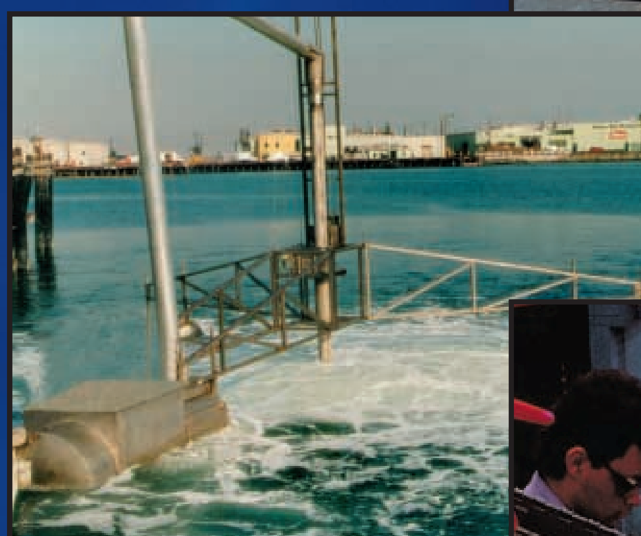
AF DRIVES

ADJUSTABLE FREQUENCY DRIVES

APPLICATION GUIDE



Cutler-Hammer

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Introduction

About This Guide

The following material is intended to acquaint the user with the theory and operation of adjustable frequency drives. This material will enable the user to better select a drive and take into consideration the parameters necessary to properly apply a drive to a given load.

The reference material provided is for the convenience of the user. It is excerpted from handbooks and standards such as NEMA, IEEE and others. It is intended as reference material for standard applications and may not cover all actual and special applications. Specific ratings and external signals used for speed control and/or logic are the customer's responsibility.

The user must determine the final suitability and acceptability for drives used on specific equipment. Contact your Cutler-Hammer sales office or distributor for additional application assistance.

Basic Motor and Adjustable Frequency Drive Theory

Introduction

This section of your *Application Guide* discusses the following topics on basic motor and adjustable speed drive theory:

- AC Motors
  - Induction Motors
  - Synchronous Motors
  - Enclosures
- Control of AC Motors
  - Adjustable Speed with AC Motors
  - AC Drive Characteristics
  - AC Drive Systems
- Benefits of Using Electric Adjustable Speed Drives
- Typical Applications of Adjustable Speed Drives

An adjustable frequency drive is a product that controls the speed, torque, horsepower and direction of an AC motor. Cutler-Hammer manufactures a complete line of adjustable frequency drives.

These drives serve commercial applications such as HVAC, and applications such as fans, pumps, conveyors, material handling and processing equipment as well as in general industries such as forest products, mining, metals and printing.

The following information provides the basics required to evaluate adjustable frequency drive application needs.

AC Motors

Cutler-Hammer adjustable frequency drives operate with standard AC motors. In some cases the existing motor or motors normally sized for a given fixed speed application can be directly applied to a drive. The user must understand the nature of the application in terms of the speed range, load characteristics and drive requirements as they relate to the AC drive system. This allows proper sizing of the motor and controller.

AC MOTOR TYPES

AC motors can be divided into two main types: Induction and Synchronous.

Induction Motors

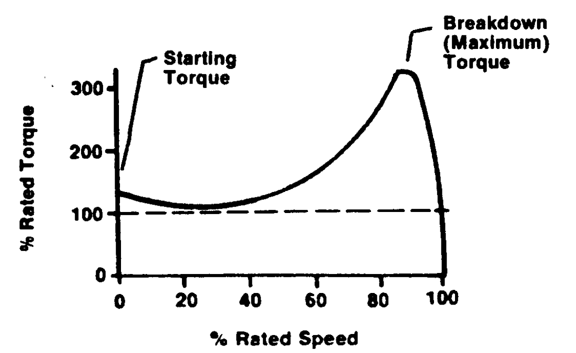
The induction motor is the simplest and most rugged of all electric motors. The three most popular types of AC induction motors are polyphase, wound rotor and single-phase.

