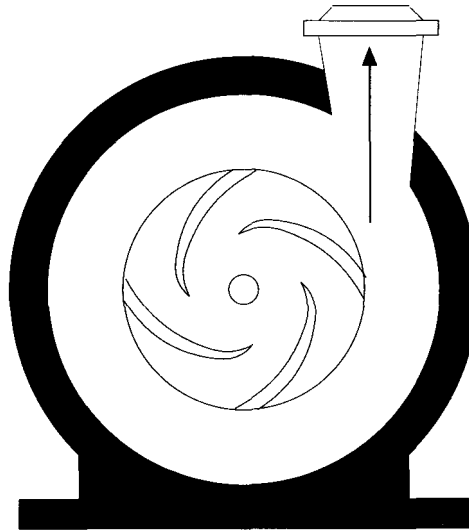
Variable Torque Applications

A variable torque load implies that torque and horsepower increase with an increase in speed. Fans and pumps are examples of variable torque. A pump used on a chilled water system is shown below.



Variable torque pumps

There are several types of pumps. The most common pump is the end-suction centrifugal pump illustrated below. There are variations of the centrifugal pump. Turbine and propeller pumps are examples. This section deals with variable torque loads. The faster a centrifugal pump turns, the more fluid it pumps and the more torque it requires. It should be noted that not all pumps are variable torque. Reciprocating pumps are constant torque.



Calculating horsepower

Calculating horsepower for a pump application is an involved process that requires someone with a thorough knowledge of the application and pumps. The following information is for illustration only. There are three related horsepower calculations involved in pump applications: liquid, mechanical and electrical.

Hydraulic head

Hydraulic head is the difference in hydraulic pressure between two points, which actually includes elevation, pressure and velocity. An increase in pump speed would cause increases in pressure and velocity which increases the hydraulic head.

Liquid horsepower

Liquid horsepower is the hydraulic power transferred to the pumped liquid. The following formula can be used to calculate liquid energy.

$$\text{Liquid Energy in ft-lb} = \text{Total Head} \times (\text{Gallons} \times \text{Weight})$$

Water weighs 8.34 pounds per gallon. If 50 gallons of water per minute were required to be moved through 100 feet of head the energy required would be 41,700 ft-lb/minute.

$$100 \text{ feet} \times (50 \text{ gallons} \times 8.34) = 41,700 \text{ ft-lb/minute}$$

If the pumps speed were increased so that 100 gallons of water were being pumped through 100 feet of head the energy would be 83,400 ft-lb/minute. Twice the energy would be required. The hydraulic head would, in actuality, also increase.

$$100 \text{ feet} \times (100 \text{ gallons} \times 8.34) = 83,400 \text{ ft-lb/minute}$$

The common method of expression is horsepower. One horsepower is equal to 33,000 ft-lb/minute.

Therefore, 41,700 ft-lb/minute is 1.26 HP and 83,400 ft-lb/minute is 2.53 HP.

$$\frac{41,700}{33,000} = 1.26 \text{ HP} \quad \frac{83,400}{33,000} = 2.53 \text{ HP}$$

Mechanical horsepower

Mechanical horsepower is the horsepower input to the pump and is equal to the liquid horsepower divided by the pump's efficiency. If the liquid horsepower is 2.53 and the pump is 75% efficient the brake horsepower is 3.4 HP.

$$\frac{1.26}{.75} = 1.7 \text{ HP} \quad \frac{2.53}{.75} = 3.4 \text{ HP}$$

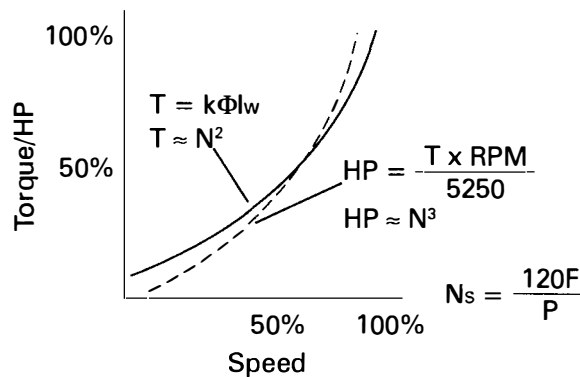
Electrical horsepower

Electrical horsepower is the horsepower required to run the motor driving the pump and is equal to the mechanical horsepower divided by the motor's efficiency. If the motor is 90% efficient the electrical horsepower is 3.78 HP. It can be seen that with an increase of pump speed there is a corresponding increase in electrical horsepower.

$$\frac{1.7}{.90} = 1.9 \text{ HP} \quad \frac{3.4}{.90} = 3.8 \text{ HP}$$

Torque/HP and speed

The speed on a pump is increased by increasing the AC drive frequency (F) to the motor. Torque (T) is affected by flux (Φ) and working current (I_w). The drive will maintain appropriate flux by adjusting the voltage and frequency ratio dependent on speed. During acceleration, working current will increase causing a corresponding increase in torque. In this application, torque increases in proportion to the speed squared. This is due to the increase in hydraulic head as the pump works harder to pump more fluid. Horsepower increases in proportion to the speed cubed due to an increase of torque and speed. The pump cannot be operated above the rated frequency of the motor (60 Hz) because the drive will no longer be able to provide constant flux. As a result, the motor will be unable to supply rated torque. The load's torque requirements increase while the motor's ability to supply torque decreases.



