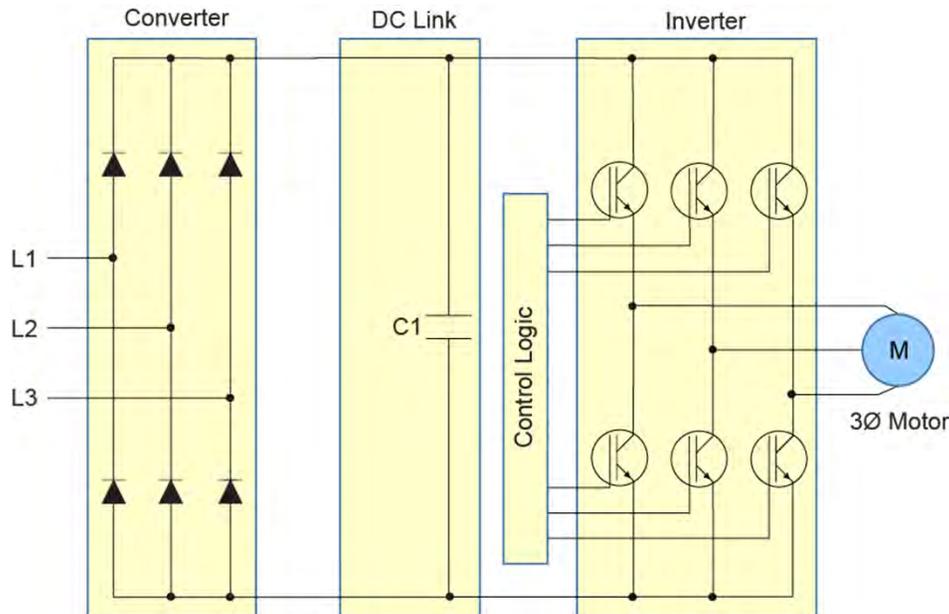# Basics of AC Drives

A quickSTEP Online Course

Course Topics

Welcome to Basics of AC Drives. This course covers the following topics:

Chapter 1 – Introduction
- Overview
- Mechanical Basics

Chapter 2 – AC Motor and Drive Basics
- AC Motor Basics
- AC Drive Basics

Chapter 3 – AC Drives
- AC Drive Hardware
- AC Drive Operation

Chapter 4 – AC Drive Applications
- Application Considerations
- Application Types

Final Exam

If you do not have an understanding of basic electrical concepts, you should complete Basics of Electricity before attempting this course.

This chapter covers the following topics:

- **Overview**

- Mechanical Basics

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Course Objectives

Upon completion of this course you will be able to…

- Explain the concepts of force, torque, angular speed, acceleration, and inertia
- Explain the difference between work and power
- Convert horsepower to kilowatts and vice versa
- Calculate synchronous speed and slip percentage
- Describe the interrelationships for the following factors: V/Hz, torque, flux, and working current
- Describe the basic functions of the following AC drive circuits: converter, DC link, and inverter
- Describe the operation of the following AC drive components: diode, SCR, and IGBT
- Explain how varying the pulse width and frequency of a PWM inverter affects motor speed
- List several ways that an AC drive can stop its associated motor
- Explain the difference between single-quadrant and four-quadrant operation
- Explain the advantage of a regenerative AC drive design

- Briefly describe each of the following AC drive control types: linear voltage/frequency, quadratic voltage/frequency, multi-point voltage/frequency, and vector control
- Identify various additional circuits and components that are often included in an AC drive configuration
- Describe common ratings for AC drive enclosures
- Describe the characteristics of constant torque, variable torque, and constant horsepower applications
- Describe important application considerations

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What is an AC Drive?

AC Drive Application Examples

Conveyor Systems

Extrusion

Machine Tools

Metal Forming

Mixer/mills

Packaging

Printing and paper machines

Pumps/fans/ compressors

Rolling mills

Textiles

Woodworking

For the purpose of this course, an AC drive is a device used to control the speed of an AC motor that control loads ranging from pumps and fans to complex machines. An AC drive may control other aspects of an application as well, but that depends on the capabilities of the drive and how it is applied.

AC drives function by converting a constant AC frequency and voltage into a variable frequency and voltage. There are many types of AC drives, but this course focuses on low voltage (less than 1000 VAC) AC drives used with three-phase induction motors, the most common pairing used in industrial applications.

The importance of controlling speed varies with the application, but, for many applications, speed control is critical because it affects many other aspects of a manufacturing process. Many processes require multiple AC drives functioning independently or in coordination. AC drives are also used in non-manufacturing applications, but the basic principles of operation are the same.

Siemens Low Voltage AC Drives

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Siemens' extensive portfolio of low voltage drives offers a high level of flexibility and functionality. Applications range from simple frequency converter tasks to motion control tasks and from single-axis to multi-axis coordinated drive systems. This course does not cover specific AC drive models, but will help you understand basic concepts needed to prepare you for more advanced learning.

Advantage of AC Drives

Fan

Pump

Conveyor

Energy Recovery

Lower Energy Costs

- Less Usage
- Reduce Demand
- Improved Power factor

Improved Process control

- Speed control
- Flow control
- Pressure control
- Temperature control
- Acceleration control
- Tension control
- Torque control
- Monitoring

Increased Productivity

- Reliability
- Smoother operation

Reduced Maintenance
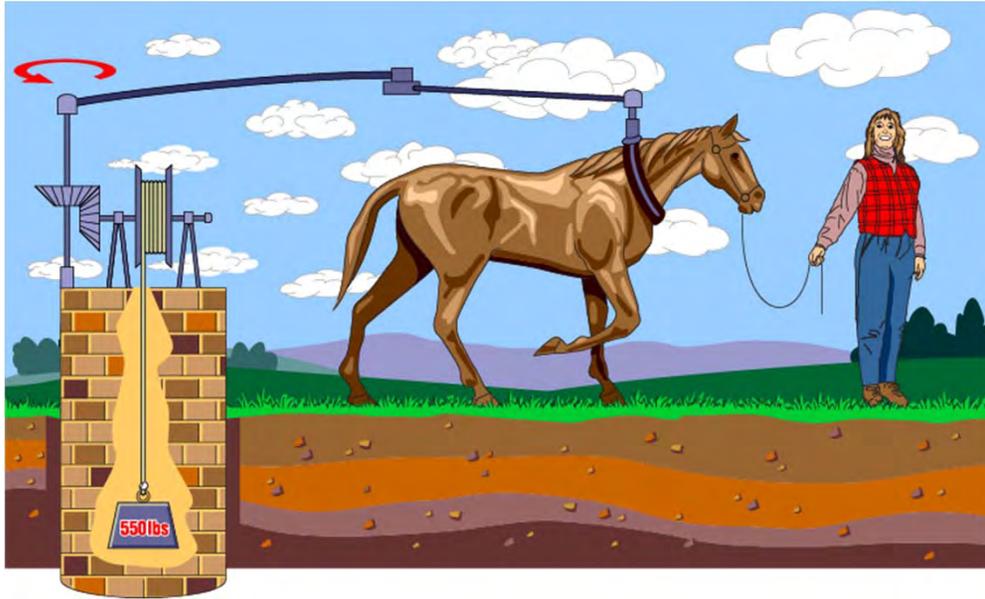
- Mechanical stress
- Shock loads
- Reduced cavitation

Fewer Flow Control Devices

- Valves
- Dampers & actuators
- Inlet vanes

Lower Installation Costs

- Contactors/control relays
- Overload relays
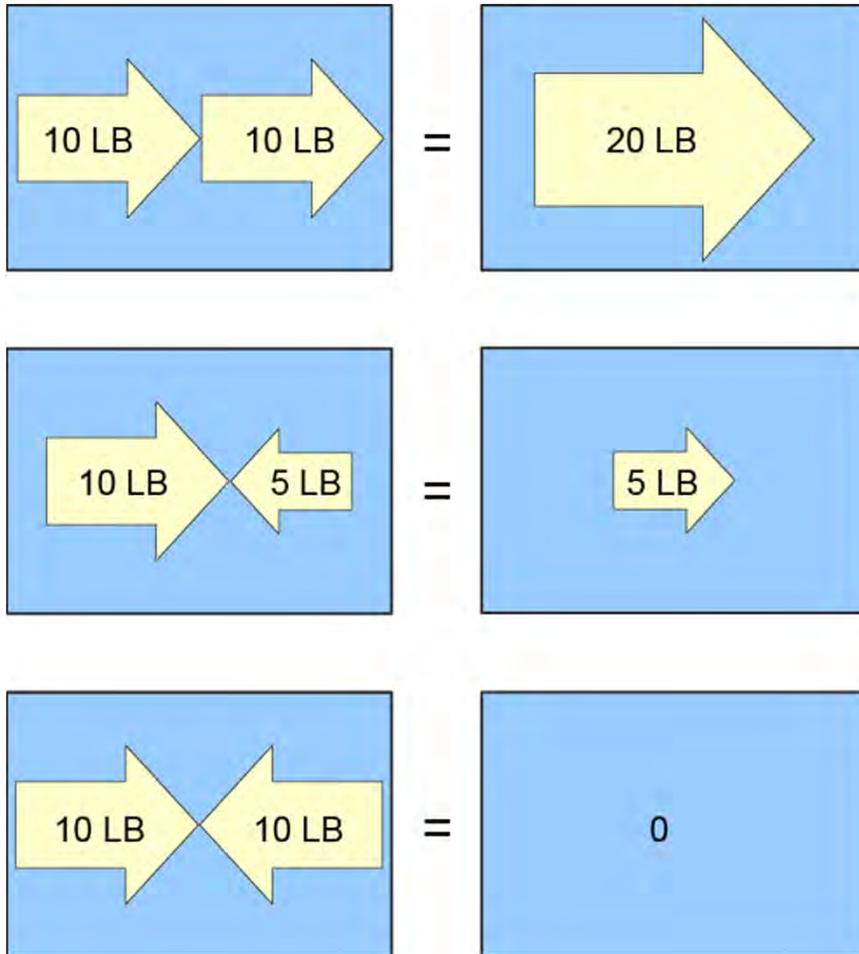- PID modules
- Control panel complexity

This chapter covers the following topics:

- Overview

- **Mechanical Basics**

Force

Before discussing AC motors and drives, it is necessary to discuss some of the basic terminology associated with their operation.

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

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 are applied in the same direction, the net force is 20 pounds. If 10 pounds of force is applied in one direction and 5 pounds of force is applied in the opposite direction, the net force is 5 pounds, and the object moves in the direction of the greater force. If 10 pounds of force is applied equally in both directions, the net force is zero, and the object does not move.

Torque

Force = 10 pounds

Torque (τ) = 10 lb-ft

|← 1 foot →|

Force = 10 pounds

Torque (τ) = 20 lb-ft

|← 2 feet →|
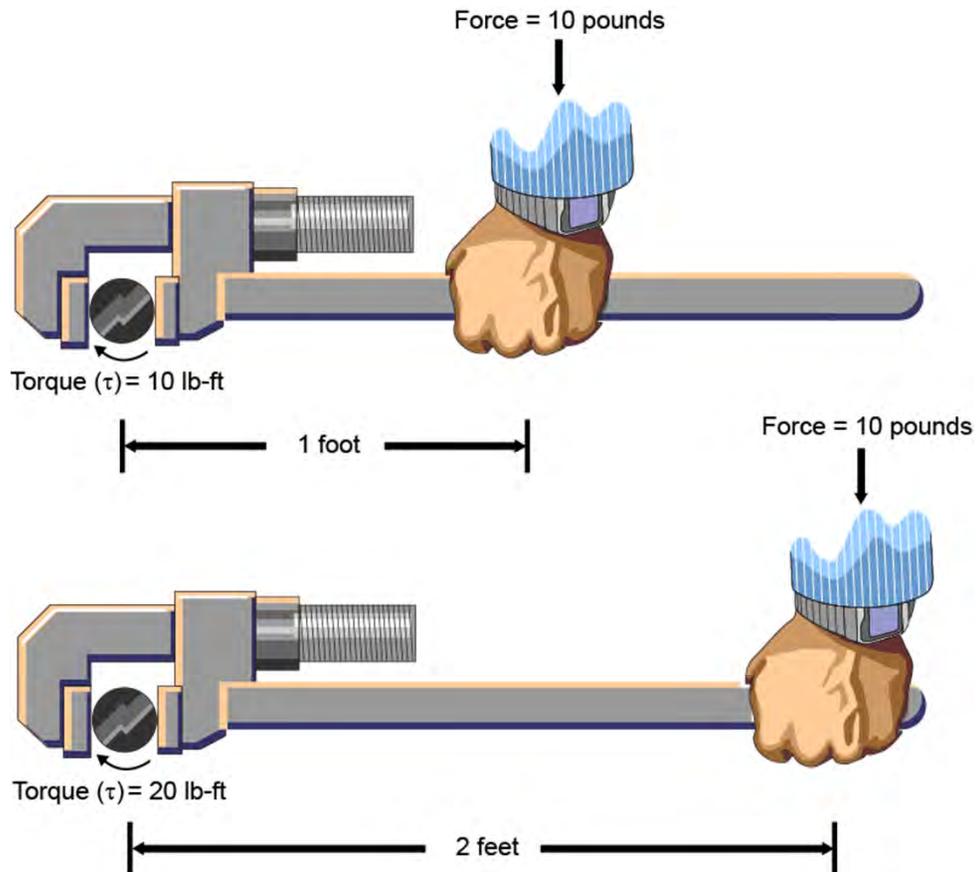
Torque is a twisting or turning force that causes an object to rotate. For example, a force applied to a point on a lever applies a torque at the pivot point.

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

Torque = Force x Radius

In the English system of measurements, torque is measured in pound-feet (lb-ft) or pound-inches (lb-in). For example, if 10 lbs of force is applied to a lever 1 foot long, the resulting torque is 10 lb-ft.

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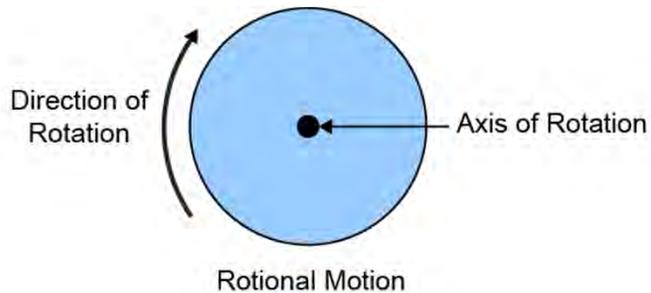
Speed
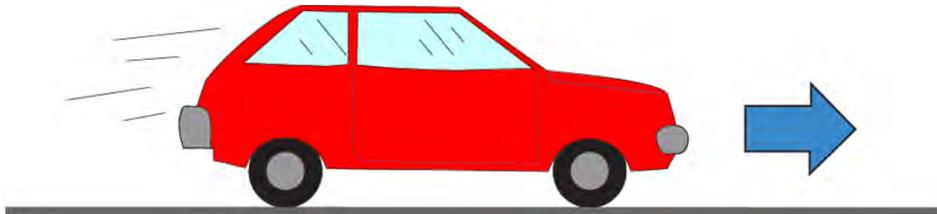
Linear Motion

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

An object in motion takes time to travel any distance. Speed is the ratio of the distance traveled, and the time it takes to travel the distance.

Linear speed is the rate at which an object travels a specified distance in one direction. Linear speed is expressed in units of distance divided by units of time.

This results in compound speed units such as miles per hour or meters per second (m/s). Therefore, if it takes 2 seconds to travel 10 meters, the speed is 5 m/s.

Angular Speed

Direction of Rotation

Axis of Rotation

Rotional Motion

The angular speed, also called rotational speed, of a rotating object determines how long it takes for an object to rotate a specified angular distance.

Angular speed is often expressed in revolutions per minute (RPM). For example, an object that makes ten complete revolutions in one minute has a speed of 10 RPM.

$$\text{Angular or Rotational Speed} = \frac{\text{Distance}}{\text{Time}} = \frac{\text{Degrees, Radians, or Revolutions}}{\text{Time}}$$

$$\text{Example:} \quad \frac{10 \text{ Revolutions}}{1 \text{ Minute}} = 10 \text{ RPM}$$

Acceleration

10 RPM ——————→ 20 RPM

Acceleration


20 RPM ——————→ 10 RPM
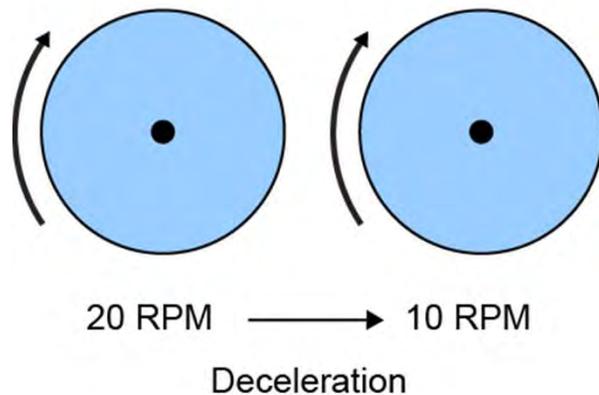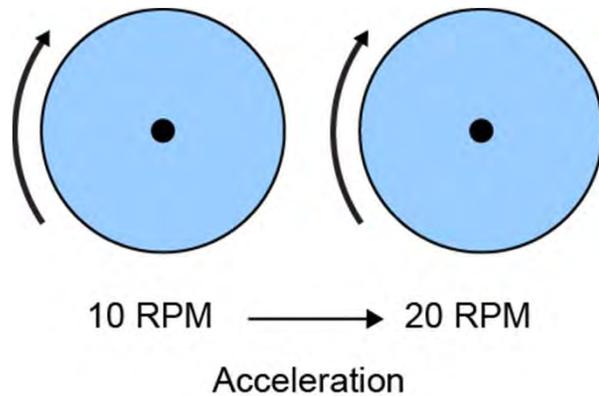
Deceleration

An increase in speed is called acceleration. Acceleration occurs when there is an increase in the force acting on the object or a reduction in its resistance to motion.

A decrease in speed is called deceleration. Deceleration occurs when there is a decrease in the force acting on and object or an increase in its resistance to motion.

For example, a rotating object can accelerate from 10 RPM to 20 RPM or decelerate from 20 RPM to 10 RPM.

Inertia and Losses
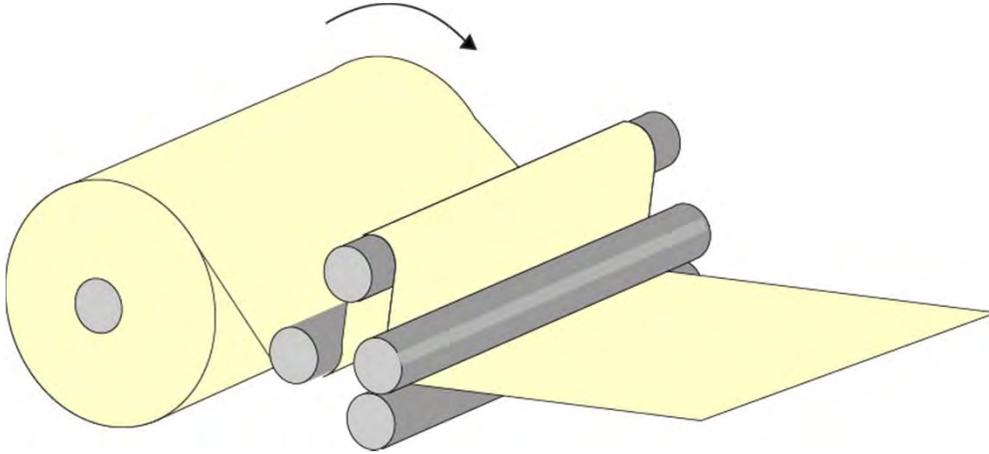
Mechanical systems are subject to the law of inertia. The law of inertia states that an object tends to remain in its current state of rest or motion unless acted upon by an external force. This property of resistance to acceleration/deceleration is referred to as the moment of inertia. The English system unit of measurement for inertia is pound-feet squared.

For example, consider a machine that unwinds a large roll of paper. If the roll is not moving, it takes a force to overcome inertia and start the roll in motion. Once moving, it takes a force in the reverse direction to bring the roll to a stop.

Any system in motion has losses that drain energy from the system. The law of inertia is still valid, however, because the system will remain in motion at constant speed if energy is added to the system to compensate for the losses.
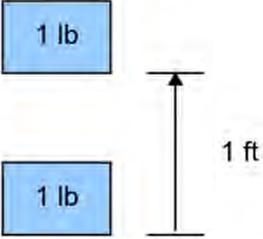
Friction is one of the most significant causes of energy loss in a machine. Friction occurs when objects contact one another. For example, to move one object across the surface of another object, you must apply enough force to overcome friction.

Work and Power

Work = Force x Distance

English unit = foot-pounds (ft-lb)

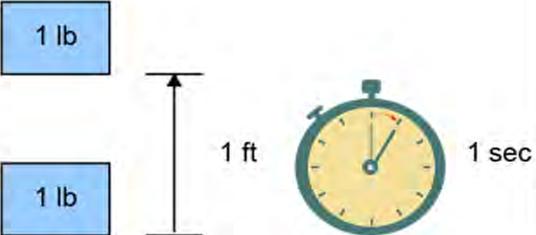1 lb-ft of work = 1 pound lifted 1 foot

1 lb

1 lb   1 ft

$$\text{Power} = \frac{\text{Work}}{\text{Time}} = \frac{\text{Force x Distance}}{\text{Time}}$$

English unit = foot-pounds per second $\left(\frac{\text{ft-lb}}{\text{sec}}\right)$

$1 \dfrac{\text{ft-lb}}{\text{sec}}$ of power = 1 pound lifted 1 foot in 1 second

1 lb

1 lb   1 ft   1 sec

Whenever a force causes motion, work is accomplished. Work is calculated by multiplying the force that causes the motion times the distance the force is applied.

Because work is the product of force times the distance applied, work can be expressed in any compound unit of force times distance. For example, in physics, work is commonly expressed in joules. 1 joule is equal to 1 newton-meter, a force of 1 newton for a distance of 1 meter. In the English system of measurements, work is often expressed in foot-pounds (ft-lb), where 1 ft-lb equals 1 foot times 1 pound.

Another often used quantity is power. Power is the rate of doing work, which is the amount of work done in a period of time.