Polyphase

The polyphase motor is divided into five classifications according to NEMA. The classification, or design, is determined by the locked rotor torque and current, breakdown torque, pull-up torque and the percent slip. The speed-torque curve and characteristics of each design are given below. These characteristics apply on operation from fixed frequency and voltage as normally supplied from commercial utility power sources at 60 Hz.

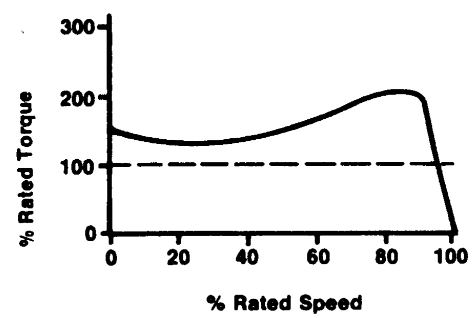
- **Design A** motors have a slightly higher breakdown and lower starting torque than Design B motors. The slip is usually 3 to 5% or less. The major difference between the Design A and Design B motor is that the starting current is limited on the Design B, but not on the Design A.

Design A Polyphase Motor **Figure 1**



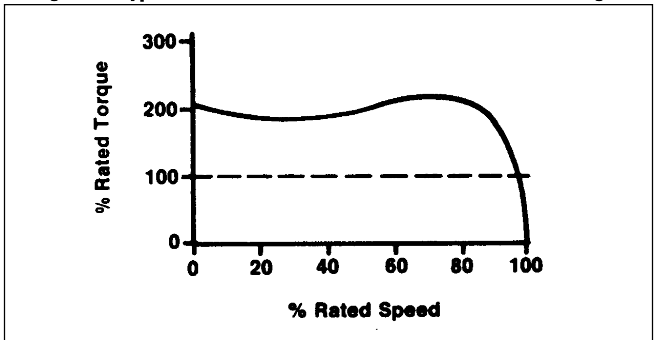
- **Design B** motors are a general purpose type motor and account for the largest share of induction motors sold. The slip of a Design B motor is approximately 3 to 5% or less.

Design B Polyphase Motor **Figure 2**



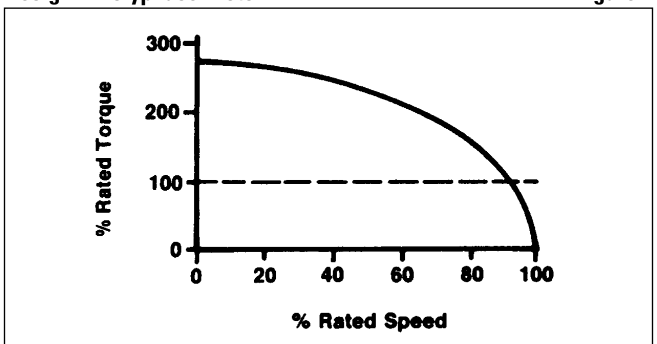
- **Design C** motors have a high starting torque with a normal starting current and low slip. The Design C motor is usually used where breakaway loads are high at starting, but are normally run at rated full load, and are not subject to high overload demands after running speed has been reached. The slip of the Design C motor is 5% or less. Design C motors should not be applied to adjustable frequency drives because of their high rotor loss.

Design C Polyphase Motor **Figure 3**



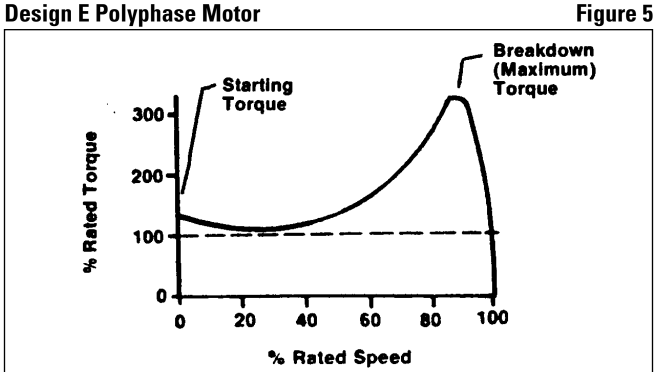
- **Design D** motors have high slip, high starting torque, low starting current and low full load speed. Because of the high amount of slip, the speed will vary if fluctuating loads are encountered. The slip of this type of motor is approximately 5 to 13%.