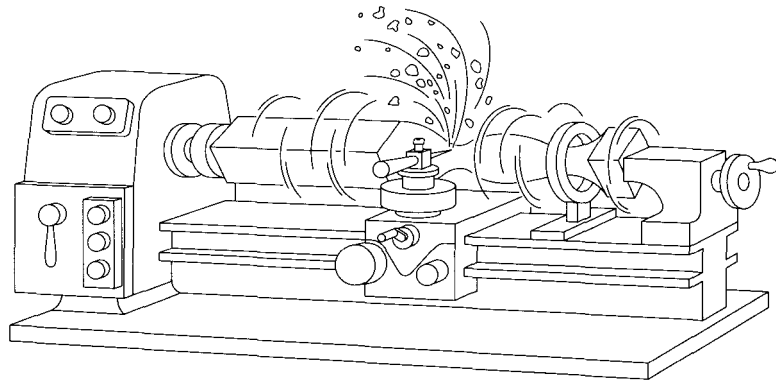
Fans

This same principal applies to fan applications. The horsepower of a fan is determined by dividing the product of air flow (in cubic feet per minute) and pressure by the product of the constant 6356 and fan efficiency. Increasing the speed of the fan increases air flow and pressure, requiring the motor to work harder (I_w increases). Torque and horsepower increase.

$$HP = \frac{Flow \times Pressure}{6356 \times Fan Efficiency}$$

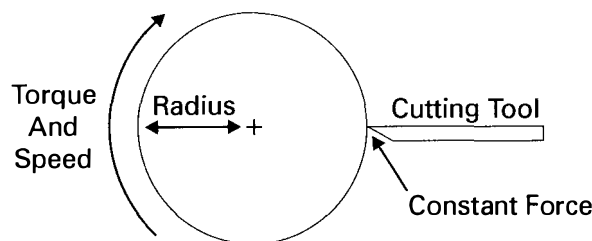
Constant Horsepower Applications

Constant horsepower applications require a constant force as radius changes. A lathe, for example, starts out with a certain diameter object. As the object is cut and shaped the diameter is reduced. The cutting force must remain constant. Another example of a constant horsepower application is a winder where radius increases as material is added to a roll and decreases as material is removed.



Relationship of speed, torque, and horsepower

Applications, such as lathes, that are driven in a continuous circular motion are sometimes referred to as spindle drives. Horsepower will remain constant in a spindle drive application. The surface speed in feet per minute (FPM) is equal to 2π times the radius (in feet) of the material times the speed in RPM. Surface speed will remain constant as the material is shaped and the radius reduced. Torque is equal to force times radius. Horsepower is equal to torque times speed.



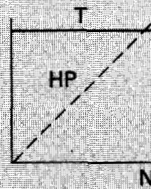
$$\text{Surface Speed (FPM)} = 2\pi \times \text{Radius} \times \text{Speed (RPM)}$$

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

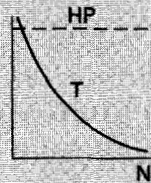
$$\text{HP} = \text{Torque} \times \text{Speed}$$

Review 7

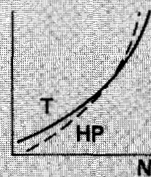
1. An application, such as a conveyor, where the torque remains essentially the same throughout the speed range is referred to as _____ torque.
2. Operating a motor above base frequency causes the motor's ability to produce torque to _____.
a. increase b. decrease
3. A variable _____ load implies that torque and horsepower increase with an increase in speed.
4. Fans and pumps are examples of _____ torque applications.
5. A constant _____ application implies that torque decreases as speed increases.
6. Identify the category of the following speed, torque, and horsepower graphs.



a. _____



b. _____



c. _____

Review Answers

- Review 1** 1) force; 2) 15; 3) torque; 4) 80; 5) inertia; 6) Speed; 7) revolutions per minute; 8) Acceleration
- Review 2** 1) Work; 2) Power; 3) voltage; 4) true; 5) watts, volt-amps; 6) power factor; 7) 24
- Review 3** 1) 5; 2) 1.15; 3) 49.6; 4) 120; 5) 1800, 1500; 6) increase; 7) decrease
- Review 4** 1) squirrel cage; 2) slip; 3) 4.2%; 4) increase; 5) working; 6) I_w , I_m ; 7) 150%, 600%
- Review 5** 1) 7.67; 2) increase, increase; 3) b; 4) horsepower; 5) SIMOVERT; 6) 650; 7) c; 8) d; 9) a
- Review 6** 1) "P"; 2) 100; 3) braking resistor; 4) 5; 5) 31; 6) flux current control; 7) 3; 8) injection
- Review 7** 1) constant; 2) b; 3) torque; 4) variable; 5) horsepower; 6) constant torque, constant horsepower, variable torque

Final Exam

The final exam is intended to be a learning tool. The book may be used during the exam. A tear-out answer sheet is provided. If the tear-out answer sheet is missing, another may be obtained by contacting the training department at (404) 740-3061. After completing the test, mail the answer sheet in for grading. A grade of 70% or better is passing. Upon successful completion of the test a certificate will be issued. Those receiving a score of less than 70% will be provided a second test.