Horsepower and Kilowatts
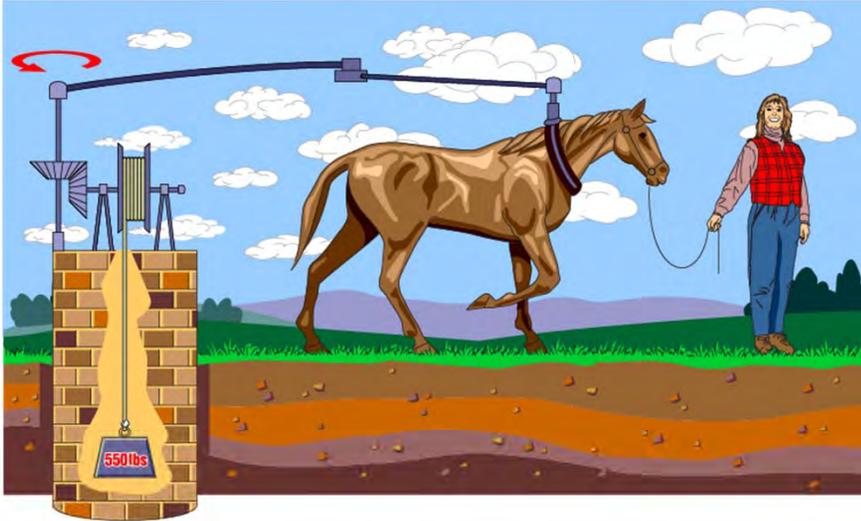
$$\text{Horsepower (HP)} = \frac{\text{Torque in lb-ft} \times \text{Speed in RPM}}{5252}$$

Power in kilowatts (kW) = 0.746 x Power in HP

Example: a 25 HP motor has an equivalent rating of 0.746 x 25 HP = 18.65 kW

Power in HP = 1.34 x power in kW

Power can be expressed in foot-pounds per second, but is often expressed in horsepower. 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 a horse would average about 550 foot-pounds of work per second. Therefore, one horsepower is equal to 550 foot-pounds per second or 33,000 foot-pounds per minute.

When applying the concept of horsepower to motors, it is useful to determine the amount of horsepower for a given amount of torque and speed. When torque is expressed in lb-ft and speed is expressed in RPM the formula for horsepower (HP) shown in the accompanying graphic can be used. Note that a change in torque or speed also changes horsepower.

AC motors manufactured in the United States are generally rated in horsepower, but motors manufactured in many other countries are rated in kilowatts (kW). Fortunately it is easy to convert between these units as shown in the accompanying graphic.

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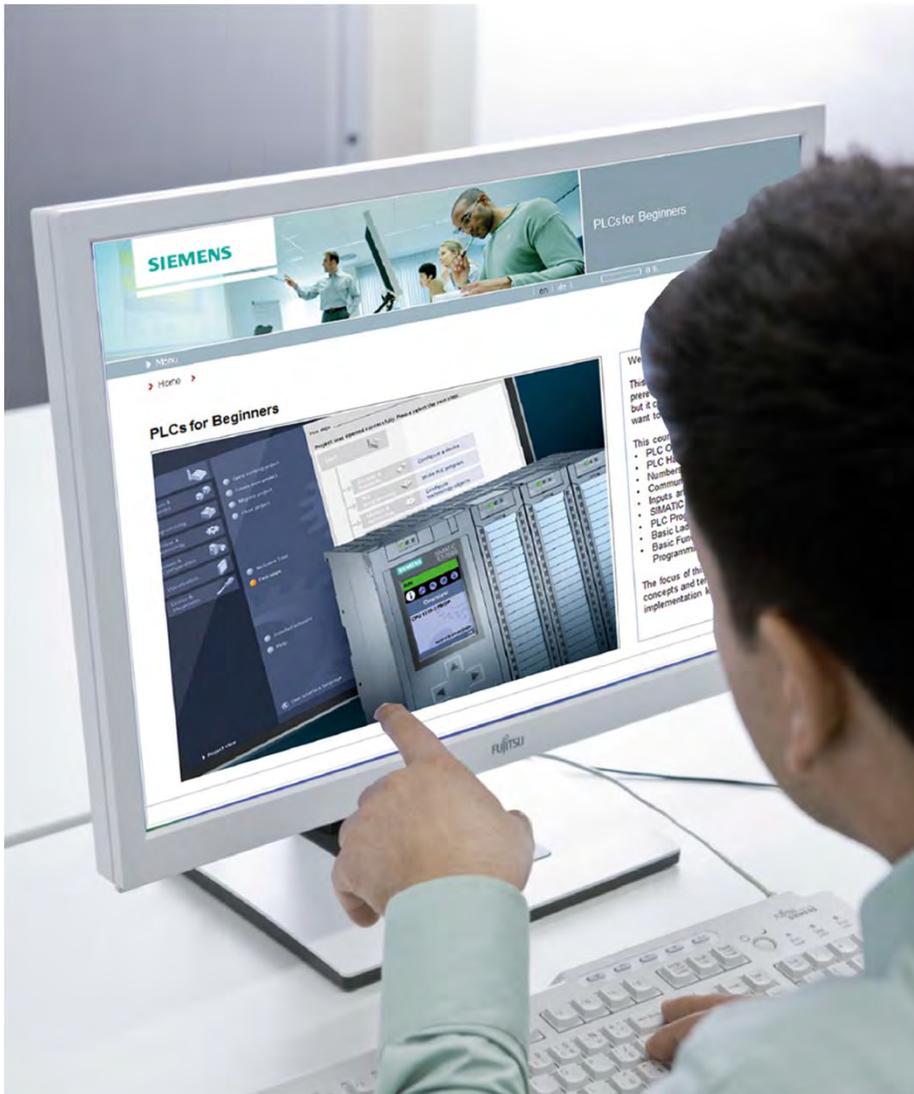
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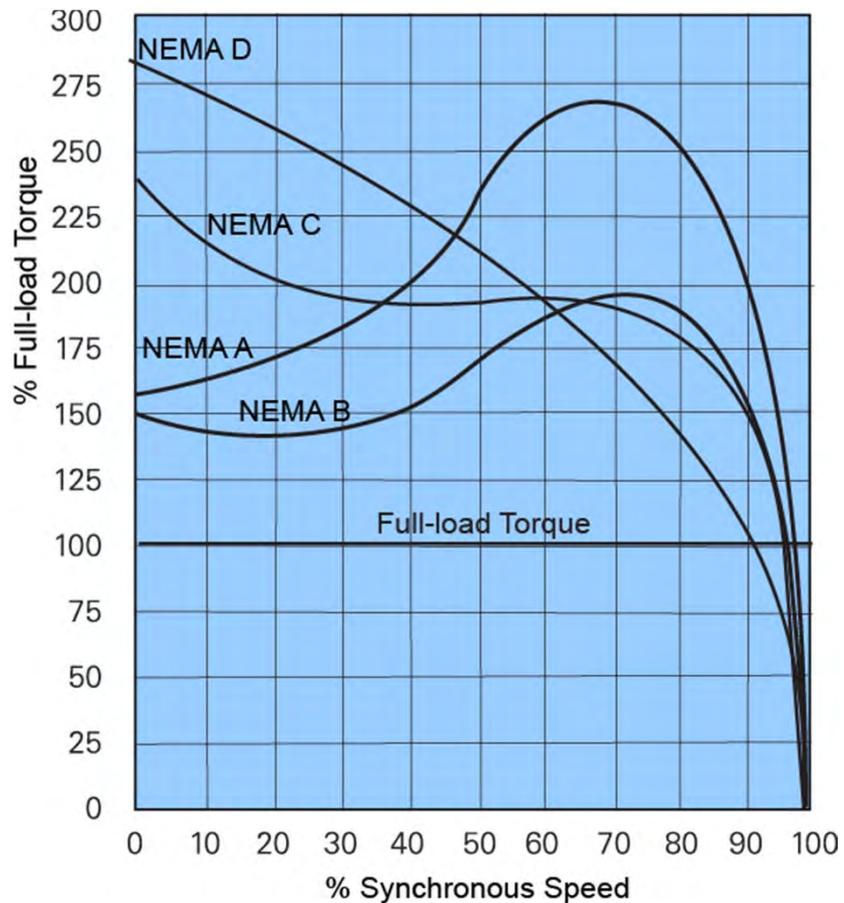
This chapter covers the following topics:

- **AC Motor Basics**
- AC Drive Basics

AC Motors

AC motors are used worldwide in many applications to transform electrical energy into mechanical energy. There are many types of AC motors, but this course focuses on three-phase AC induction motors, the most common type of motor used in industrial applications.
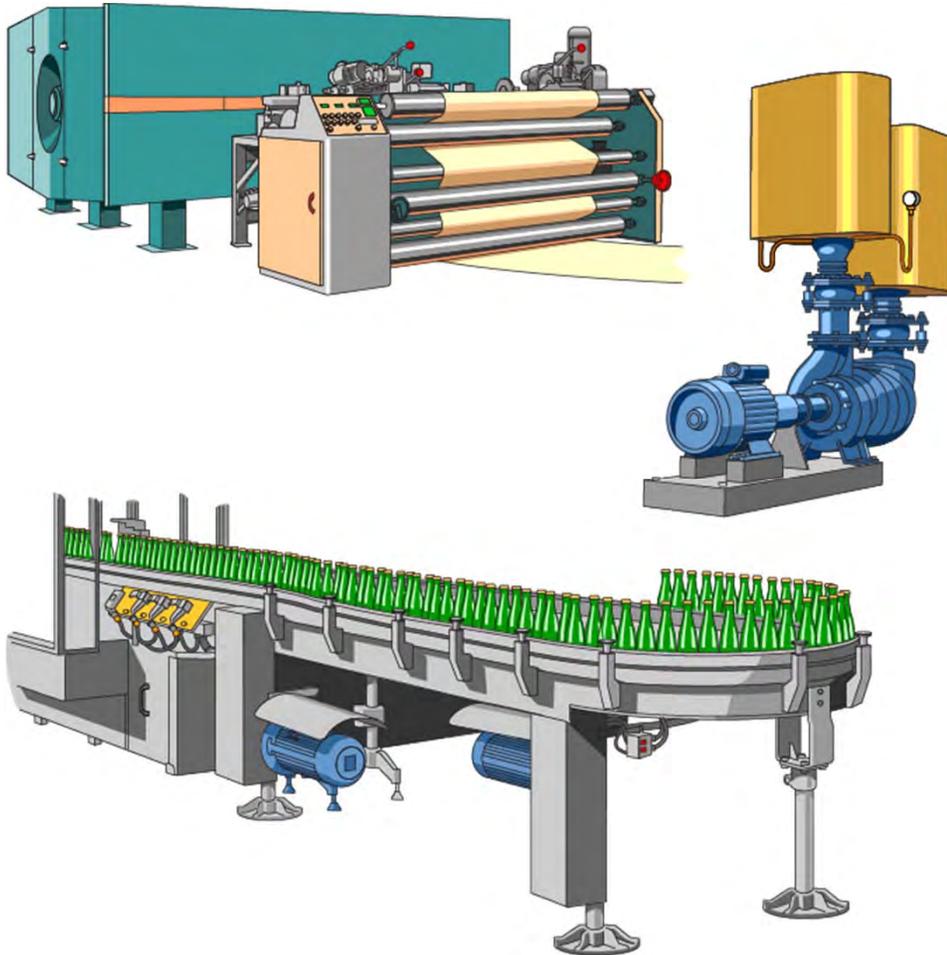
The AC motor may be part of a pump or fan or connected to some other form of mechanical equipment such as a winder, conveyor, or mixer.

The importance of controlling speed varies with the application, but, for may applications, speed control is critical. Ultimately, what is being controlled may be, for example, the rate at which items or bulk quantities move on a conveyor or the rate at which gas or liquid flow in a pipe.

Controlling this material flow, in many instances, requires controlling the speed of an AC motor. An AC drive adjusts the speed of an AC motor to meet the needs of the process.

Later in this course you will learn more about AC drives, but first we must discuss basic AC motor concepts.

Synchronous Speed (N_s) Chart

Frequency in Hz	Number of Poles	Synchronous Speed in RPM
60	2	3600
60	4	1800
60	6	1200
60	8	900
60	10	720
50	2	3000
50	4	1500
50	6	1000
50	8	750
50	10	600

2-Pole, 60 Hz Motor Example

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

The speed of a three-phase AC motor is dependent on the speed at which the magnetic field generated by its stator rotates. The speed of the rotating magnetic field is referred to as the synchronous speed (N_s) of the motor.

Synchronous speed in RPM is equal to 120 times the frequency (F) in hertz (Hz), divided by the number of motor poles (P). For example, the synchronous speed for a two-pole motor operated at 60 Hz is 3600 RPM.

The accompanying table shows the synchronous speed at 50 Hz and 60 Hz for several different motor pole numbers.
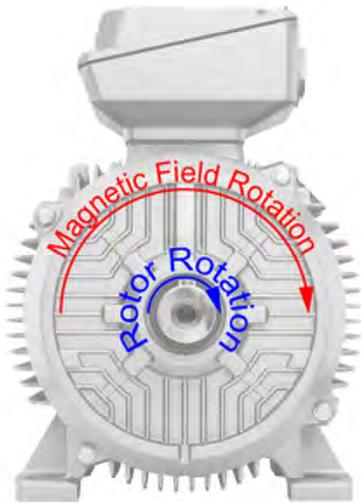
Slip

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

N_S = Synchronous Speed

N_R = Rotor Speed

Example: Synchronous Speed = 1800 RPM, Rotor Speed = 1765 RPM

$$\% \text{ Slip} = \frac{1800 \text{ RPM} - 1765 \text{ RPM}}{1800 \text{ RPM}} \times 100 = 1.9 \%$$

For a three-phase AC induction motor, the rotating magnetic field must rotate faster than the rotor to induce current in the rotor. When power is first applied to the motor with the rotor stopped, this difference in speed is at its maximum, and a large amount of current is induced in the rotor.

After the motor has been running long enough to get up to operating speed, the difference between the synchronous speed of the rotating magnetic field and the rotor speed is much smaller. This speed difference is called slip.

Slip is necessary to produce torque. Slip is also dependent on load. An increase in load causes the rotor to slow down, increasing slip. A decrease in load causes the rotor to speed up, decreasing slip. Slip is expressed as a percentage and can be calculated using the formula shown in the accompanying graphic.

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

Controlling an AC Motor

Direct Starter

One direction, one speed

Forward

t

Reversing Starter

Two directions, one speed

Forward

Reverse

t

Soft Starter

Two directions, one speed with controlled acceleration and deceleration

Forward

Reverse

t

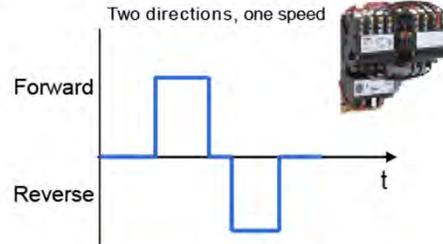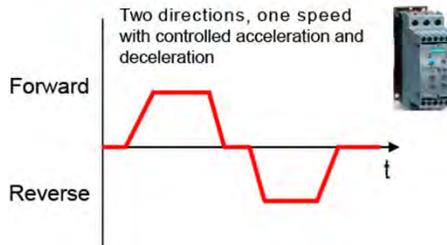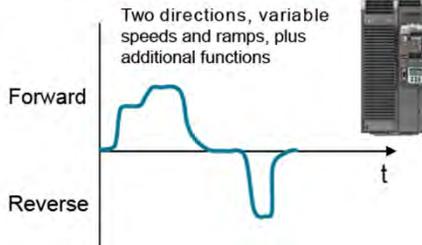**Variable Frequency Drive**

Two directions, variable speeds and ramps, plus additional functions

Forward

Reverse

t
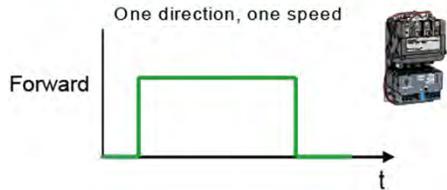
There are multiple ways to control an AC motor. For example, a direct starter, also known as a full-voltage starter, switches a constant speed motor on and off. Because the full line voltage is supplied when the motor is being started, a high inrush current is applied to the motor, and both the motor and the controlled equipment experience significant mechanical shock.

A reversing starter switches a constant speed motor on and off in both the forward and reverse directions. Because this is a full-voltage starting method, in-rush current and mechanical shock are high.

A soft starter is a solid-state reduced-voltage starter that ramps the motor up to a full speed smoothly, reducing the in-rush current and mechanical shock. Some soft starters can also gradually stop a motor. Soft starters, however, cannot control the speed of the motor after it has reached full voltage.

An AC drive is also known as a variable frequency drive because it converts the fixed supply frequency to a variable frequency, variable voltage output to control the speed of an AC motor. AC drives save energy, reduce mechanical shock, and allow the user to dynamically control the speed, torque, and direction of the motor.
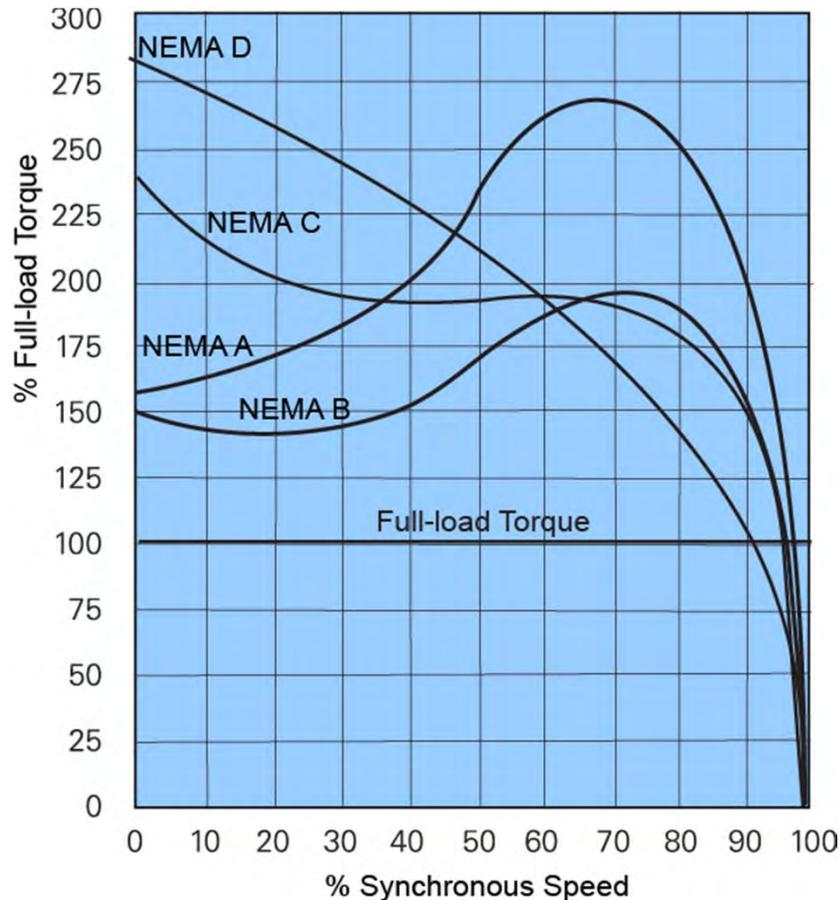
Motors are designed with speed-torque characteristics to match the requirements of common applications. The four standard NEMA motor designs (A, B, C, and D) have different characteristics.

Because motor torque varies with speed, the relationship between speed and torque is often shown in a graph called a speed-torque curve. This curve shows the motor's torque as a percentage of full-load torque over the motor's full speed range when operated at rated voltage and frequency. The accompanying graphic shows examples of the speed torque curves for the four NEMA designs.

This lesson describes NEMA B, C, and D motor designs with emphasis on NEMA design B, the most common three-phase AC induction motor design.

NEMA A motors are the least common type and have a speed-torque curve similar to that of a NEMA B motor, but have higher starting torque.

The graph shows % Full-Load Torque (y-axis, 0 to 250) versus % Synchronous Speed (x-axis, 0 to 100) with points A (Starting Torque), B (Pull-up Torque), C (Breakdown Torque), and D. Values shown: 178.6 lb-ft, 134.0 lb-ft, 89.3 lb-ft, Full-load Torque, Slip 1.9%.

$$HP = \frac{Torque\ (lb\text{-}ft) \times Speed\ (in\ RPM)}{5252}$$

$$Torque\ (lb\text{-}ft) = \frac{HP \times 5252}{Speed\ (in\ RPM)}$$

For a 30 HP, 1765 RPM, NEMA B motor

$$Torque = \frac{30\ HP \times 5252}{1765\ RPM} = 89.3\ lb\text{-}ft$$
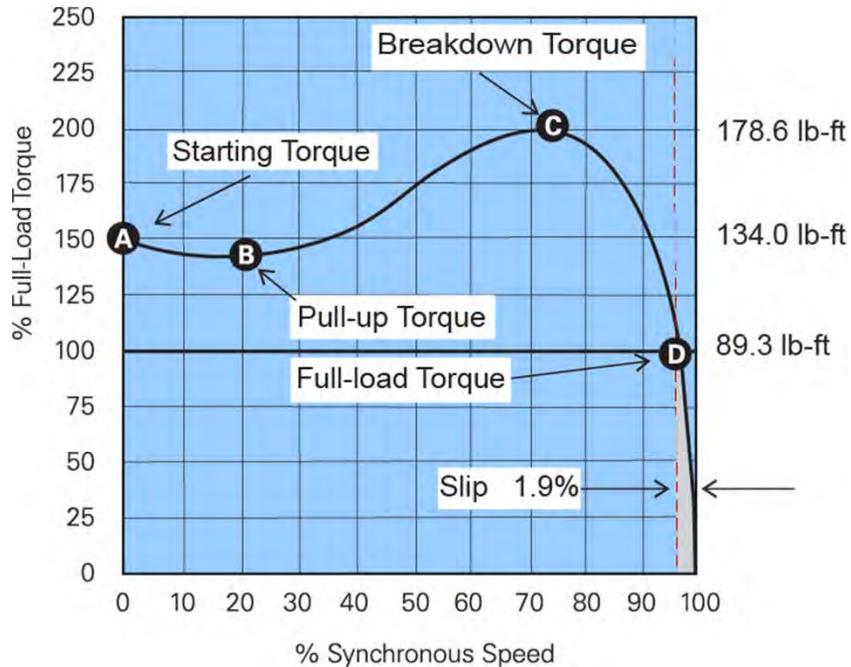
Starting torque, also referred to as locked rotor torque, is the torque that the motor develops each time it is started at rated voltage and frequency. When voltage is initially applied to the motor's stator, there is an instant before the rotor turns. At this instant, a NEMA B motor develops a torque approximately equal to 150% of full-load torque. For the 30 HP, 1765 RPM motor used in this example, that's equal to 134 lb-ft of torque.