Design D Polyphase Motor **Figure 4**



- **Design E** motors are designed to be high efficiency motors. They have a very low slip and very high starting current.

Design E Polyphase Motor **Figure 5**



Wound Rotor Motors

The wound rotor motor allows controllable speed and torque compared to the conventional induction motor. Wound rotor motors are generally started with a secondary resistance in the rotor. As the resistance is reduced, the motor will come up to speed. The motor can then develop substantial torque while limiting the locked rotor current. The secondary resistance can be designed for continuous service to dissipate the heat produced by continuous operation at reduced speed and frequent start/stops or acceleration of a large inertia load. This external resistance gives the motor a characteristic that results in a large drop in rpm for a small change in load. Reduced speed typically can be provided down to approximately 50% of rated speed with low efficiency.

When a wound rotor motor has a large secondary resistance, it is not suitable for adjustable frequency drive use. The large resistance results in substantial power losses. These motors are sometimes used in slip recovery systems. The slip recovery unit converts the rotor energy and passes it back onto the utility line, while providing speed control similar to that of the secondary resistor control. This approach significantly reduces the motor inefficiency.

If the motor can be operated with a shorted secondary or with a minimum resistor value, it probably can be operated from an adjustable frequency drive. The issue then becomes one of determining why the wound rotor was selected initially to assure that the application does not require its special operating characteristics.

Single-Phase Motors

Single-phase motors are most commonly found in the fractional horsepower range with some integral sizes available. The most common single-phase motors are listed below:

- **Shaded-Pole** motors have a low starting torque and are available only in fractional horsepower sizes. The slip of a shaded-pole motor is 10% or more at rated load.
- **Split-Phase** motors have low or moderate starting torque and are limited in size to about 1/3 horsepower.
- **Capacitor-Start** motors produce greater locked rotor and accelerating torque than the split-phase motor and are available in sizes ranging from fractional to 10 horsepower.
- **Split-Capacitor** motors are similar to the capacitor-start motor, but produce a higher power factor ratio.

In general, single-phase motors are not suited for adjustable frequency drive use. This is due to the starting technique, limiting operation to only 60 Hz.

Synchronous Motors

Synchronous motors operate at synchronism with line frequency and are inherently constant speed motors without sophisticated electronic control. The two most common types of synchronous motors are self-excited and DC-excited.

Self-Excited Motors

These motors use a self-starting circuit and require no external excitation. Reluctance, hysteresis and permanent magnet designs are the three main types of self-excited motors available:

- **Reluctance** designs have horsepower ratings that range from fractional to about 30 hp. The fractional motors have low torque while the integral motors have moderate torque.
- **Hysteresis** designs have only fractional horsepower ratings and are primarily used as timing and servo motors. Hysteresis motors are more costly than the reluctance type and are used when precise constant speed is a requirement.
- **Permanent-Magnet** motors are becoming increasingly popular in the fractional and lower integral horsepower ranges of 1/4 to 5 hp. The permanent-magnet motor has relatively high efficiency and power factor.

  Reluctance and permanent-magnet motors are used on special adjustable frequency drive systems, typically in multi-motor applications requiring exact speed matching between drives.

DC-Excited Motors

These motors require direct current supplied through slip rings for excitation. Because DC-excited motors have inherent low starting torque and require a DC power source, a starting system providing full motor protection is needed. The starting system must apply the DC field excitation at the proper time, remove field excitation at rotor pull-out, and protect the windings against thermal damage under out-of-step conditions. These motors are generally large horsepower and are not typically used for adjustable frequency drive operation.