Questions

1. _____ is a twisting or turning force that causes an object to rotate.
 - a. Torque
 - b. Friction
 - c. Inertia
 - d. Acceleration
2. If 50 pounds of force were applied to a lever 3 feet long, the torque would be _____ lb-ft.
 - a. 16.7
 - b. 53
 - c. 47
 - d. 150
3. The rate of doing work is called _____.
 - a. inertia
 - b. speed
 - c. power
 - d. energy
4. A motor with a rating of 60 KW would have an equivalent rating of _____ HP.
 - a. 45
 - b. 80
 - c. 65
 - d. 120
5. Magnetic lines of flux (Φ) in an AC motor are proportional to _____.
 - a. voltage divided by frequency
 - b. frequency divided by frequency
 - c. rotor speed divided by synchronous speed
 - d. synchronous speed divided by rotor speed

6. A four-pole motor operating at 50 Hz has a synchronous speed of _____ RPM.
 - a. 1500
 - b. 3000
 - c. 1800
 - d. 3600
7. A motor with a synchronous speed of 900 RPM and a rotor speed of 850 RPM has _____ % slip.
 - a. 3
 - b. 9.4
 - c. 5.5
 - d. 20
8. The most common and most suitable NEMA design motors for use on AC drives is NEMA _____.
 - a. A
 - b. B
 - c. C
 - d. D
9. _____ torque is also referred to as starting torque.
 - a. Pull up
 - b. Accelerating
 - c. Breakdown
 - d. Locked rotor
10. A NEMA B motor that is started by connecting it to the power supply at rated voltage and frequency has a typical starting current of _____ %.
 - a. 100
 - b. 150
 - c. 200
 - d. 600
11. The temperature rise of a motor with Class F insulation is _____ °C with a 10° C hot spot.
 - a. 60
 - b. 105
 - c. 80
 - d. 125
12. The volts per hertz ratio of a 460 VAC, 60 Hz motor is _____ V/Hz.
 - a. 3.8
 - b. 7.67
 - c. 5.1
 - d. 9.2
13. A motor operated within a speed range that allows a constant volts per hertz ratio is said to be _____.
 - a. constant hp
 - b. variable torque
 - c. constant torque
 - d. variable flux

14. The section of an AC drive that controls output voltage and frequency to an AC motor is the _____ .
- a. converter
 - b. DC link
 - c. inverter
 - d. L1 choke
15. The typical DC link voltage of an AC drive connected to 480 VAC is _____ VDC.
- a. 460
 - b. 650
 - c. 600
 - d. 1200
16. The catalog number for a 3 HP, 230 VAC Siemens MicroMaster is _____ .
- a. 6SE3011-5BA00
 - b. 6SE3015-8DC00
 - c. 6SE3014-0DC00
 - d. 6SE3018-8BC00
17. A MicroMaster is capable of delivering up to _____ % of drive rated current for one minute.
- a. 150%
 - b. 250%
 - c. 200%
 - d. 300%
18. To get four-quadrant operation with a Siemens MicroMaster an optional _____ must be used.
- a. DC injection brake
 - b. converter bridge
 - c. braking resistor
 - d. 4-digit LED display
19. A centrifugal pump is a _____ application.
- a. constant torque
 - b. constant flux
 - c. constant HP
 - d. variable torque
20. If a conveyor has an effective tension (T_E) of 1000 pounds, and a maximum speed of 100 FPM, the required horsepower is _____ HP.
- a. 3
 - b. 25
 - c. 10
 - d. 45

Notes

Notes

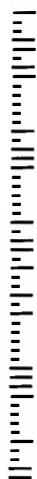


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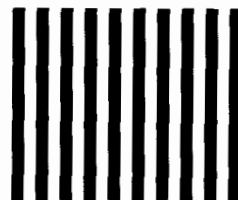
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AC Formulas

$N_s = \frac{120F}{P}$	$T = k\Phi I_w$	$E = k\Phi N$
$HP = \frac{T \times RPM}{5250}$	$I_m = \frac{E}{2\pi F L_M}$	$\Phi \approx \frac{E}{F}$
$PF = \frac{PT}{PA}$	$I_s = \sqrt{I_m^2 + I_w^2}$	
$KW = .746 \times HP$	$HP = 1.341 \times KW$	
$\% \text{ Slip} = \frac{N_s - N_R}{N_s} \times 100\%$		
$3\text{-Phase KW} = \frac{V \times I \times PF \times 1.732}{1000}$		
$3\text{-Phase Amps} = \frac{746 \times HP}{1.732 \times V \times \text{Eff} \times PF}$		
$3\text{-Phase Eff} = \frac{746 \times HP}{1.732 \times V \times I \times PF}$		
$3\text{-Phase PF} = \frac{746 \times HP}{1.732 \times V \times I}$		

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