As the motor picks up speed, torque decreases slightly until point B on the graph is reached. The torque available at this point is called pull-up torque. For a NEMA B motor, this is slightly lower than starting torque.

As speed continues to increase from point B to point C, torque increases up to a maximum value at approximately 200% of full-load torque. This maximum value of torque is referred to as breakdown torque. The 30 HP motor in this example has a breakdown torque of 178.6 lb-ft.

Torque decreases rapidly as speed increases beyond breakdown torque until it reaches full-load torque at a speed slightly less than 100% of synchronous speed. Full-load torque is developed with the motor operating at rated voltage, frequency, and load.
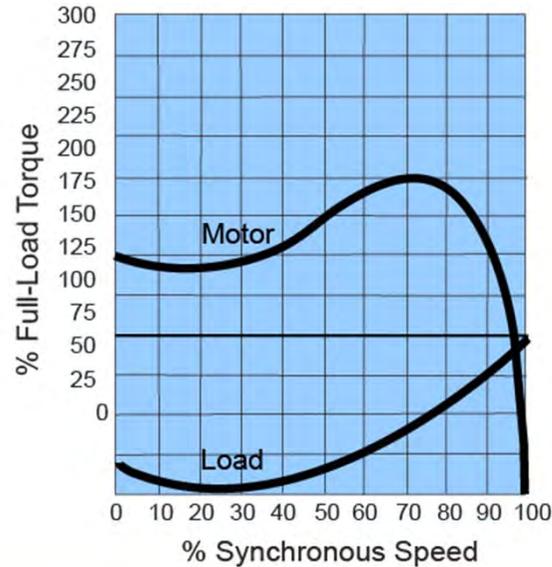
Matching a Motor to a Load

One way to evaluate whether the torque capabilities of a motor meet the torque requirements of the load is to compare the motor's speed-torque curve with the speed-torque requirements of the load.

A table, like one shown in yellow, can be used to find the load torque characteristics. NEMA publication MG 1 is one source of typical torque characteristics.

Load Description	Load Torque as % Full-Load Drive Torque		
	Break-away	Accel-erating	Peak Running
Actuators:			
Screw-down (rolling mills)	200	150	125
Positioning	150	110	100
Agitators			
Liquid	100	100	100
Slurry	150	100	100
Blowers, centrifugal:			
Valve closed	30	50	40
Valve open	40	110	100
Blowers, positive displacement, rotary, bypassed	40	40	100
Calenders, textile or paper	75	110	100

Load Characteristics

Constant HP	Constant Torque	Variable Torque	
$T \approx \dfrac{1}{N}$	$T = Constant$	$T \approx N$	$T \approx N^2$
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

HP = Horsepower, N = Speed, T = Torque

When selecting the motor for an application, it is necessary to know the horsepower, torque, and speed characteristics of the load. Loads generally fall into one of the following three categories.

Variable Torque - The load increases as speed increases. Pumps and fans are examples.

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

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

Load Characteristics – Example Applications

Application	Load Type CT	Load Type VT	Speed Control Range	Application	Load Type CT	Load Type VT	Speed Control Range
Agitators	●		30 to 1	Kiln Drives	●		10 to 1
Blowers, Positive Displacement	●		10 to 1	Lift Applications	●		100 to 1
Braiders	●		10 to 1	Line Shafts	●		10 to 1
Can Making	●		15 to 1	Mills	●		10 to 1
Centrifugal Fans		●	4 to 1	Mixers	●		4 to 1
Centrifugal Pumps		●	3 to 1	Monorails	●		10 to 1
Centrifuges	●		30 to 1	Packaging Equipment	●		20 to 1
Coaters	●		4 to 1	Palletizers	●		10 to 1
Coilers	●		60 to 1	Positioning	●		100 to 1
Compressors	●		10 to 1	Pumps, Positive Displacement	●		10 to 1
Conveyors	●		20 to 1	Presses	●		30 to 1
Cranes	●		100 to 1	Rolling Mills	●		10 to 1
Cut-to-length	●		100 to 1	Rotary Tables	●		100 to 1
Debarkers	●		20 to 1	Shakers	●		10 to 1
Diverters	●		40 to 1	Slitters	●		100 to 1
Dryers		●	10 to 1	Sorters	●		40 to 1
Edge Trimmers	●		15 to 1	Spindles	●		100 to 1
Elevators	●		100 to 1	Spray Painting	●		40 to1
Extruders	●		60 to 1	Stackers, Storage & Retrieval	●		10 to 1
Feeders	●		4 to 1	Tension Reels	●		100 to 1
Flocators	●		10 to 1	Test Stands	●		100 to 1
Fly Cut Off	●		100 to 1	Transfer Lines	●		10 to 1
Grinders	●		10 to 1	Unwinder, Web/Wire	●		100 to 1
Hoists	●		100 to 1	Webs	●		100 to 1
HVAC		●	3 to 1	Wind Tunnels		●	4 to 1
Indexers	●		20 to 1	Winders, Web/Wire	●		100 to 1
Injection Molding	●		40 to 1	Wire Drawing	●		40 to 1

The accompanying table lists examples of motor load applications. For each application, the table identifies the load torque characteristics as constant torque (CT) or variable torque (VT) and shows the typical speed control range. The speed control range for the motor is the ratio of maximum speed to minimum speed.

Motor Performance Under Load
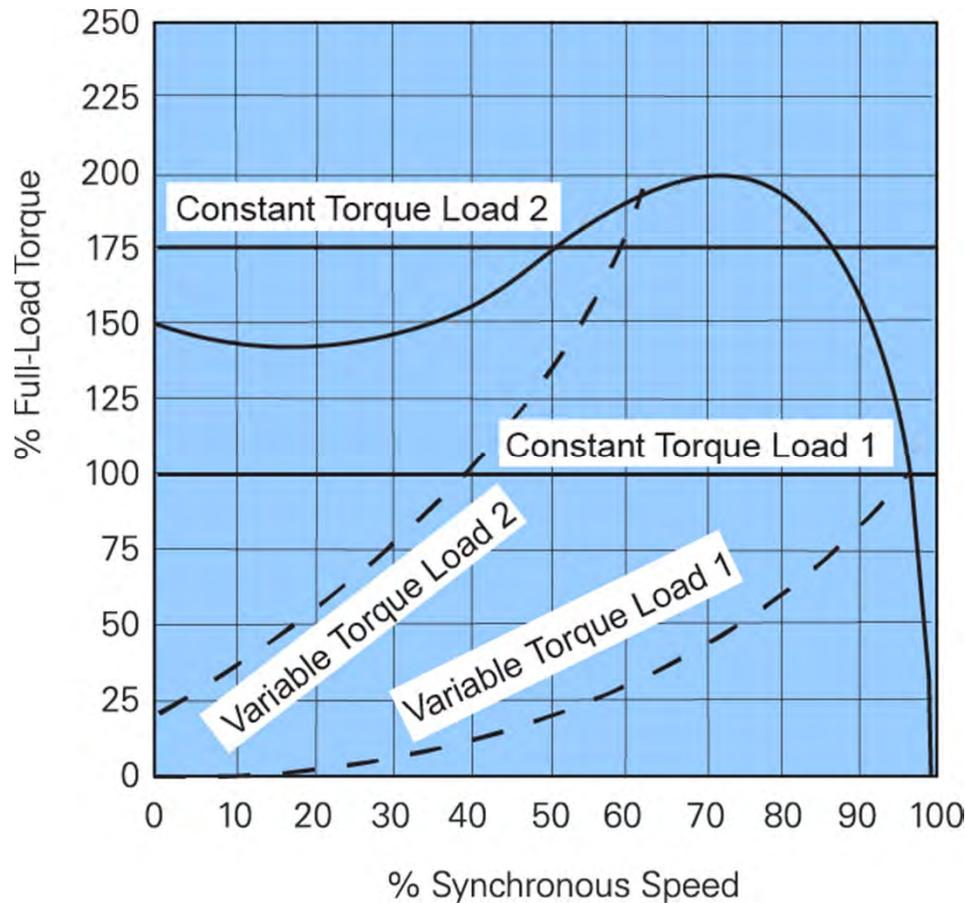
Speed-torque curves are useful for understanding motor performance under load. The accompanying speed-torque curve shows four load examples.

- Variable Torque Load Characteristics 1 and 2
- Constant Torque Load Characteristics 1 and 2

This motor is appropriately sized for constant torque load 1 and variable torque load 1. In each case, the motor will accelerate to its rated speed.

With constant torque load 2, the motor does not have sufficient starting torque to turn the rotor. With variable torque load 2, the motor cannot reach rated speed.

In these last two examples, the motor may overheat if it does not have overload protection.

NEMA B Motor Full-Voltage Starting Current
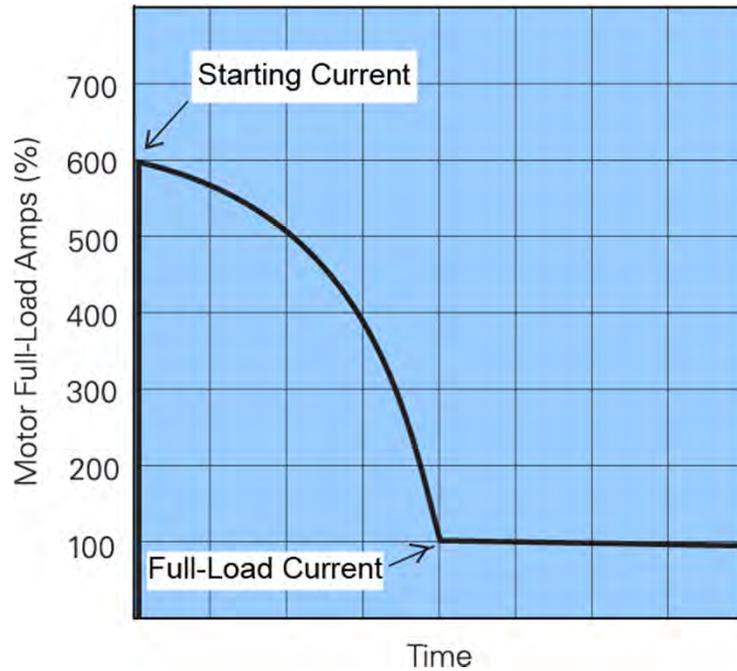
Starting current, also referred to as locked rotor current, is the current supplied to the motor when the rated voltage is initially applied with the rotor at rest. Full-load current is the current supplied to the motor with the rated voltage, frequency, and load applied and the rotor up to speed.

- For a standard efficiency NEMA B motor, starting current is typically 600 to 650% of full-load current.

- Premium efficiency NEMA B motors typically have a higher starting current than standard efficiency NEMA B motors. The starting current can be as high as 1200% of full load current on some NEMA B motors. NEMA A motors also typically have a higher starting current than standard NEMA B motors.

- Knowledge of the current requirements for a motor is critical for proper application.

- On large motors, the high starting current is reflected back into the power lines of the electric utility. This can result in things such as voltage flicker and computer malfunctions. In some systems, it can limit the ability of the system to meet the supply demands.

- Utilities may require the end-user to address the high starting currents.

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NEMA C Motor Speed-Torque Curve
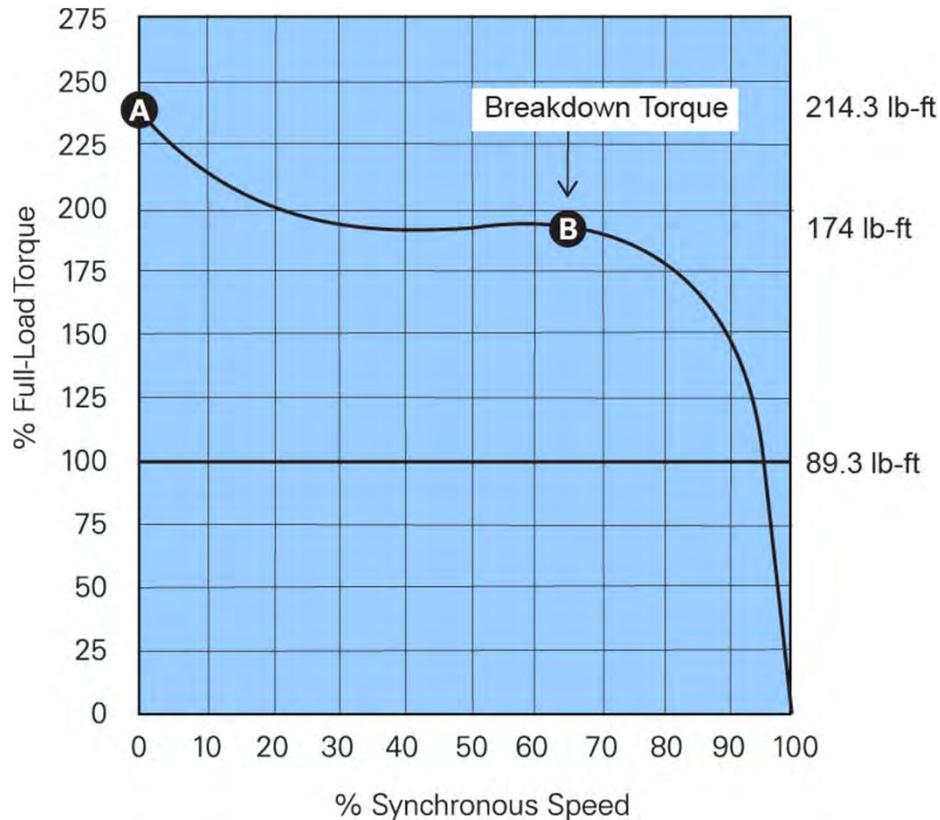
NEMA C motors are designed for applications that require a high starting torque for hard to start loads, such as heavily-loaded conveyors, crushers, and mixers.

Despite the high starting torque, these motors have relatively low starting current. Slip and full-load torque are about the same as for a NEMA B motor. NEMA C motors are typically single speed motors which range in size from approximately 5 to 200 HP.

The accompanying speed-torque curve is for a 30 HP NEMA C motor with a full-load speed of 1765 RPM and a full-load torque of 89.3 lb-ft. In this example, the motor has a starting torque of 214.3 lb-ft, 240% of full-load torque, and a breakdown torque of 174 lb-ft.

NEMA D Motor Speed Torque Curve
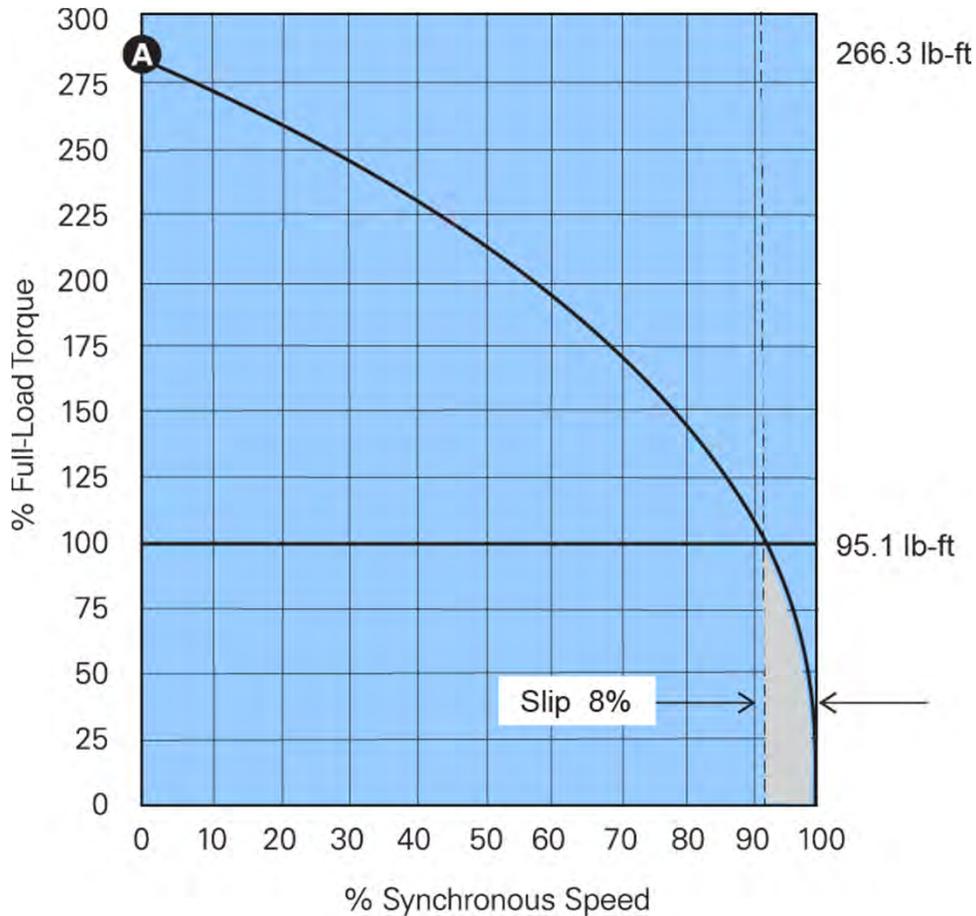
The starting torque of a NEMA design D motor is approximately 280% of the motor's full-load torque. This makes it appropriate for very hard to start applications such as punch presses and oil well pumps. NEMA D motors have no true breakdown torque. After starting, torque decreases until full-load torque is reached. Slip for NEMA D motors ranges from 5 to 13%.

The accompanying speed torque curve is for a 30 HP NEMA D motor with a full-load speed of 1656 RPM and a full load torque of 95.1 lb-ft. This motor develops approximately 266.3 lb-ft of starting torque.

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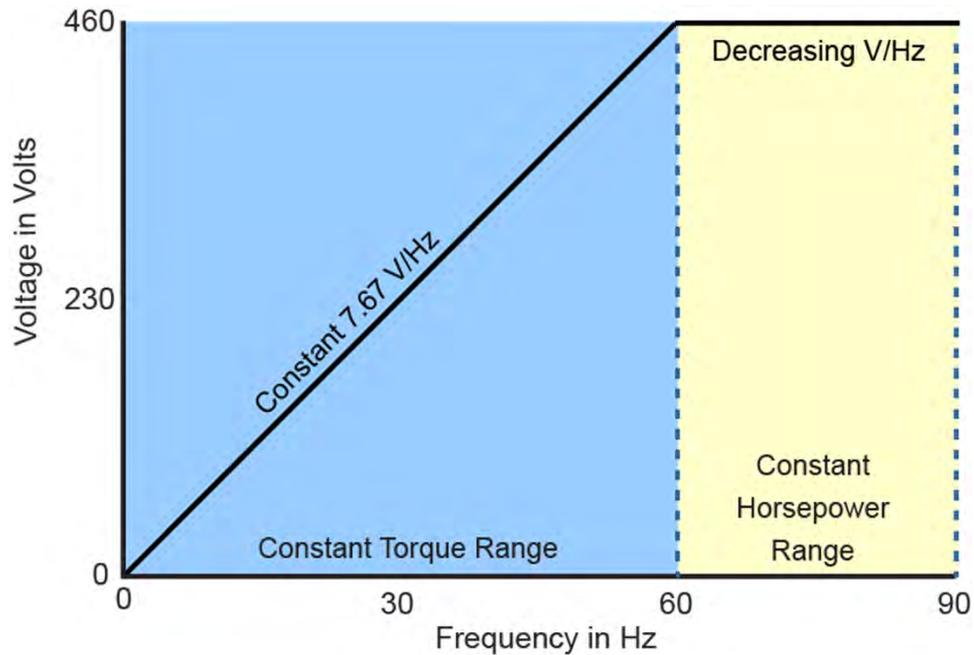
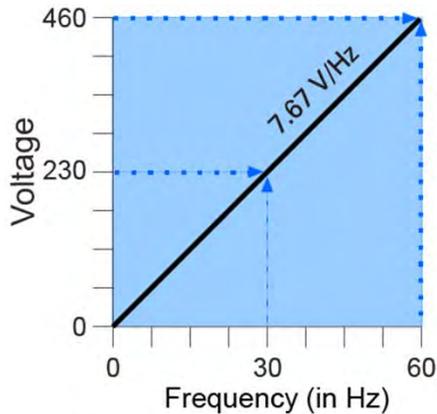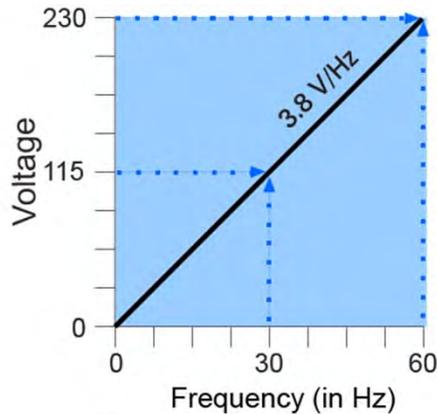This chapter covers the following topics:

- AC Motor Basics
- **AC Drive Basics**

Volts Per Hertz Ratio

$$\frac{230}{30} = 7.67 \text{ V/Hz} \qquad \frac{460}{60} = 7.67 \text{ V/Hz}$$

$$\frac{115}{30} = 3.8 \text{ V/Hz} \qquad \frac{230}{60} = 3.8 \text{ V/Hz}$$

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

Proportional to $= \propto$, Flux $= \Phi$, Voltage $= E$, Frequency $= F$

$$T = k\Phi I_w$$

Torque $= T$, Motor Constant $= k$, Working current $= I_w$

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 and voltage. Operating a motor at other than the rated frequency and voltage affect both motor current and torque.

The volts per hertz (V/Hz) ratio is the ratio of applied voltage to applied frequency for a motor. 460 VAC is a common voltage rating for an industrial AC motor manufactured for use in the United States. These motors typically have a frequency rating of 60 Hz. This provides a 7.67 V/Hz ratio.

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. The accompanying graphs illustrate the constant volts per hertz ratio of a 460 volt, 60 Hz motor and a 230 volt, 60 Hz motor operated over the constant torque range.

The V/Hz ratio affects motor flux, magnetizing current, and torque. If the frequency is increased without a corresponding increase in voltage, motor speed increases, but flux, magnetizing current, and torque decrease.