Enclosures

The basic protective enclosures for AC motors are: open dripproof (ODP), totally enclosed fan cooled (TEFC), totally enclosed non-ventilated (TENV) and totally enclosed air over (TEAO). Other special enclosures available include: pipe-ventilated, weather protected, water cooled and explosion-proof.

Ventilation

The system for ventilating motors depends on the type of motor enclosure mentioned previously and is described as follows:

- **ODP (Open Dripproof)** — The ODP motor is ventilated (cooled) by means of a shaft mounted internal fan which drives air through the open ends of the motor and discharges it out the sides. These motors are often supplied as protected, fully-guarded or splash-proof.
- **TEFC (Totally Enclosed Fan Cooled)** — This type of motor is cooled by air passing over the outer frame of the motor. The air is supplied by a shaft mounted fan opposite the shaft end of motor.
- **TENV (Totally Enclosed Non-Ventilated)** — This type of motor has a shaft mounted internal fan used to circulate air within the motor to prevent hot spots. No external fan or air is supplied. These are suitable for very dirty and contaminant laden environments that would clog most exposed cooling fans. These motors dissipate their heat through their frames and are thus oversized compared to other enclosure types. They are generally available only in smaller hp ratings (up to 7-1/2 hp).
- **TEAO (Totally Enclosed Air Over)** — This type of motor is cooled by externally provided air blowing over the frame. The air may be supplied by an integrally mounted blower and motor or from a separate source. This type of ventilation promotes constant cooling at all operating speeds of the motor and makes it very suitable for a wide range of adjustable speed drive operations.
- **Special Enclosures** — The Pipe-Ventilated motor is available in an open or totally enclosed type of enclosure and is used in very dirty environments. Ventilating air (supplied by the user) enters and exits the motor through inlet and outlet ducts or pipes. The air is circulated by means either integral or external to the motor.

  The Weather-Protected motor uses an open type enclosure for ventilation. The motor is constructed to minimize the entrance of rain, snow and airborne particles to the electrical parts of the motor. External air can be circulated through the motor for cooling.

  Totally Enclosed Air-to-Air and Totally Enclosed Water-to-Air cooled enclosures are normally used on high horsepower motors that generate large amounts of heat. A heat exchanger is used for both types to remove the heat generated by the motor. An AC motor driven blower circulates air through the windings and heat exchanger tubes. The heat in the heat exchanger is removed by either an external air system (air-to-air) or water provided by the user (water-to-air cooled).

  The Totally Enclosed Water Cooled motor is cooled by circulating water. Explosion proof motors are designed to operate in hazardous environments such as explosive vapors, coal or grain dust and other classified areas. These are selected by the appropriate Class, Group, and Division of hazard as defined by the National Electrical Code (NEC).

Control of AC Motors

The most common control of an AC motor is by using a motor starter. This device connects the motor to the commercial AC power line. It is rated to operate with the typical high starting (inrush) current that occurs when a motor is directly connected to the utility power source. A motor starter also contains a protective device known as a motor overload. This device is designed to protect the motor from continued overloads and stalling due to excessive machine loads on starting or jamming when operating.

With the above method of control, AC motors will operate as described by their NEMA characteristics for their design type on utility power. This includes a prescribed overload capability, regulation due to slip, starting inrush current and starting (locked rotor) torque. The load on the driven machine determines the acceleration time and motor load (or overload).

Special control hardware is available to modify some of the above characteristics. Part winding motor starters will reduce the inrush current on AC motors. Solid-state motor starters will control the acceleration time or current for certain types of loads. None of these special controllers will provide for adjustment of the operating speed of the AC motor.

Adjustable Speed with AC Motors

Adjustable speed can be obtained from AC motors in two ways. One method is to couple a speed changing device to the constant speed AC motor. The other is to change the speed of the AC motor by modifying its power input.

Common types of speed changing devices include: adjustable diameter pulley and belt apparatus, hydraulic couplings, mechanical speed changers and eddy-current clutches. In all of these types of systems, the motor operates at a constant speed.