Variable Speed-Torque Curves
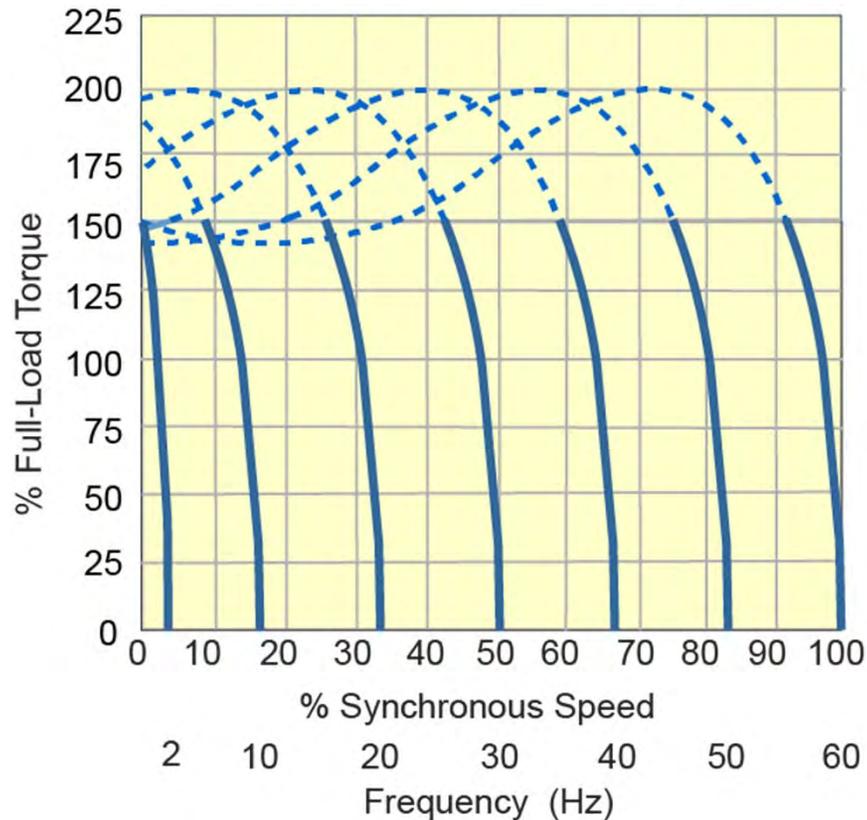
When a NEMA B motor is started at full voltage, it develops approximately 150% starting torque and a high starting current. When the motor is controlled by an AC drive, the motor is started at reduced voltage and frequency. As the motor is brought up to speed, voltage and frequency are increased, and this has the effect of shifting the motor's speed-torque curve to the right. The dotted lines on the accompanying speed-torque curve 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. 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 constant.

Some applications require higher than 150% starting torque. This is possible if the drive and motor are appropriately sized. Typically drives are capable of producing over 100% of drive nameplate rated current for one minute. The drive must be sized to take into account the higher current requirement.

Constant Torque and Constant Horsepower Ranges

$$\text{Torque (lb-ft)} = \frac{\text{Horsepower (HP)} \times 5252}{\text{Speed (RPM)}} \qquad \text{HP} = \frac{\text{Torque (lb-ft)} \times \text{Speed (RPM)}}{5252}$$
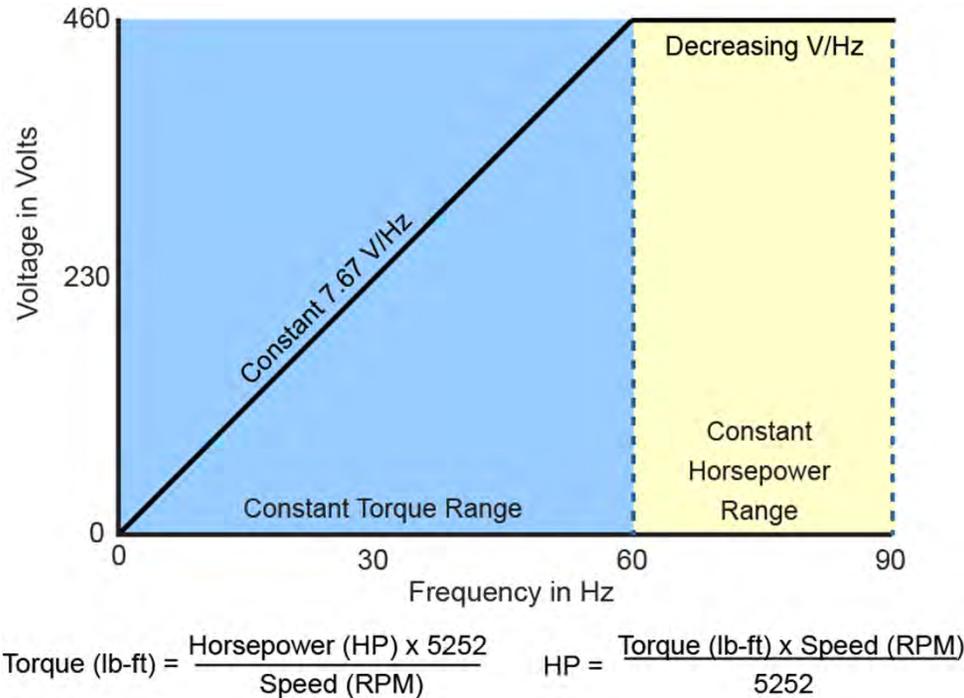
AC motors operated with constant voltage and frequency have constant flux and therefore constant torque through the normal speed range. An AC drive is capable of operating a motor with constant flux from approximately 0Hz to the motor's rated nameplate frequency (typically 60Hz). This is the constant torque range. The top end of this range is the motor's base speed. As long as a constant volts per hertz ratio is maintained the motor will have constant torque characteristics.

Some applications require a motor to be operated above base speed, but the applied voltage cannot be increased above the rated value for an extended time. Therefore, as frequency is increased, stator inductive reactance increases and stator current and torque decrease. The region above base speed is referred to as the constant horsepower range because any change in torque is compensated by the opposite change in speed.

If a motor operates in both the constant torque and constant horsepower ranges, constant volts per hertz and torque are maintained up to 60 Hz. Above 60 Hz, the volts per hertz ratio and torque decrease as speed increases.

Continuous and Intermittent Torque Ranges
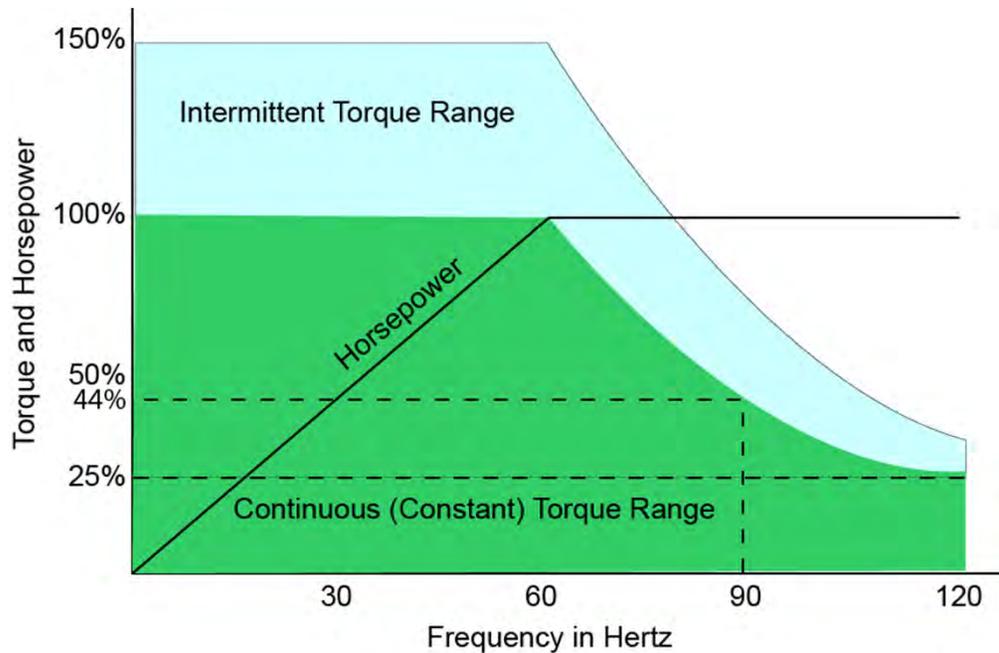
AC motors operating within rated values can continuously apply load torque. For example, the accompanying graph shows the continuous torque range (in green) for a typical AC motor. The sample motor can be operated continuously at 100% torque up to 60 Hz. Above 60 Hz the V/Hz ratio decreases and the motor cannot develop 100% torque, but can still be operated continuously at 25% torque at 120 Hz.

This sample 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, assuming that the associated drive can supply the current. As with the continuous torque range, the amount of torque that can be provided intermittently decreases above base speed.

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Chapter 3 – AC Drives
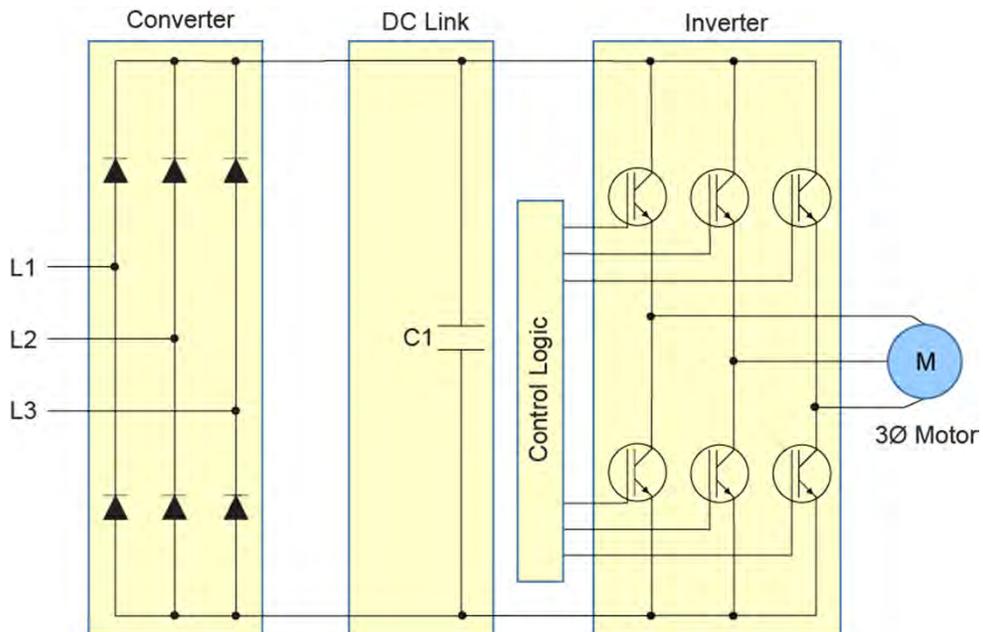
This chapter covers the following topics:

- **AC Drive Hardware**

- AC Drive Operation

Converter   DC Link   Inverter

AC Power

C1

M

3Ø Motor

~ stands for AC
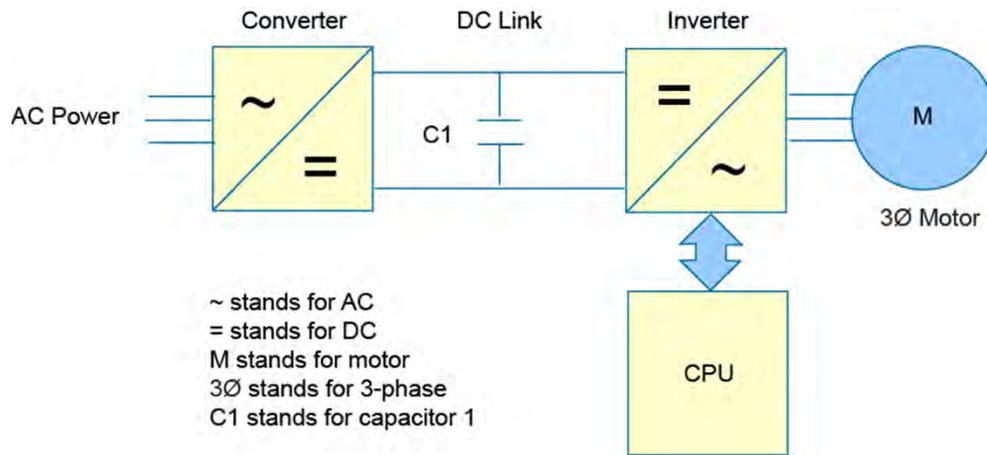= stands for DC
M stands for motor
3Ø stands for 3-phase
C1 stands for capacitor 1

CPU

AC drive, inverter, converter and variable frequency drive are all terms that are often used in reference to equipment designed to control the speed of an AC motor. AC drives consist of the following sections.

Power Section
The power section of a basic AC drive circuit is composed of the following components.

- The rectifier, often called a converter, with power semiconductor devices, coverts incoming AC power to DC.

- The DC link with a DC link capacitor (C1) that smooths the DC and stores energy. Some drives also use an inductor in the DC link for additional filtering.

- The inverter, with power semiconductor devices, converts the DC power to AC for variable speed control.
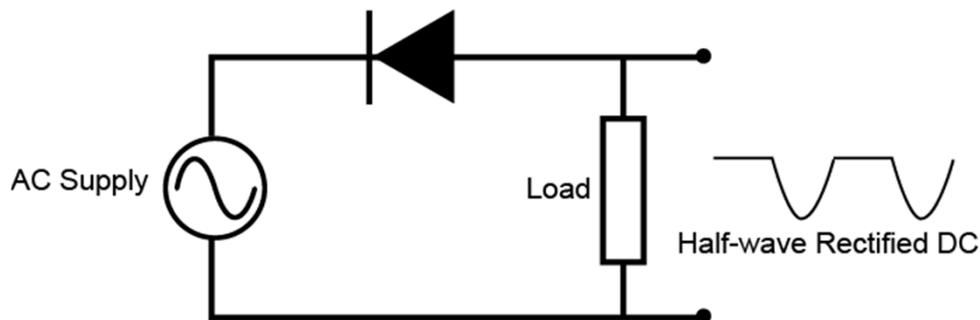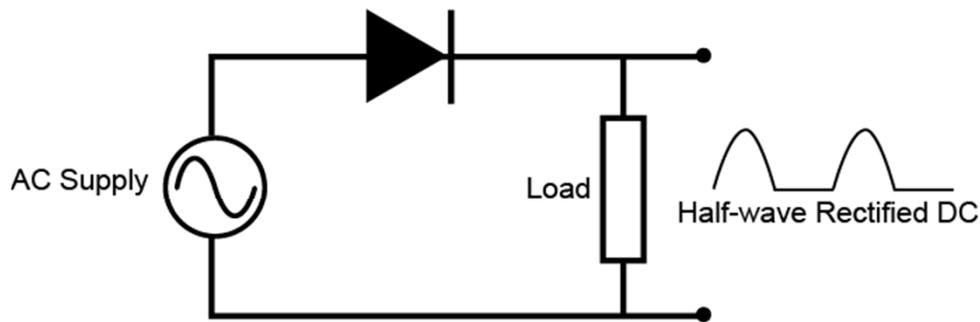
Control Section
The control section includes a CPU (central processing unit) or control logic which is required to control the output of the inverter and perform a variety of other functions.

Interface Section
AC drives typically have a number of input/output interfaces. These include hardwired inputs and outputs, communications, and operator panels.

Diodes

+ Anode   Cathode -

Electron Flow

AC Supply   Load

Half-wave Rectified DC

AC Supply   Load

Half-wave Rectified DC
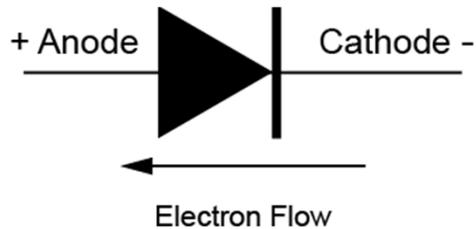
A diode is a semiconductor device that has two terminals, an anode and a cathode. There are various types of diodes, but diodes used in the converter and inverter sections of AC drives are power devices designed to handle the current and voltage needed for these applications.

Diodes primarily conduct current in one direction, when the anode is more positive than the cathode. When the polarity is reversed, as long as the voltage is not above the rated value for the device, only a small leakage current flows.

The ability of a diode to conduct current in only one direction allows them to be used in rectifier circuits that convert AC to DC.

Converter and DC Link

Converter

3-Phase AC Input

A   B   C

Output without
DC Link Capacitor

Converter

3-Phase AC Input

A   B   C

C1

Output with
DC Link Capacitor
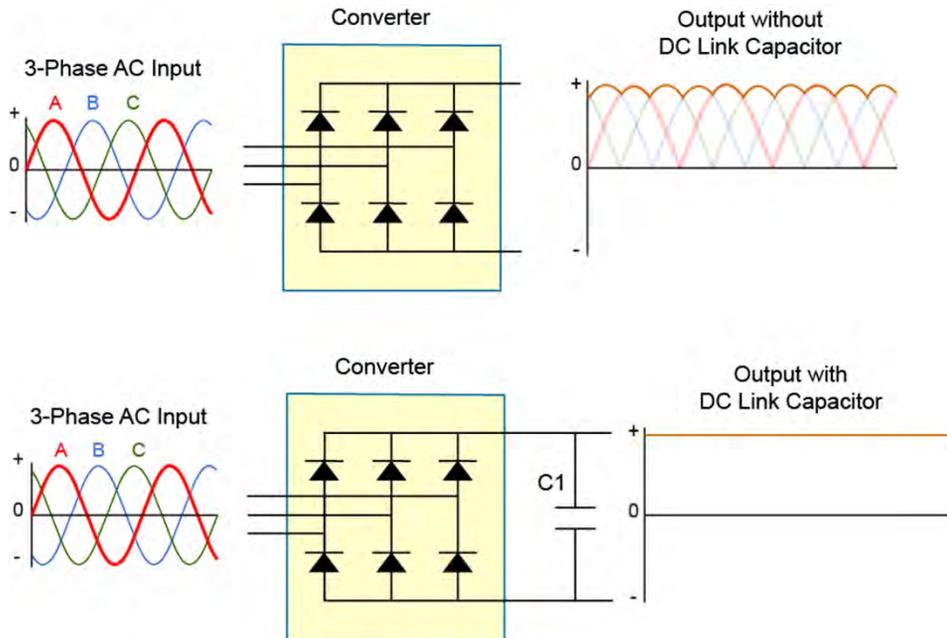
As the accompanying graphic shows, a converter section is designed to convert AC to DC. In this example, as is often the case, the input is three-phase AC.

Without the DC link capacitor, the resultant DC has undesirable variations, referred to as ripple. With a DC link capacitor, most of this ripple is removed. In essence, the DC link capacitor functions like a battery providing power to the inverter section. Unlike a battery, however, the DC link capacitor is continually supplied with energy by the converter.

The amplitude of the DC link voltage V_{DCLink} is determined by the line voltage, the type of voltage rectification, and the load.

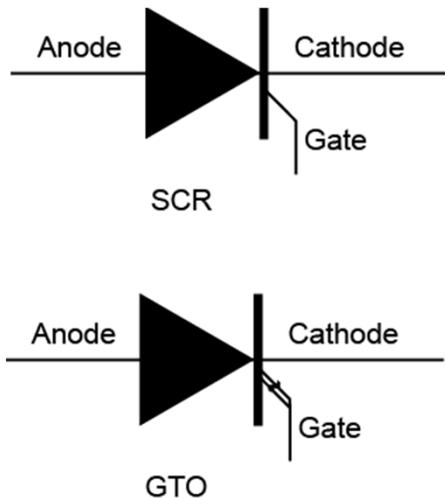**Unregulated (uses thyristors or diodes)**
No Load – $V_{DCLink} = 1.41*VLne$
Partial Load – $V_{DCLink} = 1.35*VLine$

Full Load – $V_{DCLink} = 1.32*VLine$

Regulated (uses IGBTs) – Active Front End
$V_{DCLink} > 1.42*VLine$

Silicon Controlled Rectifiers (SCRs)

SCR

GTO

A silicon controlled rectifier (SCR) is device similar to a diode, but with the following three electrodes: anode, cathode, and gate. An SCR is one of a number of semiconductor devices that are referred to as thyristors.

Like a diode, an SCR primarily conducts current in one direction, when the anode is sufficiently more positive than the cathode by an amount referred to as SCR's breakover voltage.

The voltage differential required for conduction can be reduced by applying a pulse of current to the gate. Once the SCR begins conduction, it remains in conduction for the as long as the anode remains more positive than cathode.

The ability to control when in a half cycle an SCR begins conducting by the timing of a gate pulse, allows SCRs to be used to control the effective value of voltage applied to a load.

One type of SCR that offers additional control, is a gate-turn-off SCR, also called a GTO. GTO's not only can be triggered on by a gate pulse, but can also be triggered off by a gate pulse of the opposite polarity.

AC Drive Power Transistors
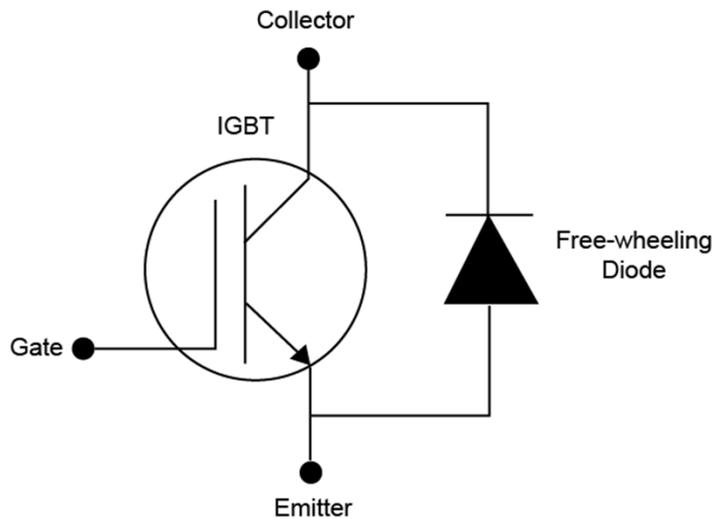
AC drive inverter circuits often use insulated gate bipolar transistors (IGBTs). IGBTs provide the high switching speed necessary for modern inverter operation. IGBTs are capable of switching on and off several thousand times a second. An IGBT can turn on in less than 400 nanoseconds and off in approximately 500 nanoseconds.

An IGBT has three leads: a gate, a collector, and an emitter. When a positive voltage (typically +15 VDC) is applied to the gate, the IGBT turns on. This is similar to closing a switch. When the IGBT is turned on, current flows 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.

Typically, each switch element is made up of an IGBT and a diode, called a free-wheeling diode. The free-wheeling diode protects the IGBT by conducting current when the IGBT turns off, and the motor's collapsing magnetic field causes a current surge. This is also the path used when the motor is connected to an overhauling load.

An overhauling load is a load that is going faster than the speed set point. In this situation, the drive attempts to slow down the motor, and the motor becomes a generator and returns energy to the drive.

Control Logic and Inverter
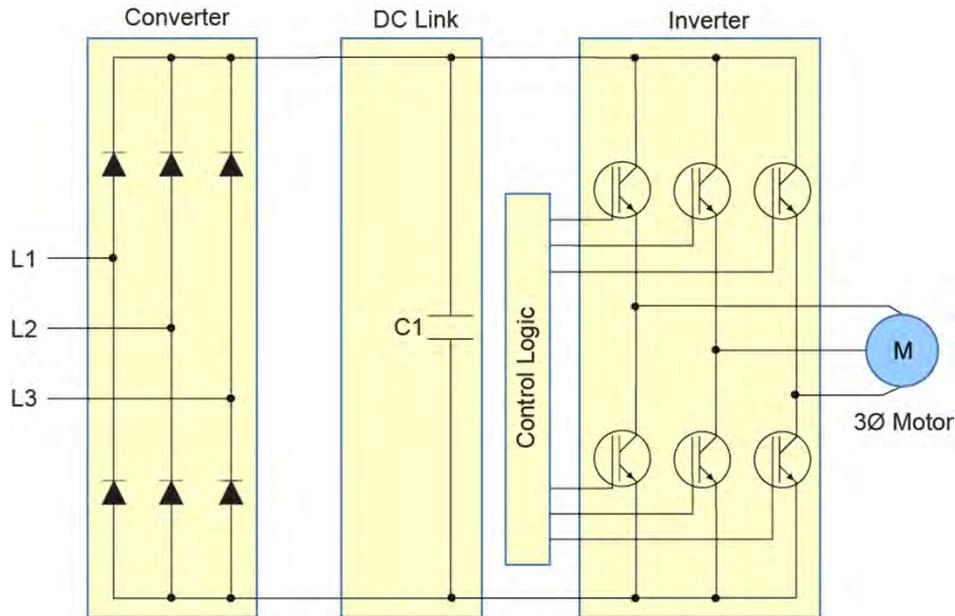
The control logic and inverter sections function to control the voltage and frequency applied to the AC motor. The accompanying graphic shows a basic AC drive with six IGBTs in the inverter section. The switching of each IGBT is controlled by the control logic. For the purpose of simplicity, the free-wheeling diodes are not shown.

There are a variety of ways to control the voltage and frequency applied to the motor. The most common approach is to switch the IGBTs in such as manner as to control the frequency and width of pulses applied to each motor phase. This is an approach referred to as pulse width modulation (PWM).

Pulse Width Modulation

Lower Frequency and Lower Voltage
Shorter "On" Duration = Lower Voltage

Appied Voltage for One Phase
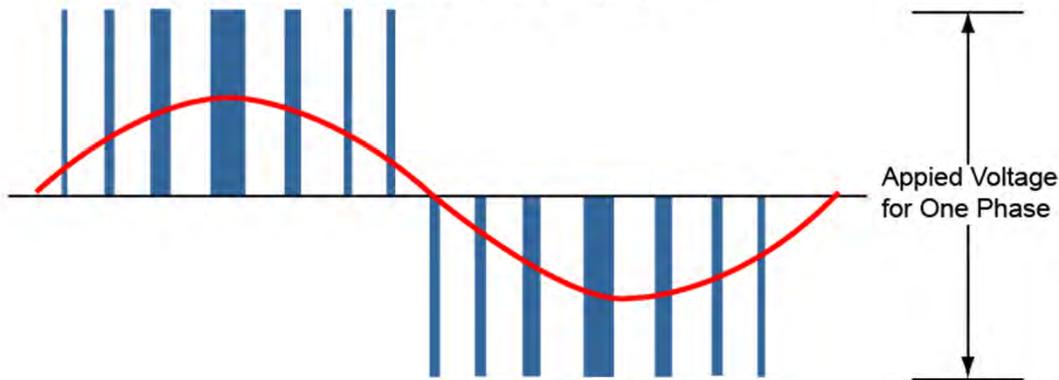
Higher Frequency and Higher Voltage
Longer "On" Duration = Higher Voltage

Appied Voltage for One Phase
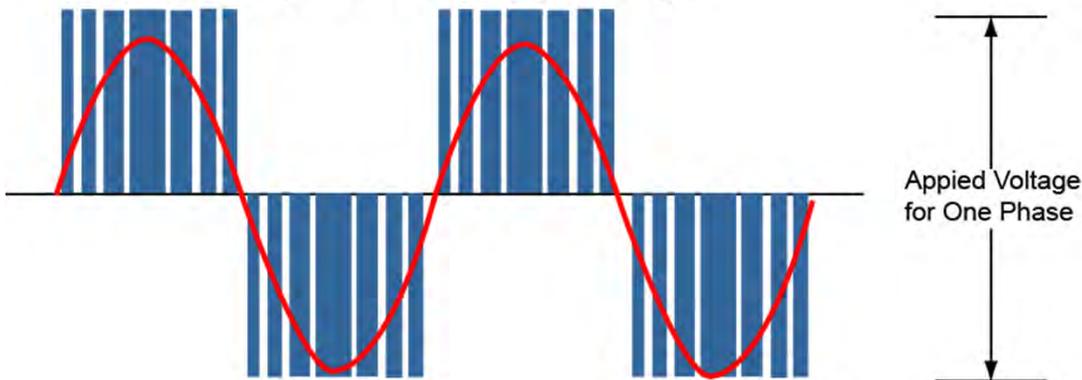
A pulse width modulation (PWM) inverter controls the speed of an induction motor by varying the frequency and pulse widths of the voltage applied to the motor. This is done by controlling the IGBTs in the inverter.

The accompanying graphic shows two representative PWM signals associated with a single phase of inverter output. The voltage and frequency applied to the motor is the same for each phase, but each phase is shifted in time in the same manner as a typical three-phase voltage.
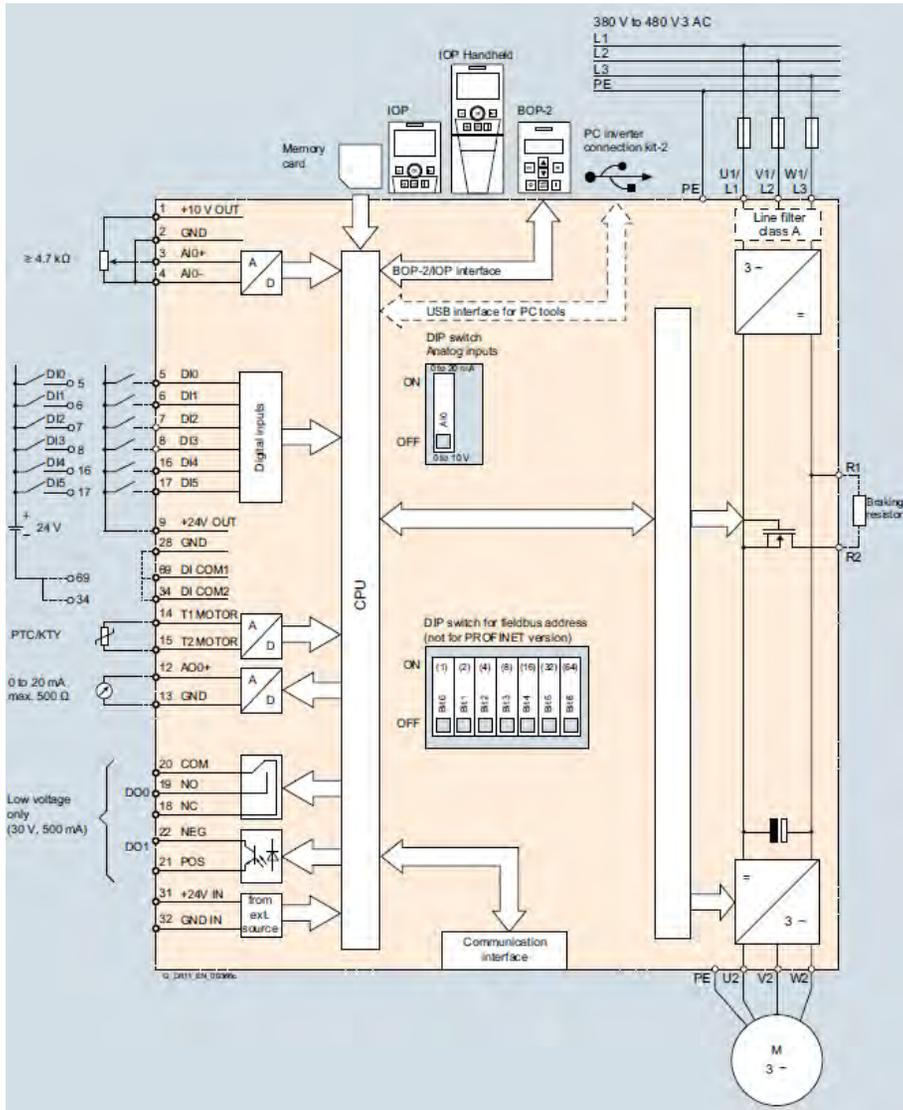
AC drives typically have additional circuits for connection to other devices through digital inputs and outputs, analog inputs and outputs, other common drive signals, operator panels, and communications (computer interface, PLC interface).

Digital inputs can be used to control the logic functions of the drive. Digital inputs can include signals for start/stop, forward/reverse, fixed speed selection, stopping methods, interlocking, and enabling other functions. Digital outputs are used to provide signals to other equipment to indicate drive status or operational conditions.

Analog inputs can be used to control references for speed, tension, or other conditions, or to provide feedback representative of application conditions. Analog outputs can be used to send signals representing actual conditions such as drive current or motor speed to display devices or other equipment.

In addition to analog and digital inputs and outputs, there are other common drive signal connections. For example a PTC/KTY input is often provided for connection to a motor temperature sensor.

Other typical signal connections include encoder interfaces for speed or position feedback and communication interfaces for interconnection to other devices or networks.

Additional Hardware Components

AC Supply

Circuit Breaker and/or Fuses

Input Contactor

EMC Filter

Input Line Reactor

Operator Panel

Control Unit

Power Module

I/O

Output reactor

Induction Motor

Braking Chopper

Braking Resistor

Sinusoidal or dv/dt Filter
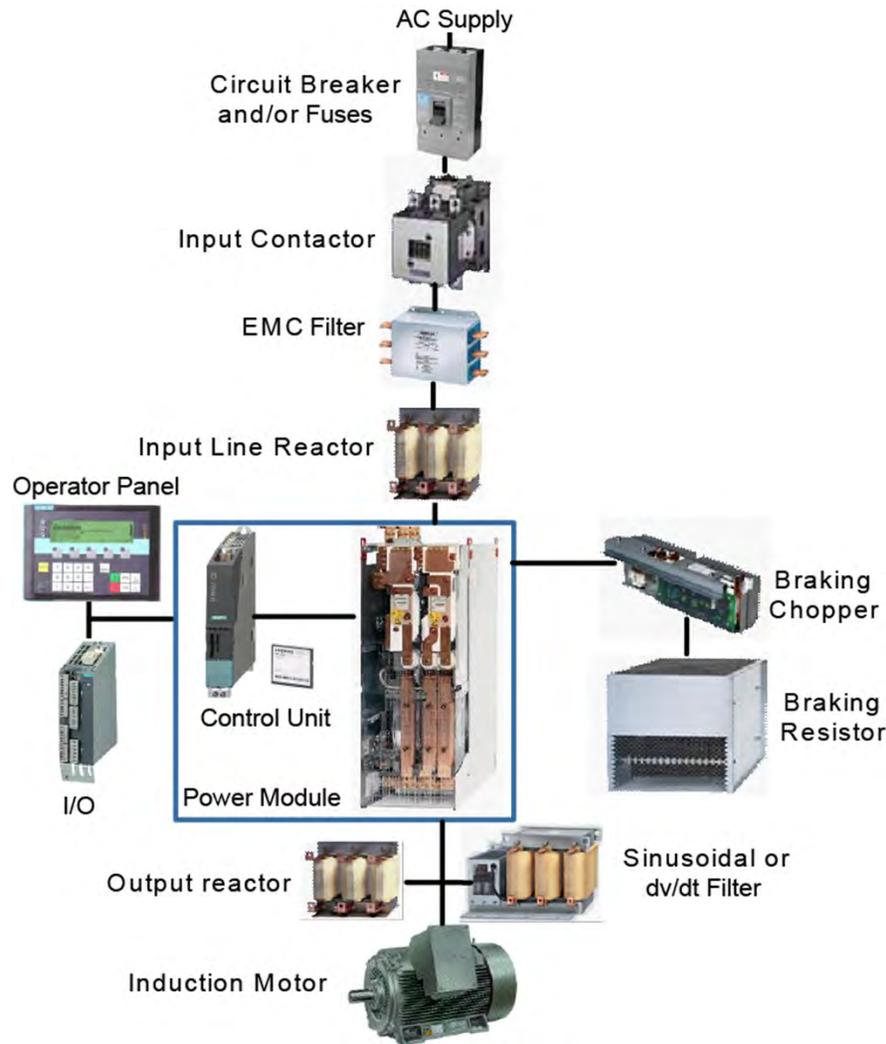
In addition to the components discussed thus far, other components are also required in a typical drive application. Some examples are shown in the accompanying graphic and described below.

- Circuit Breaker and/or Fuses - needed to meet NEC code requirements for protection from overloads, short circuits, and ground faults
- Input Contactor - used to remove power from the drive
- EMC Filter - used to reduce RFI noise and required to meet European standards
- Input Line Reactor - smooths power line disturbances, inrush current, and harmonics
- Braking Chopper (if not internally supplied) - switching device that controls the power applied to the dynamic braking resistor
- Braking Resistor - resistor grid that absorbs and dissipates energy from the load during dynamic braking
- Output Reactor - smooths output power disturbances and reduces fast rise times (dv/dt) for increased motor protection
- dv/dt filter – reduces voltage peaks and fast rise times (dv/dt) for increased motor protection.
- Sine wave filter - reduces voltage peaks at the motor by filtering the drive PWM waveform to approximate a sine wave

Multi-Axis Configurations

Converter   DC Link   Inverter

AC Power

Single-Axis AC/AC Drive

DC Bus   Inverter

Converter   Inverter

AC Power

Inverter

Multiple-Axis Drive
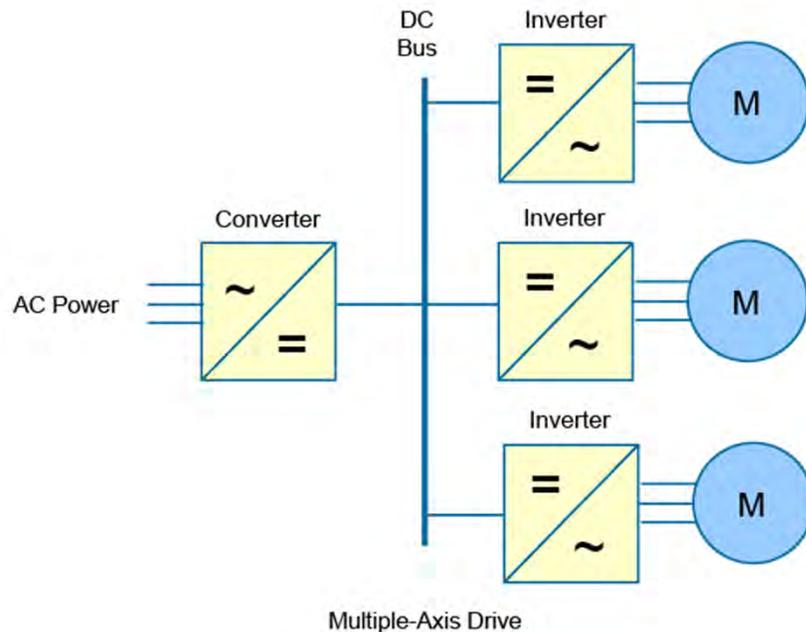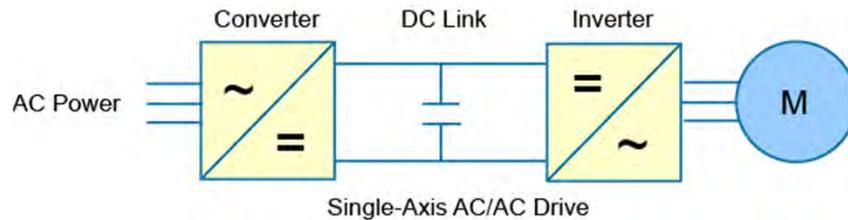
The drive configurations shown thus far have been single axis AC/AC drives which convert an AC input to DC and then back again to AC to a motor or possibly multiple motors, but all at the same speed.

In contrast, a multi-axis drive utilizes multiple inverters. A single converter converts the AC to DC which is distributed along a "common" DC bus. The inverter sections perform as previously described to convert DC to AC to allow for independent control of each motor.

The reasons for using a common DC bus design are discussed later in the course.

NEMA, UL, and CSA Enclosure Types

Provides a degree of protection for the following conditions	Indoor			Outdoor	
	1[1]	12	4X	3R[1]	4X
Access to hazardous parts	•	•	•	•	•
Ingress of solid foreign objects (falling dirt)	•	•	•		
Ingress of solid foreign objects (circulating dust, lint, fibers, and flyings[2])		•	•		
Ingress of solid foreign objects (Settling airborne dust, lint, fibers, and flyings[2])		•	•		
Ingress of solid foreign objects (windblown dust, lint, fibers, and flyings)					•
Ingress of water (dripping and light flashing)		•	•		
Ingress of water (hosedown)					•
Ingress of water (hosedown and splashing water)			•		
Ingress of water (rain, snow, and sleet[3])				•	•
Oil and coolant seepage		•			
Corrosive agents			•		

1. These enclosures may be ventilated.
2. These fibers and flyings are nonhazardous materials and are not considered Class III type ignitable fibers or combustible flyings.
3. External operating mechanisms are not required to be operable when the enclosure is ice covered.

Enclosure ratings identify an enclosure's ability to resist external environmental influences. In North America, ratings found in the following publications are most commonly used.

- National Electrical Manufacturers Association (NEMA Standard 250)
- Underwriters Laboratories, Inc. (UL50 and UL 508)
- Canadian Standards Association (CSA Standard C22.2 No. 94)

The rating numbers described in these publications are used to identify the degree of protection provided by each enclosure type number. UL and CSA require enclosure testing, but NEMA does not. The accompanying chart shows a summary of the degree of protection provided by selected enclosure types.

1st No.	Protection Against Access to Hazardous Parts / Solid Object Protection	2nd No.	Water Protection
0	Not protected	0	Not protected
1	Back of the hand protection / Protected against objects > 50 mm	1	Protected against dripping water
2	Finger protection / Protected against objects > 12 mm	2	Protected against dripping water with enclosure tilted up to 15°
3	Tool protection / Protected against objects > 2.5 mm	3	Protected against spraying water
4	Wire protection / Protected against objects > 1 mm	4	Protected against splashing water
5	Wire protection / Protected against dust	5	Protected against water jets
6	Wire protection / Dust tight	6	Protected against heavy seas
		7	Protected against temporary immersion
		8	Protected against prolonged immersion

Enclosure ingress protection (IP) rating numbers are also provided by the International Electrotechnical Commission (IEC publication 60529). These are commonly used international ratings.

Each rating number has two digits. The first digit represents the degree of protection against access to hazardous parts and the degree of protection from foreign objects.