Adjusting speed operation of an AC motor by controlling its power input requires the use of an adjustable frequency drive (AFD).

AC Drive Characteristics

AC adjustable frequency drives convert 3-phase, 50 or 60 Hz input power to an adjustable frequency and voltage source for controlling the speed of AC squirrel cage induction motors.

The frequency of the power applied to an AC motor determines the motor speed and is based on the following equation:

$$N = \frac{120f}{P}$$

Where: N = speed (rpm)
f = frequency (Hz)
P = number of poles

The number of poles is considered a constant since this design characteristic is already manufactured into the motor.

The AFD controls the frequency (f) and voltage applied to the motor. The speed (N) of the motor is then proportional to this applied frequency. The frequency is adjusted by means of a keypad, a potentiometer or an external signal, depending on the application.

To maintain constant motor torque, the drive controller automatically maintains the voltage and frequency output at a constant relationship for any motor speed. This is called the Volts per Hertz ratio (V/Hz).

AC Drive System

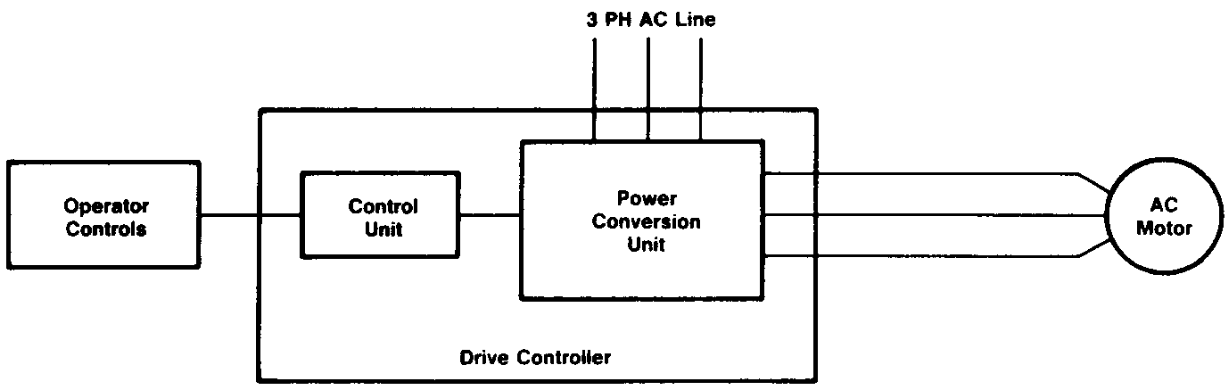
An AC adjustable frequency drive system typically consists of three basic parts: operator controls, drive controller (referred to as an AFD) and an AC motor. Figure 6 shows an AC drive system.

The **Operator Controls** allow the operator to start, stop and change direction and speed of the motor by simply pressing an input key, turning a potentiometer or adjusting another operator device. These controls may be an integral part of the controller or may be remotely mounted. Programmable controllers are often used for this function.

The **Drive Controller** converts fixed voltage AC to an AC adjustable frequency and voltage source. It consists of a control unit and a power conversion unit.

Basic Motor and Adjustable Frequency Drive Theory

AC Adjustable Frequency Drive System **Figure 6**



The **Control Unit** oversees the operation of the drive and provides valuable system diagnostic information. The **Power Conversion Unit** performs several functions. It rectifies the incoming fixed AC voltage (changes AC to DC). The resultant DC voltage is filtered by a low pass filter to obtain a DC voltage bus. The **Power Conversion** (inverter) **Unit** then produces an AC current and voltage output having the desired frequency.

Speed and load feedback may be provided to cause the motor to more closely match the desired speed (Figure 7). Additional circuits help protect the controller, motor and driven machine from line voltage transients, overloads and various circuit faults.

The AC motor converts the adjustable frequency AC from the drive controller to rotating mechanical energy.