The second digit represents the degree of protection from water.
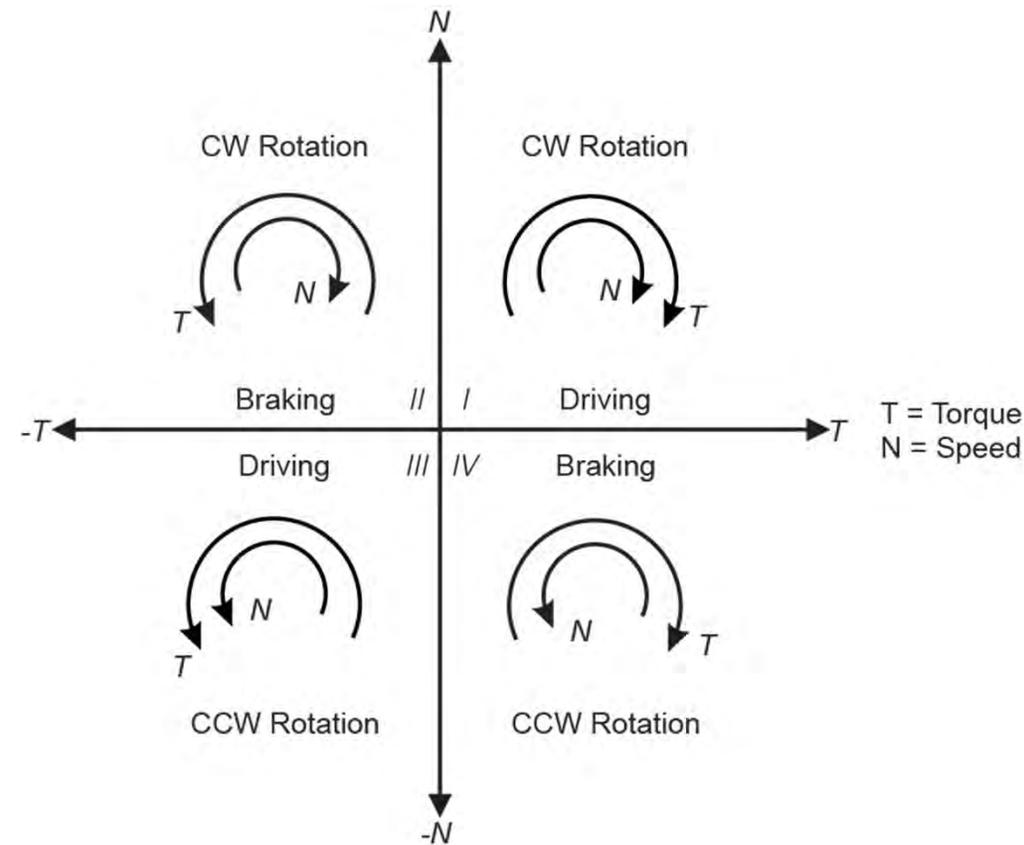
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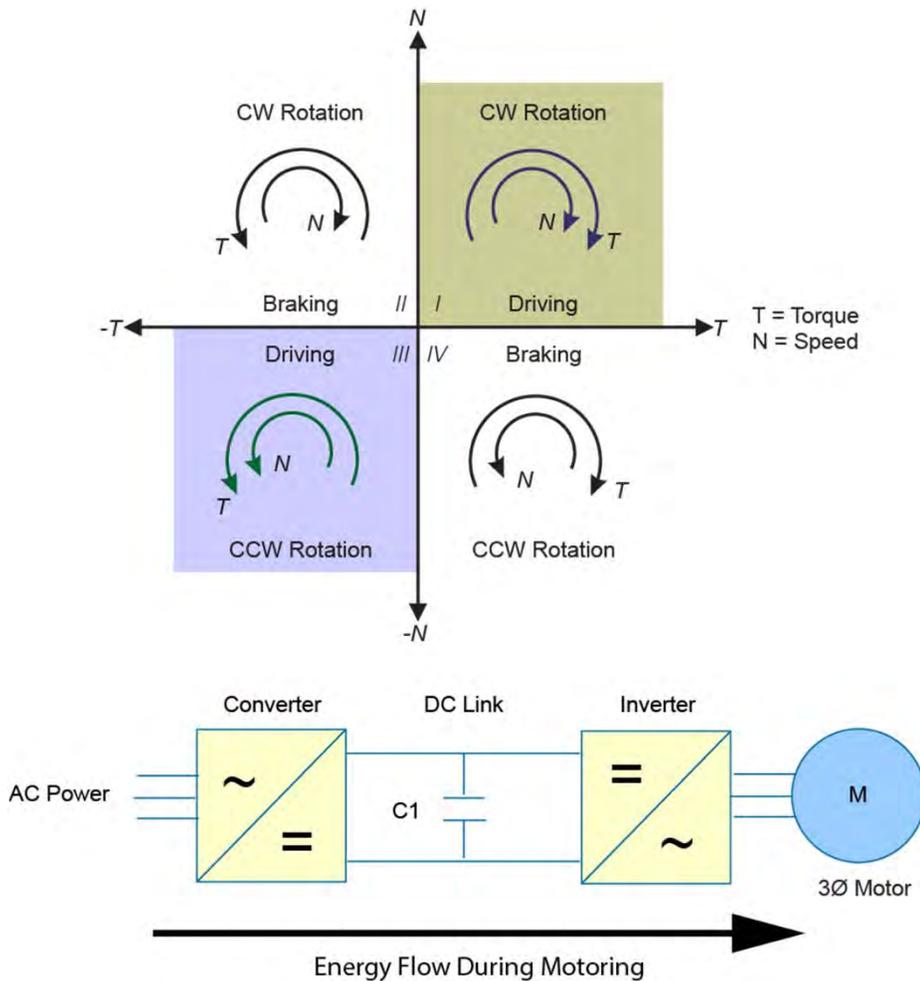For additional information: www.usa.siemens.com/sitrain

This chapter covers the following topics:

- AC Drive Hardware

- **AC Drive Operation**

CW Rotation   CW Rotation

Braking   II | I   Driving

T = Torque
N = Speed

Driving   III | IV   Braking

CCW Rotation   CCW Rotation

Converter   DC Link   Inverter

AC Power

C1

M

3Ø Motor

Energy Flow During Motoring

In the accompanying speed-torque chart there are four quadrants defined by the directions of motor rotation and torque.

Motoring operation occurs when the drive operates in quadrants I or III, where the speed and torque arrows have the same direction.

Quadrant I is forward motoring or driving clockwise (CW). 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, you can let off the accelerator a little. When the car comes to an incline, a little more gas is required to maintain speed.

Quadrant III is reverse motoring or driving counter-clockwise (CCW), Reverse motoring is achieved by reversing the direction of the rotating magnetic field. This applies torque in the opposite direction than in quadrant I, so the motor turns in the reverse direction.

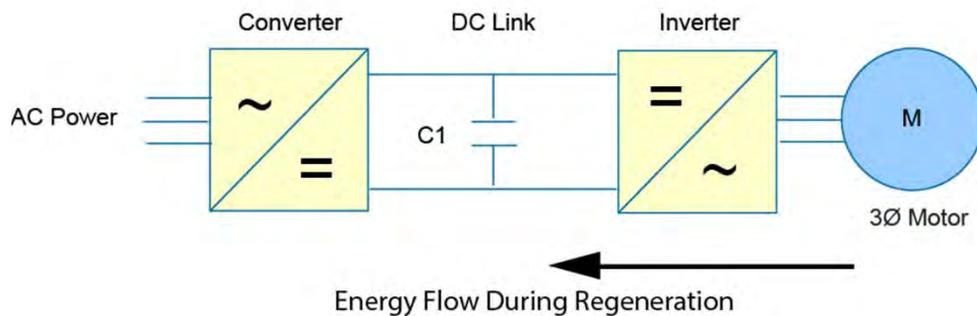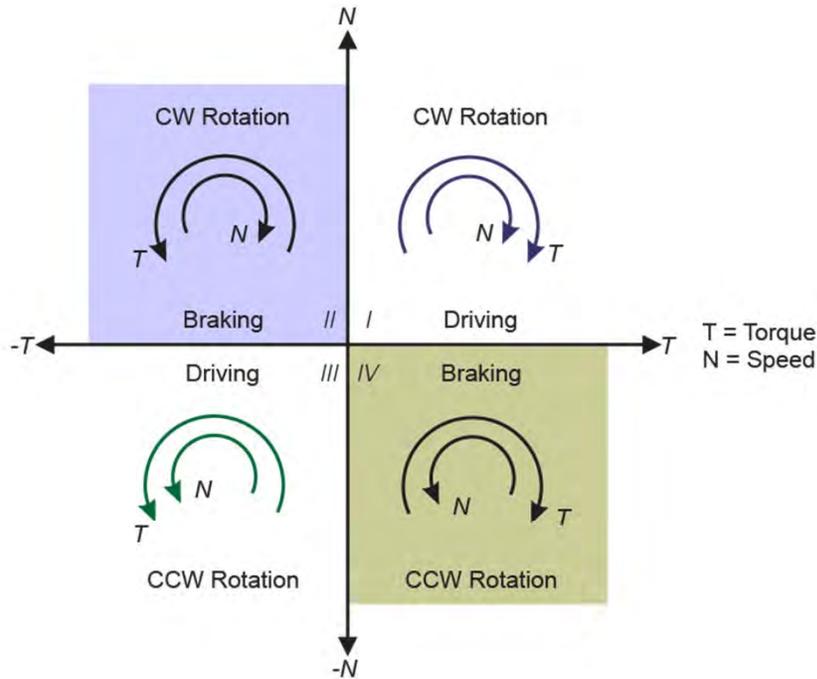| Ways to Stop the Motor and Load	Comments
Coast to Stop	This is the simplest stopping method, but one that is too slow for some applications. It involves turning off the drive's output pulses and allowing the friction of the load to dissipate the energy of motion in the form of heat.
Controlled Deceleration	This involves reducing the velocity reference or set point in a controlled manner to decelerate the motor and load. Depending on the inertia of the load and the speed of the ramp, the drive may use the motor's regenerated energy to stop the load.
Removal of the Run command (Ramped Stop)	This is also a controlled deceleration, but initiated by removing the drive's Run command.
Alternative Ramp Down	This is also a controlled deceleration, but initiated by a different command source, such as a digital input, and has a different ramp down time.
DC Injection Braking	This braking method involves removing the pulses that drive the motor and replacing them with a DC voltage. This replaces the motor's rotating magnetic field with a stationary field. This method can stop the motor quickly, but the energy of motion is also quickly transformed into heat, and the motor and drive must be able to dissipate this heat.
Compound Braking	Compound breaking uses a combination of controlled deceleration and DC injection braking. This method can stop the motor quickly with less stress on the drive. As the motor is ramped down, the motor begins acting like a generator, dumping excess energy back to the drive. The drive monitors the DC link voltage and applies DC injection braking when this voltage exceeds a certain value.

In order to understand the various methods used to stop an AC motor and its associated load in a system controlled by an AC drive, it is helpful to know some basic laws of science.

One of these laws, often referred to as the first law of thermodynamics, is that energy cannot be created or destroyed, only transformed from one type to another.

Another important law requires the conservation of momentum, which is the product of mass and velocity. This means is that, in order to stop a motor and its connected load, all of the energy of motion must be transformed to another type of energy. In addition, the greater the momentum of the motor and its load, the more energy there is to transform.

Because application requirements vary, a variety of braking methods have been developed. The accompanying table summarizes some of the more common methods of braking used with AC drives. There are additional braking methods, and one of these methods, dynamic braking, is explained later in this course.

Regenerative Operation

N

CW Rotation   CW Rotation

Braking   II | I   Driving

-T ←   → T   T = Torque
                            N = Speed

Driving   III | IV   Braking

CCW Rotation   CCW Rotation

-N

Converter   DC Link   Inverter

AC Power   C1   M

3Ø Motor

Energy Flow During Regeneration

The dynamics of certain loads may require four-quadrant operation, where torque can be applied in either direction regardless of the direction of motor rotation.

Quadrants II and IV are braking quadrants because, as shown in the accompanying graphic, the direction of torque is opposite to the direction of motion.

Torque always acts 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 energy from the shaft into electrical energy which is returned to the AC drive. This is similar to driving a car downhill. The car's engine acts as a brake.

This type of operation is regenerative operation for the drive and must be considered when evaluating the drive for an application.

Note that in the graphic, the regenerative energy arrow stops at the DC Link which has upper and lower voltage limits that, when exceeded, result in a drive fault. Dynamic braking can address this in some situations.

Regenerative Applications

Application	Application
Can Making	Palletizers
Centrifugal Fans	Positioning
Centrifuges	Presses (Blanking Type)
Coaters	Presses (Punch Type)
Coilers	Presses (Reciprocating)
Conveyors (Belt and Chain)	Press Feeders
Cranes (Tower Type)	Rolling Mills
Cut-to-length	Rotary Tables
Debarkers	Slitters
Edge Trimmers	Spindles
Elevators	Spray Painting
Fly Cut Off	Stackers (Storage & Retrieval)
Hoists	Tension Reels
Kiln Drives	Test Stands
Lift Applications	Transfer Lines
Line Shafts	Unwinder (Web/Wire)
Mill Applications	Web Applications
Monorails	Winders (Web/Wire)
Packaging Equipment	Wire Drawing

Regenerative operation is more characteristic of some applications than others. The accompanying table lists applications for which regenerative operation is common. Drives used in these applications must be cable of handling regenerative energy.

Dynamic Braking

Converter | DC Link | Inverter

R1

C1

Control Logic

L1
L2
L3

M

3Ø Motor
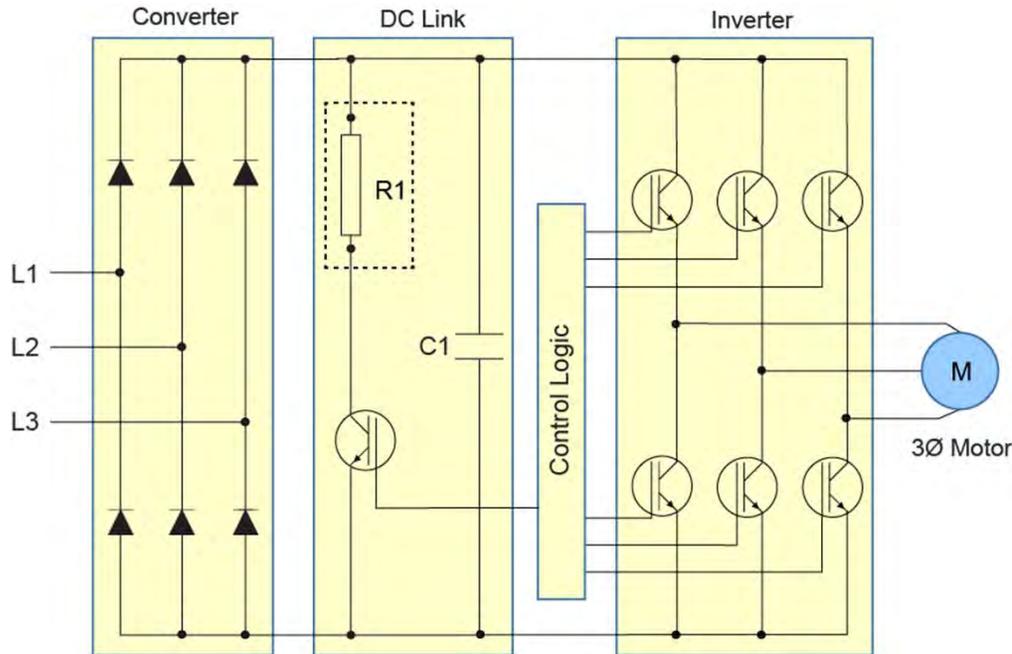
Dynamic braking resistor (R1) is usually mounted external to the drive.

Dynamic braking is also referred to as pulsed-resistor braking. The accompanying graphic shows an AC drive with a dynamic braking circuit composed of R1 and a switching transistor that is controlled by the control logic.

The converting rectifier diodes supply current in only one direction. When the load attempts to go faster than the set motor speed, a condition referred to as an overhauling load (Quadrants II or IV), the motor generates electrical energy back to the DC link.

Regeneration also occurs if the load is stopped quicker than it would normally stop in a non-powered state.

As the voltage on the DC link capacitor increases during regeneration, the braking transistor switches on to dissipate the energy across the resistor and decrease the DC link voltage.

During normal operation (motoring quadrants I and III) the dynamic braking circuit is turned off.

Another way to handle the regenerative energy is to utilize a regenerative-capable converter.
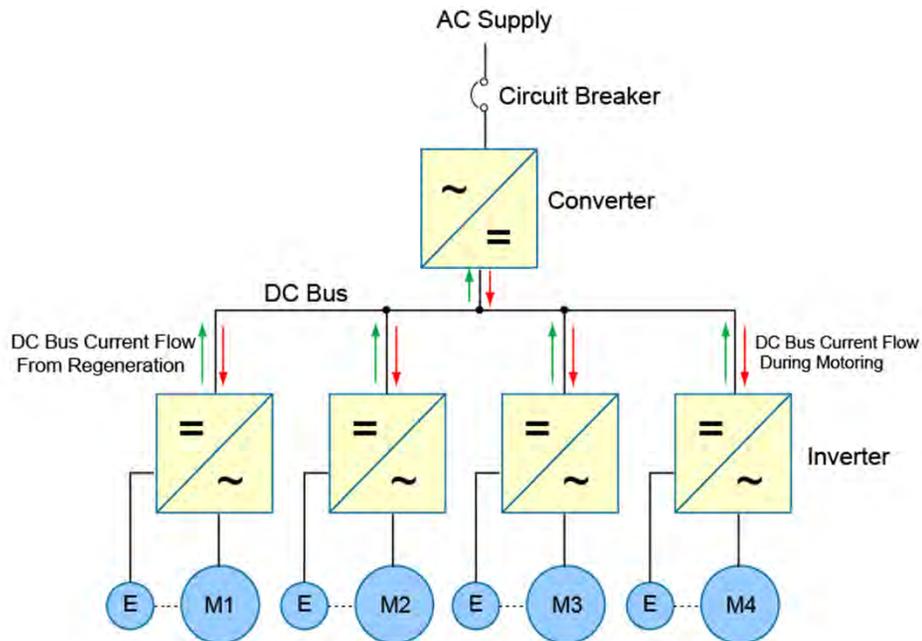
Regenerative-Capable Single Axis AC Drive
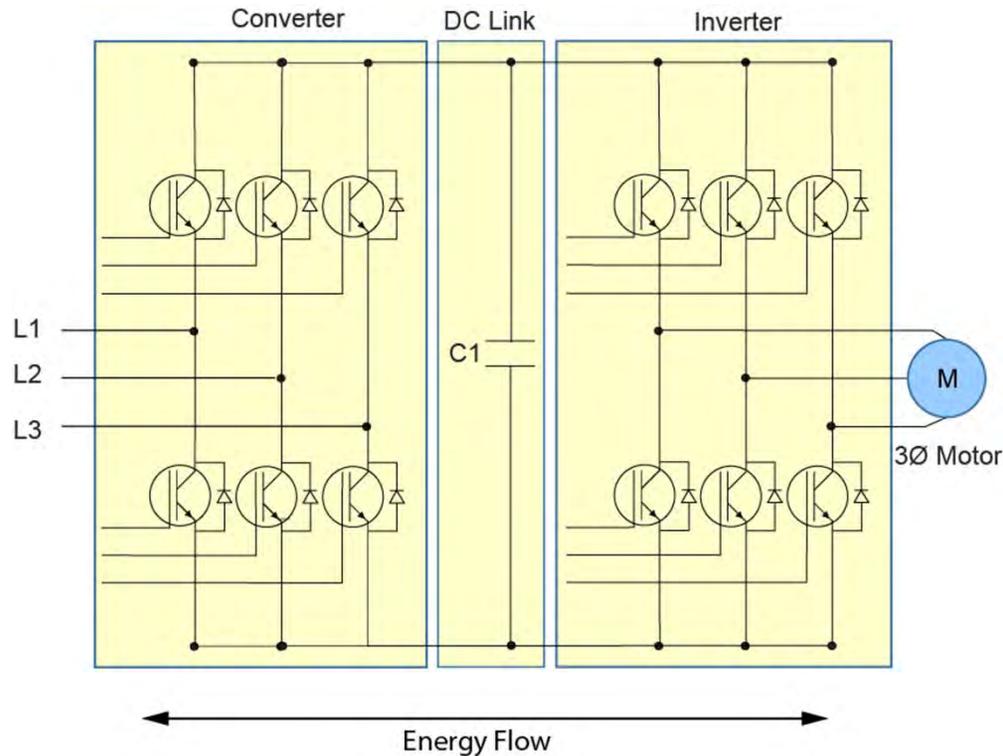
Many AC drives have a converter section that uses diodes to rectify the incoming alternating current. These designs are simple and inexpensive, but they are not designed to return energy to the source when the motor is operating as a generator.

There are a variety of additional converter designs and some of these designs regenerate current to the supply when the motor is operating as a generator.

For example, a Siemens fundamental frequency front end (F3E) converter is an example of a regenerative-capable drive. An F3E converter incorporates both IGBTs and diodes. When the drive is providing power to the motor, the diodes provide DC current to the DC link. When the motor is operating as a generator, the IGBTs in the converter return energy to the supply.

F3E converters are used in industrial applications where regeneration is needed, but the need for clean power is not critical.

Common DC Bus and Regeneration

AC Supply

Circuit Breaker

~ / = Converter

DC Bus

DC Bus Current Flow From Regeneration

= / ~ Inverter

DC Bus Current Flow During Motoring

E - M1   E - M2   E - M3   E - M4

Advantages

Because energy from regeneration is either used by other drives in a coordinated system or returned to the source, the cost required to power the system is reduced.

Because one large converter typically has a smaller footprint as compared to multiple smaller AC/AC drives, factory floor space is reduced.

Because fewer parts are required, initial cost and installation and maintenance costs are reduced.
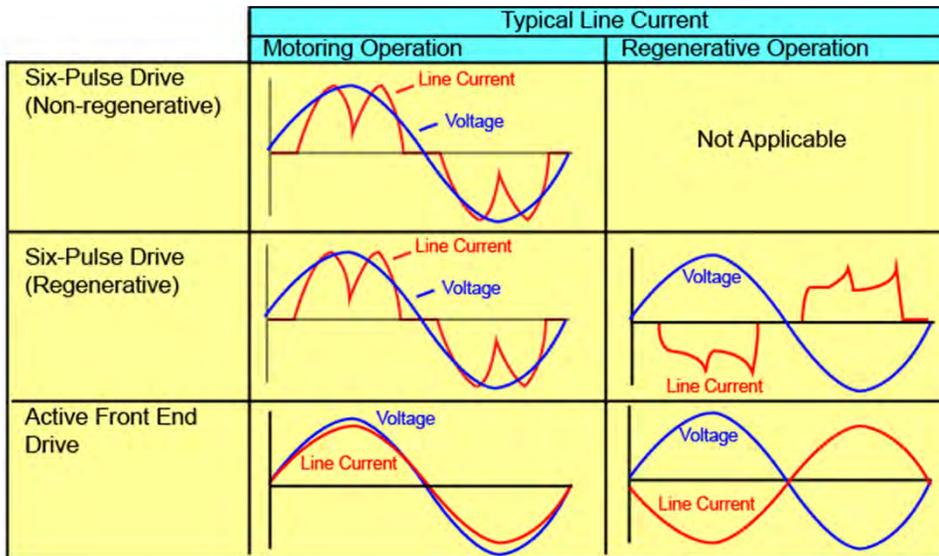
Because this approach simplifies close coordination of multiple motors as required for many applications, system performance is improved.

As previously discussed, a common DC bus drive system has multiple sections which provide power to a common DC bus. The converter section can be regenerative or non-regenerative.

The accompanying graphic shows one converter supplying four inverters, each powering its own motor. In this example, the converter and inverters are capable of regenerative operation. When any motor is functioning as a generator, it returns energy to the DC bus through its inverter. This reduces the energy needed from the AC supply. If the energy provided from one or more motors during regeneration is more than sufficient to power the remaining motors, the unused energy is returned through the converter to the AC supply.

The accompanying graphic also lists potential advantages of this type of configuration.

Active Front End (Active Infeed) Converter

Typical Line Current		
	Motoring Operation	Regenerative Operation
Six-Pulse Drive (Non-regenerative)	Line Current / Voltage	Not Applicable
Six-Pulse Drive (Regenerative)	Line Current / Voltage	Voltage / Line Current
Active Front End Drive	Voltage / Line Current	Voltage / Line Current

Active Front End (AFE)

Active Interface Module (AIM) — Clean Power Filter

Active Line Module (ALM)

AC Source — DC Link

Another converter design uses an active front end, sometimes called active infeed. This design also returns power to the supply during regeneration and uses both diodes and IGBTs in the active line module that includes the DC link. However, the active front end design also has an active filter, called an active interface module, on the supply side of the active line module.

The active interface module significantly reduces harmonic distortion during both motor and generation operation. For this reason, active front end converters are used for regenerative applications where it is necessary to meet clean power specifications, such as IEEE standard 519 requirements for low harmonic distortion.
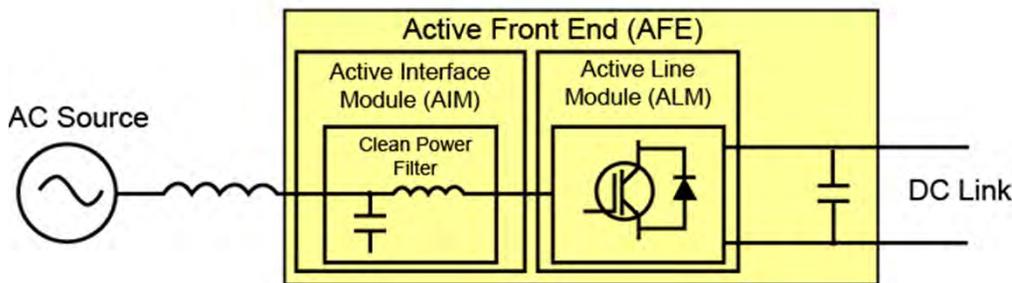
Active Front End designs are available for both single axis and multi-axis operation. For the multi-axis design, the Active Front End Converter will regenerate energy to the line side when the regenerative energy from the motors exceeds the energy required by the motoring loads.

Control Modes

Volts per Hz (V/Hz) Control Method

Field-oriented Control Method
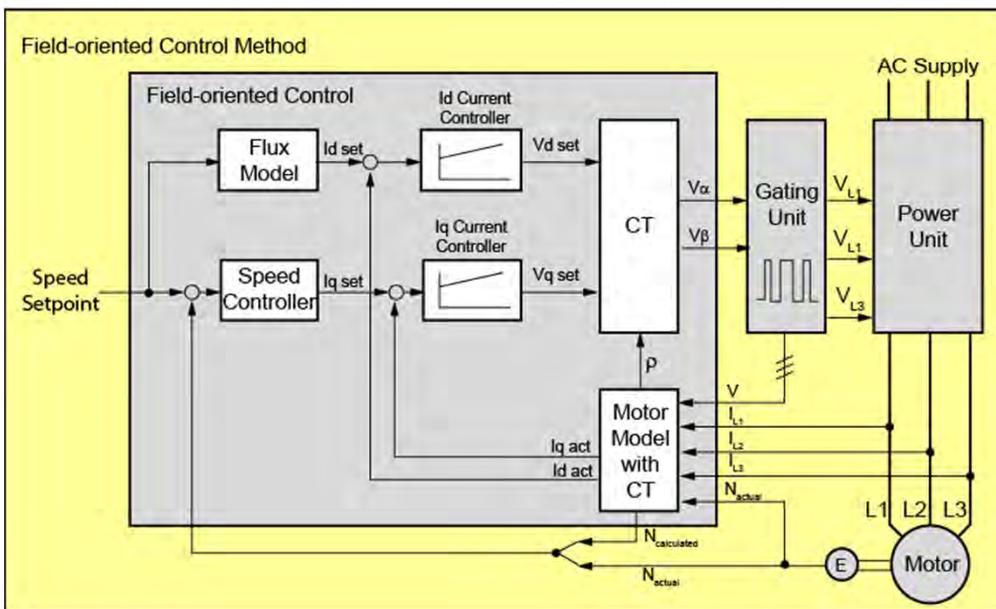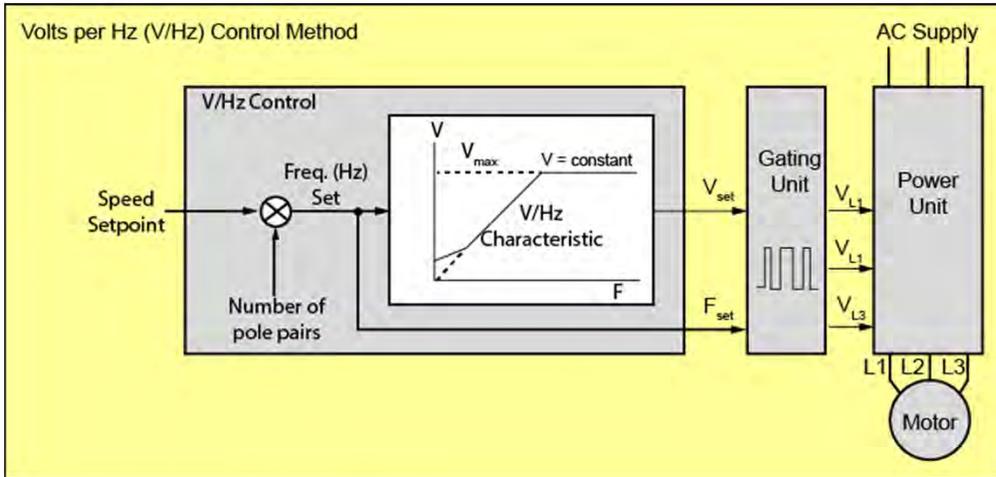
As previously discussed, pulse width modulation (PWM) provides variable voltage and frequency for control of a motor. However, there are various control modes that can be used to determine the PWM output. The following control modes are commonly used.

- V/Hz control
- Vector control without a sensor, also called sensorless vector control.
- Vector Control with a sensor, also called closed-loop vector control.
- Torque control without a sensor
- Torque control with a sensor

The control mode selected determines how the IGBTs are operated to produce the PWM output and affects the ability of a drive to control motor speed, especially at low speeds.
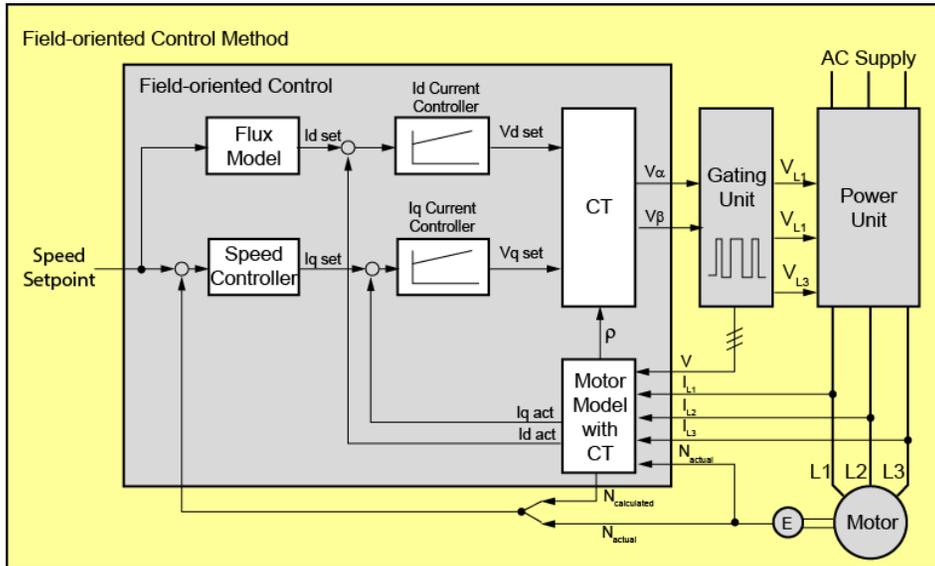
Control Modes - Volts/Hertz Control
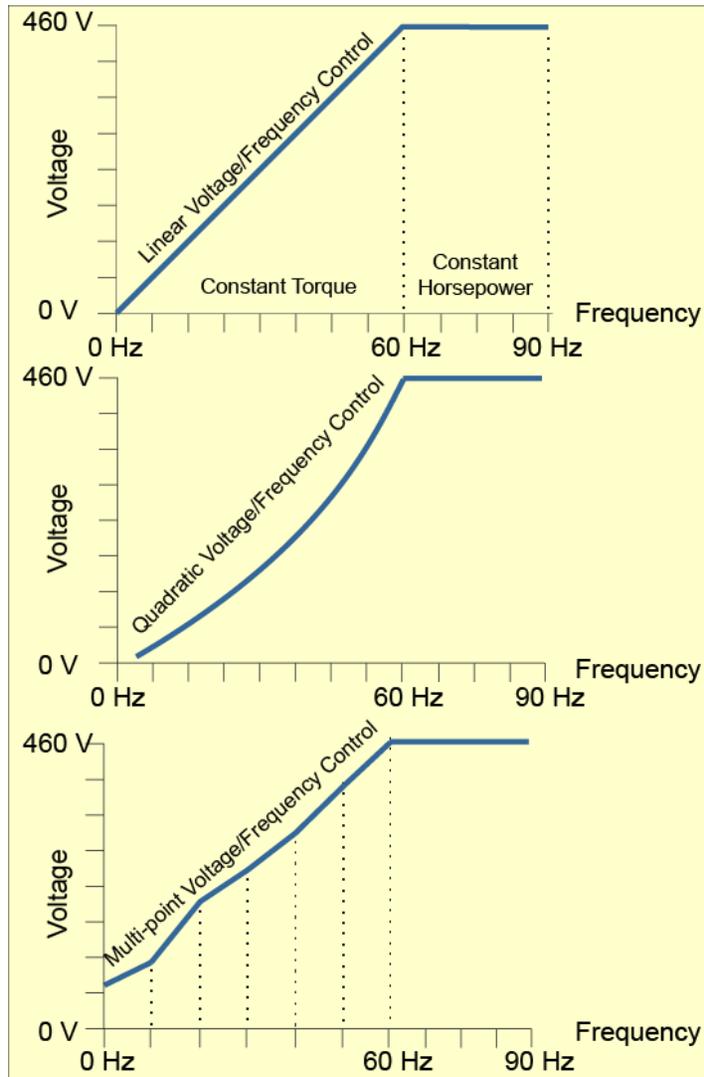
Linear voltage/frequency control is the simplest type of control. Using a 460 VAC, 60 Hz motor as an example, motor speed is controlled by varying the amplitude and frequency of voltage applied to the motor while maintaining a constant voltage/frequency ratio from 0 and 60 Hz. This type of control is suitable for a wide range of applications, but it is not the best choice for applications requiring good torque control at low speeds, more precise speed regulation, or high dynamic performance.

Quadratic, or parabolic, voltage/frequency control is a mode of operation with a voltage/frequency characteristic that matches the torque requirements of simple fan and pump applications. For such applications, the starting torque is low and a relatively low voltage can be applied at low frequencies, but the load increases in a non-linear fashion requiring a corresponding increase in the voltage/frequency ratio.

When even more customization of the voltage/frequency characteristic is required, some drives provide the capability for multi-point voltage/frequency control. Multi-point, or programmable, voltage/frequency control allows for multiple programmable variations from the linear V/Hz characteristic to compensate for specific motor and machine torque characteristic variations

Control Modes - Vector Control

Field-oriented Control Method

Vector control is used when an application demands highly accurate speed control, maximum dynamic response, or speed regulation that is load-independent. There are two types of vector control: closed-loop vector control, often referred to simply as vector control (VC), and sensorless vector control (SLVC). Both utilize a motor model in the drive for estimating and regulating the motor's magnetizing current (I_d) and working current (I_q).

Closed-loop vector control requires a speed sensor, typically a pulse encoder, to provide speed feedback and produces the best speed regulation at all speeds. This method can provide full torque control even at zero speed.

Control quality depends on the quality of the motor model, which is based on precise knowledge of a motor's rotating magnetic field.

- The motor model must be precisely tuned to the connected motor.
- Tuning is part of the commissioning process.
- Motor nameplate data is entered as first part of commissioning.
- The converter measures motor characteristics at stand still and during motor rotation.

Sensorless vector control uses internal computer algorithms based upon a mathematical motor model to provide excellent speed regulation and dynamic performance. As the name implies, sensorless vector control achieves this performance without motor speed feedback from an encoder or other speed sensor. When motor speed is calculated at very low speeds, based on a small counter electromotive force (CEMF) and known corrections for stator resistance, slight variations in stator resistance and other parameters have an effect on the speed calculation. This makes sensorless vector control less effective below a few hertz than closed-loop vector control.

Simulators

Engineered to provide a real-world experience, Siemens simulators are fully functional, ready-to-use systems available in a variety of configurations.

System-level design makes the simulators an invaluable tool for program testing and debugging, reinforcing learning, shop floor troubleshooting, and more. With portable construction and hard-shell cases, they can be easily transported. Custom-built systems are also available.
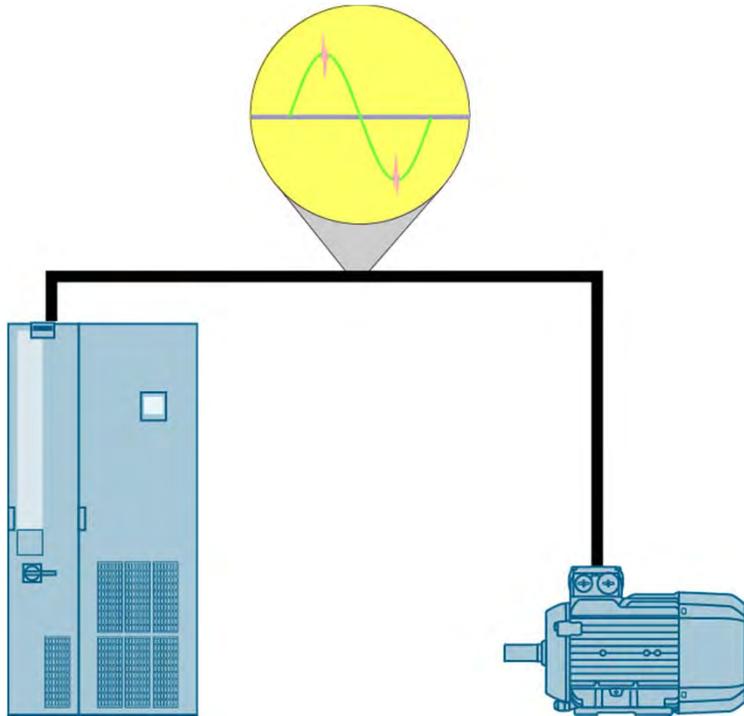
For additional information: www.usa.siemens.com/sitrain

Chapter 4 – AC Drive Applications
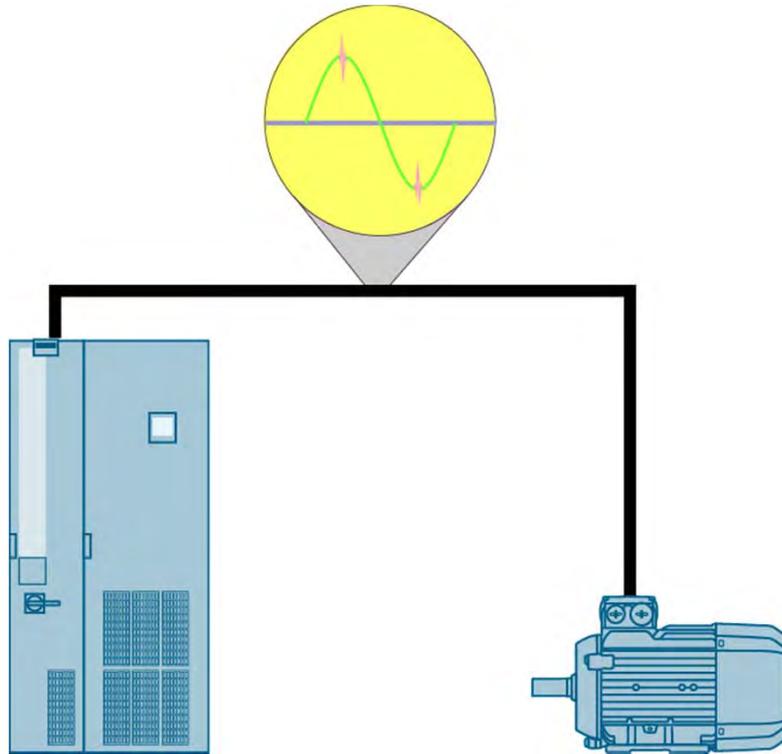
This chapter covers the following topics:

- **Application Considerations**

- Application Types

# AC Motor and Drive Application Considerations

An AC drive may have more capability than its motor. Drives can run at higher frequencies than may be suitable for a motor and can run at speeds too low for self-cooled motors to develop sufficient air flow. Therefore, It is important to carefully match the motor and drive to the application.

Harmonics, voltage spikes, and voltage rise times of AC drives are not identical. Some AC drives have more sophisticated filters and other components designed to minimize undesirable heating and insulation damage to the motor. This must be considered when selecting an AC drive/motor combination.

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, such as shielded cables or cables in metal conduit, have greater capacitance. Spikes occur on the output of AC drives because of the charging current in the cable capacitance. Higher voltage (460 VAC) and higher capacitance (longer cables) result in higher current spikes. Voltage spikes caused by long cable lengths can potentially shorten the life of the AC drive and motor.

A high efficiency motor with a 1.15 service factor is recommended when used with an AC drive. However, the service factor must be reduced to 1.0 because of the additional heat created by the harmonics produced by the drive.

Overload Ratings

Low Overload Example

High Overload Example
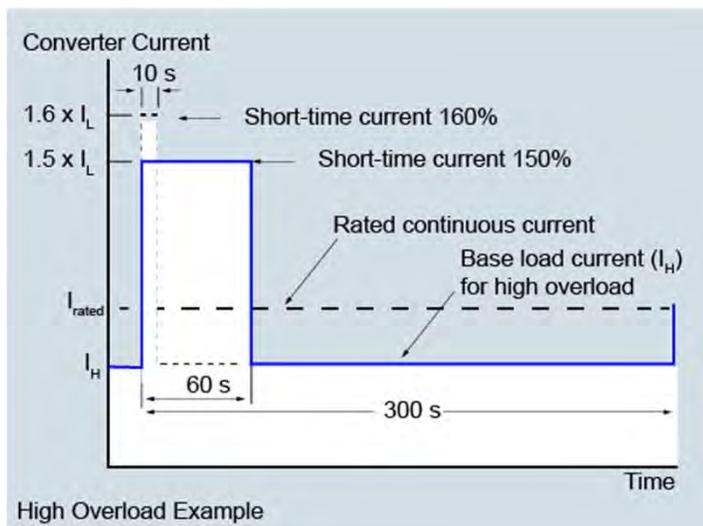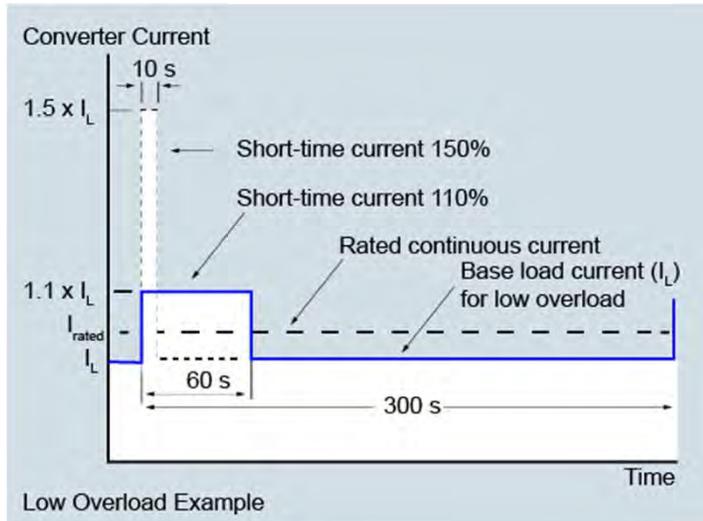
Many applications require an AC drive to handle short-time overloads that occur when the load torque required is greater than the continuous torque rating for the drive. Examples of the situations in which a short-time overload can occur include:

- To overcome breakaway torque during starting
- To accelerate the load
- To handle shock loads and other rapid changes in a process
- To ramp speed down rapidly in emergency stop situations

For AC drives to have the ability to handle short-time overloads, they must not reach the limit of their thermal capacity during normal operation.

Overloads are typically specified for variable torque, constant torque, and high performance applications.

As shown in the accompanying examples, overload ratings for AC drives typically specify the overload percentage and duration for both low overloads and high overloads.

Derating Considerations

|	
High Altitude	• At high altitudes, the air density is lower • Low density air provides less insulation, so the voltage derating is required. • Low density air does not conduct heat as effectively, so current derating is required.
High Ambient Temperature	• At higher ambient temperatures, components do not cool as effectively, so current derating is required.
High Pulse Frequency	• At higher pulse frequencies, inverter switching components generate more heat, so current derating is required

AC drives have published standard ratings based upon specific environmental conditions (temperature, airflow, humidity, altitude, etc.) and operating conditions (base carrier frequency, overload considerations, etc.)

When the drives are required to operate outside of the standard values, it is often necessary to derate the output of the drive. The accompanying graphic identifies some of the conditions that can require derating. Additionally, there are published specification boundaries that cannot be exceeded.

Additional Application Considerations

- **Motor Specifications** – Motors used with AC drives should comply with NEMA MG1 Part 31 inverter duty or have equivalent capabilities.

- **Motor Lead Length** – The drive manufacturer's published data concerning the allowable distance between drive and motor should be consistently observed.

- **Overload considerations** – Overload profiles that go beyond the standard high and low overload ratings must be evaluated in the drive selection process.

- **Harmonics to the Line** – All six-pulse drives generate harmonics to the line. The harmonic distortion level can be 25 to 50%. Standards such as IEEE 519 and end-user specifications often limit the value to less than 5%. It is important to understand and address this requirement.

- **Machine Safety Considerations** - All relevant safety requirements must be applied to limit the potential for injury or damage during normal operation and in the event of failure of a machine or component.

- **Arc Flash** – Arc flash safety must be addressed to ensure a safe working area.

- **Interface Capabilities** – How a drive interfaces with the plant communications system is an important consideration.

- **Support Capability** – The ability of a drive manufacturer to provide service and support is also a critical consideration.

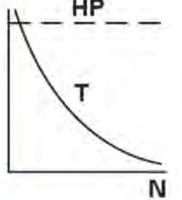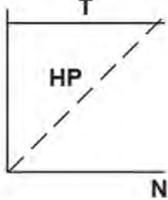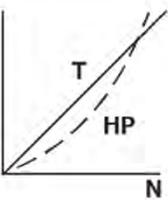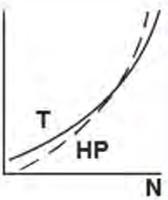# Totally Integrated Automation (TIA)
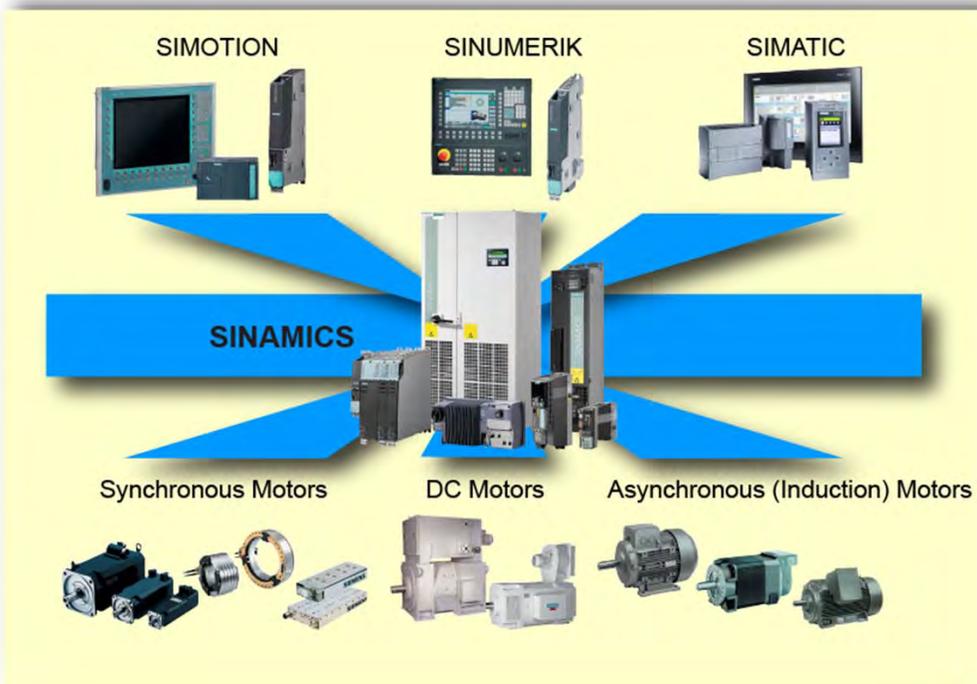
Totally Integrated Automation (TIA) is more than a concept. TIA is a design strategy developed by Siemens that emphasizes the seamless integration of automation, networking, drives, and control products.

The TIA strategy is the cornerstone of development for a wide variety of Siemens products. Siemens drive products are important elements of TIA.

TIA is important not just because it simplifies the engineering, startup, and maintenance of systems that utilize Siemens products, but also because it lowers the life-cycle costs for these systems.

Additionally, by reducing the time needed for the engineering and startup of systems, TIA helps Siemens customers reduce time to market and improve overall financial performance.
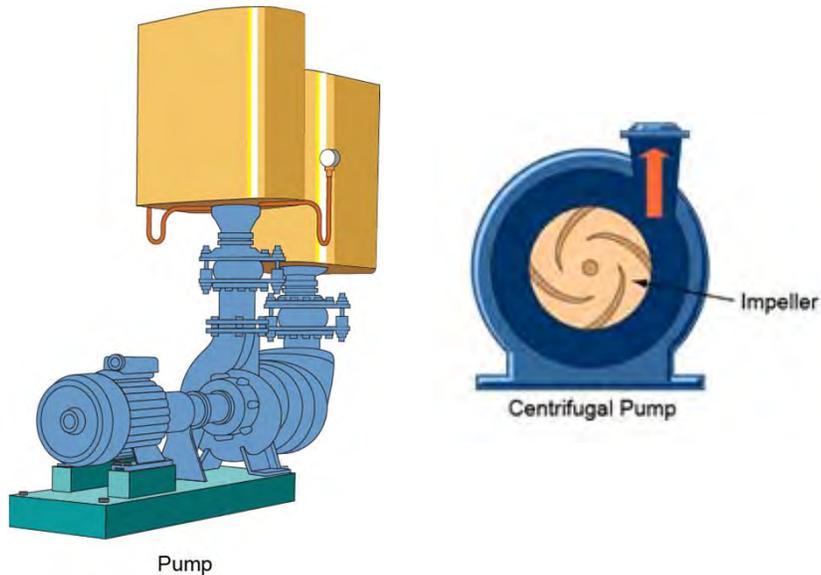
SIEMENS

Constant HP	Constant Torque	Variable Torque	
$T \approx \dfrac{1}{N}$	$T = \text{Constant}$	$T \approx N$	$T \approx N^2$
HP = Constant	$HP \approx N$	$HP \approx N^2$	$HP \approx N^3$

This chapter covers the following topics:

- Application Considerations

- **Application Types**

Variable Torque Applications

Pump

Centrifugal Pump
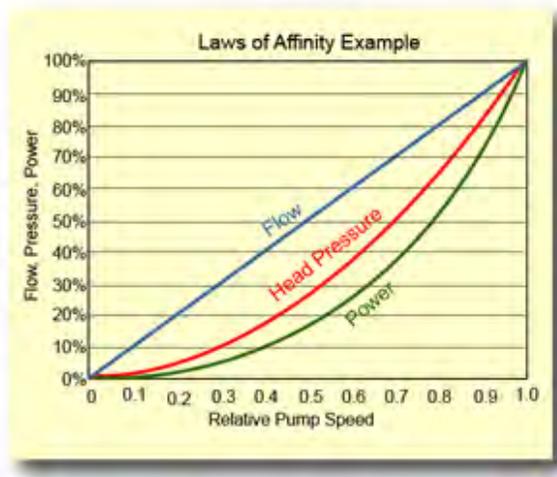
Impeller

Laws of Affinity Example

Variable torque loads are loads that require an increase in torque as speed increases. For these loads, horsepower also increases with speed. Fans and pumps are examples of variable torque loads.
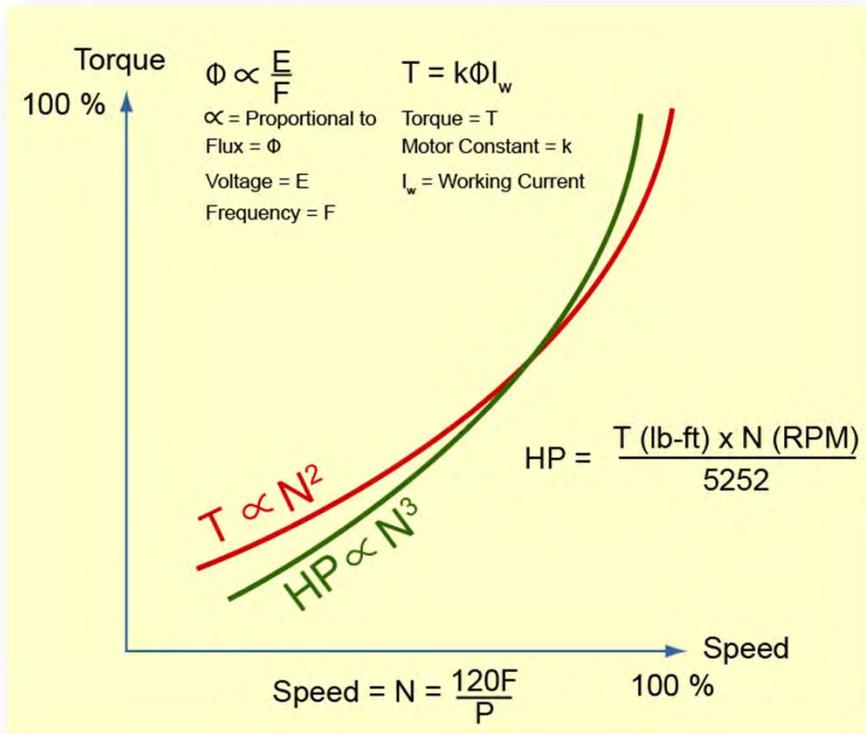
One type of pump is a centrifugal pump. Within a centrifugal pump, an impeller is rotated by a motor attached to the pump. The rotating impeller develops pressure (referred to as head) to move the fluid being pumped.

According to what are referred to in hydraulics as the laws of affinity, for a given impeller diameter, the flow is proportional to the shaft speed, the head is proportional to the square of the shaft speed, and the power applied is proportional to the cube of the shaft speed.

These laws of affinity show how energy can be saved by operating centrifugal pumps and fans at optimum efficiency.

Torque

$$\Phi \propto \frac{E}{F} \qquad T = k\Phi I_w$$

$\propto$ = Proportional to   Torque = T
Flux = Φ Motor Constant = k
Voltage = E I_w = Working Current
Frequency = F

$T \propto N^2$

$HP \propto N^3$

$$HP = \frac{T \text{ (lb-ft)} \times N \text{ (RPM)}}{5252}$$

$$\text{Speed} = N = \frac{120F}{P}$$

Speed

For a centrifugal pump, as with a constant torque application, the speed of the motor increases with frequency. However, as described by the laws of affinity, the required torque is proportional to the square of the speed, and the required horsepower is proportional to the cube of the speed. The reduction in horsepower results in energy savings. This explains why the quadratic voltage/frequency response discussed earlier in this course is ideal for this type of application.

The accompanying graphic shows the typical torque and horsepower required for a centrifugal pump application. The speed of the pump is limited to the speed that the motor can provide at rated frequency. This is because the drive cannot increase voltage above the rated value. Therefore, the motor cannot supply the torque required to exceed the rated speed.

Fan applications are also variable torque applications. Increasing the speed of the fan increases air flow and pressure, requiring the motor to work harder. This requires a non-linear increase in working current because the required torque increases with the square of the current.

Constant Torque Applications
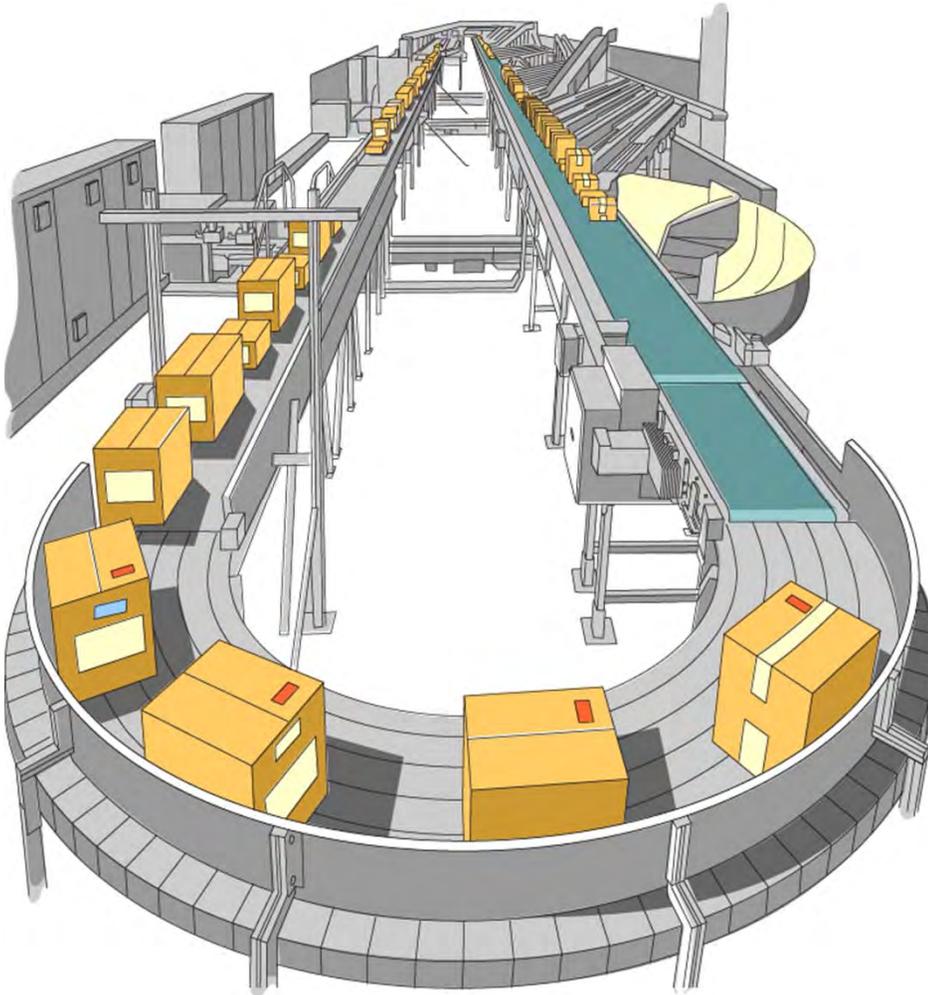
The term constant torque implies that the torque required to keep the load running is the same throughout the speed range; however, this is not exactly correct.

In this context, constant torque refers to the motor's ability to maintain constant flux. The actual torque produced does vary with the load and peak torques in excess of the rated continuous torque can occur at any speed.

One example of a constant torque load is a conveyor. Conveyors are found in all sorts of applications and environments and vary widely in terms of their capabilities.

Constant Torque Conveyor Applications
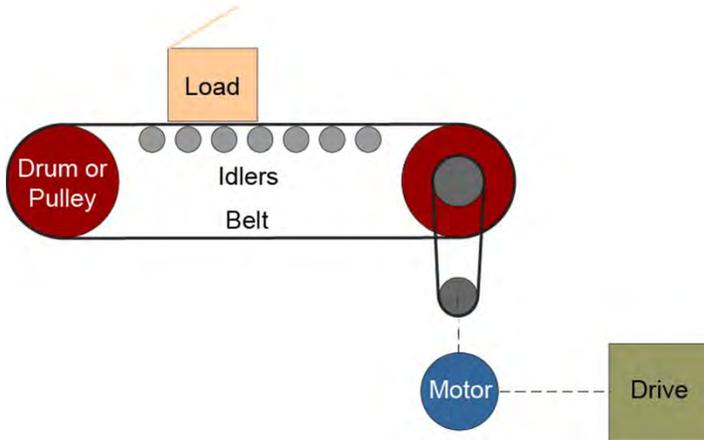
Many conveyors are made up of belts, which support the load; drums or pulleys, which support the belts and maintain tension; and idlers, which support the belts and loads.

Keep in mind that many conveyors can have multiple sections and some sections may need to run at different speeds than others. For these applications, multiple AC drive-motor combinations are used with the drives networked for coordination.

The speed of the conveyor can be increased by increasing the frequency applied to the motor. Torque, however, is dependent on flux and working current. Because flux is inversely proportional to frequency, both flux and torque decrease as frequency increases, unless voltage is also increased.
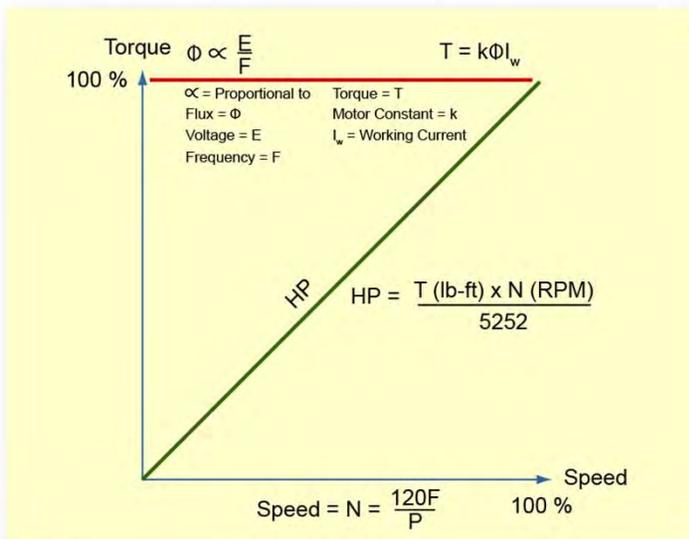
An AC drive can maintain constant flux up to base speed by maintaining a constant voltage/frequency ratio. During acceleration, however, working current increases causing a temporary increase in torque. Once the new speed is reached, both working current and torque settle back to nominal running values.
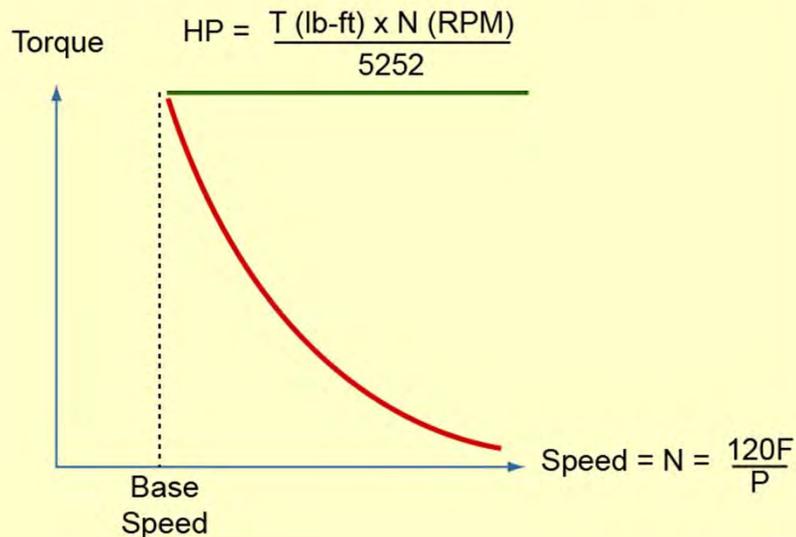
Keep in mind that the motor can only provide constant torque up to rated frequency. If the frequency applied to the motor is increased above the rated value, the voltage/frequency ratio and torque decrease.

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Constant Horsepower Applications
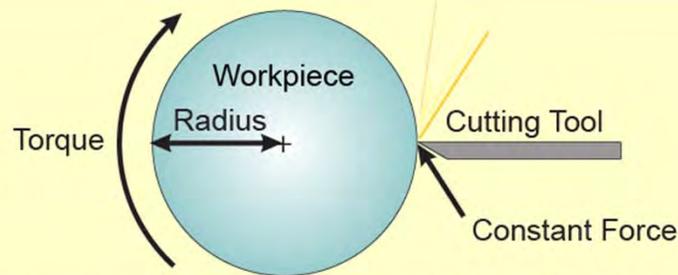
Surface Speed = 2π x Workpiece Radius x Rotational Speed

Torque Required by Load = Force x Workpiece Radius

$$HP = \frac{T \text{ (lb-ft)} \times N \text{ (RPM)}}{5252}$$
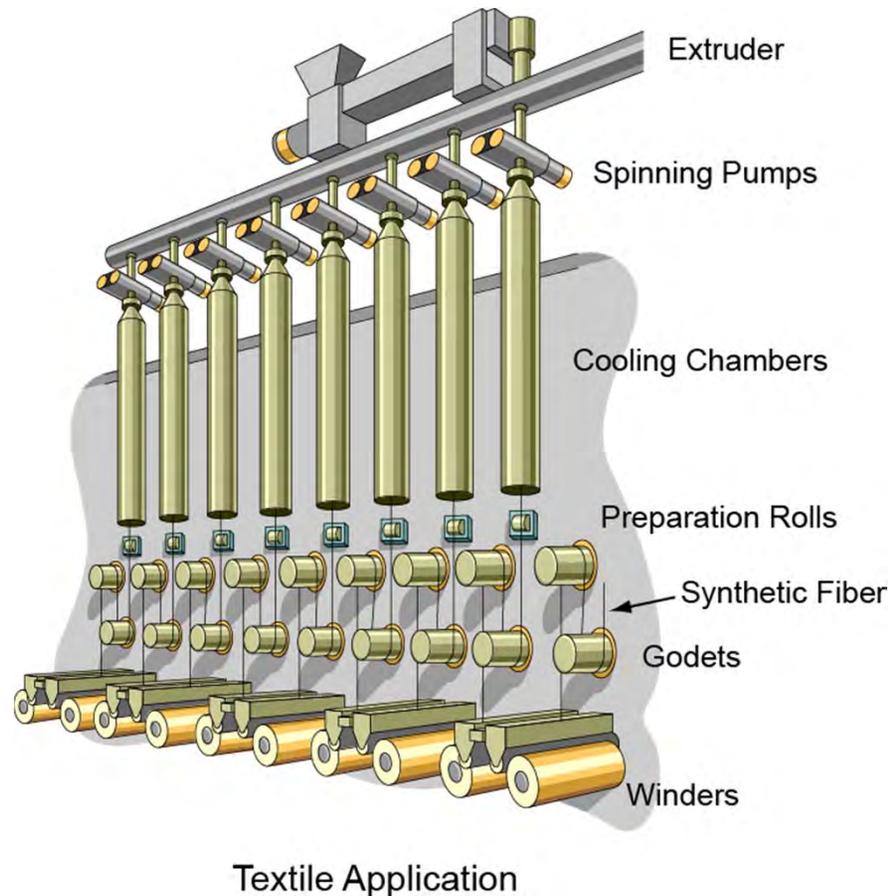
$$Speed = N = \frac{120F}{P}$$

Constant horsepower applications require a constant force as the radius changes. One example is a winder application. For such an application, the radius increases as material is added to a roll. Similarly, in an unwinding application, the radius decreases as material is removed. In either case, the tension on the material must be controlled.

Another constant horsepower application is a lathe spindle. The rotating motion of the workpiece being machined on a lathe is controlled by a spindle drive. The spindle drive must maintain a constant surface speed as material is removed from the workpiece. This requires the motor speed to increase as the radius of the workpiece is reduced. In addition, as the radius of the workpiece decreases, because torque is the product of the force applied times the radius, the torque required by the load also decreases.

As a result of this inverse relationship between the load torque required and the motor speed, the motor can be operated above base speed. Because horsepower is proportional to the product of torque times speed, the range above base speed is referred to as the constant horsepower range.

Complex Applications

Textile Application

Labels: Extruder, Spinning Pumps, Cooling Chambers, Preparation Rolls, Synthetic Fiber, Godets, Winders

In addition to the basic applications discussed in this course, there are many complex applications. Most of these complex applications incorporate multiple motors and drives. In many cases, these applications require a coordination of control to ensure that the proper speed and tension is maintained in all phases of the application.

For example, the accompanying graphic shows a portion of a spinning machine for producing synthetic fibers. In such an application, various motors run the extruder, spinning pumps, preparation rolls, godets, traversing devices, and winders. In order for this operation to function properly, the operation of multiple drives must be coordinated.

There are many other examples of applications that offer similar or even greater complexity. In order to determine the appropriate drives for use in such an application a number of factors must be considered. In addition to the basic application engineering issues, factors such as commonality of design, reliability, technical support, and employee training must be considered.

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