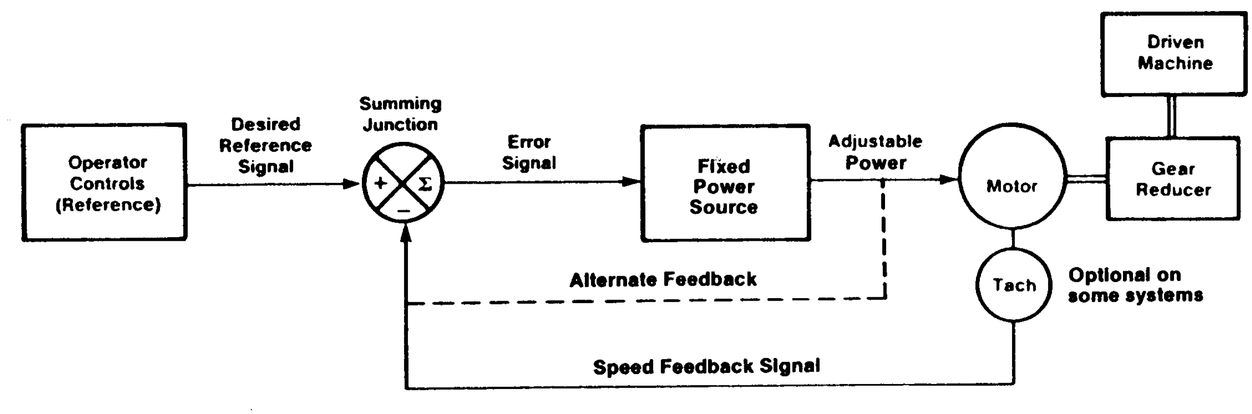
Benefits of Using Electric Adjustable Speed Drives:

- **Controlled starting** — Limited starting current, reduction of power line disturbance on starting, lower power demand on starting.
- **Controlled acceleration** — Soft start, adjustable acceleration based on time or load, reduced motor size for pure inertial load acceleration.
- **Adjustable operating speed** — Enables optimizing of process, change in process, energy savings, allows process start at reduced speed, allows remote adjustment of speed by programmable controller, process controller or computer.
- **Adjustable torque limiting** — Protects machinery from damage, protects process or product.
- **Controlled stopping** — Soft slow down, timed stopping, fast reversal with much less stress on AC motor than plug reverse.

Typical Applications of Adjustable Speed Drives:

- Conveyors, belts, chains, screws, bulk material, packaged material.
- Fans, blowers, compressors, pumps.
- Machine tools, grinders, lathes, stamping presses.
- Custom machinery, labelers, packaging machines, bottle washers, wire drawing, textiles, etc.
- Extruders.
- Process machinery, kilns, blenders, agitators. See the section on load types for particular evaluation of specific loads.

Drive Control System **Figure 7**



Basic Mechanics

Introduction

This section of your *Application Guide* discusses the following topics on basic principles of mechanics:

- Torque
- Calculation of Horsepower
- Inertia
- Speed Reducer Selection
- Gear Reducer Selection
- Other Gear Issues

In order to apply electrical drives properly, certain mechanical parameters must be taken into consideration. This section explains what these parameters are and how to calculate or measure them.

Torque

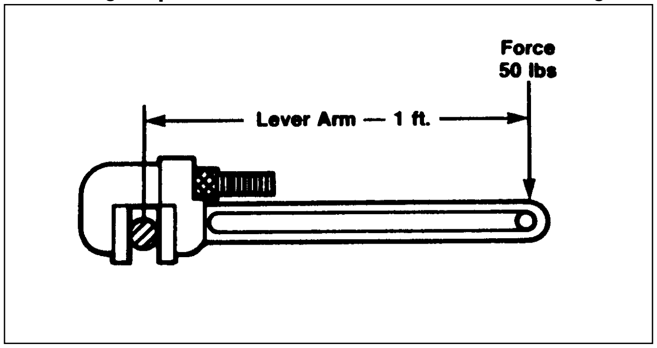
Torque is the action of a force producing or tending to produce rotation. Unlike work (which only occurs during movement) torque may exist even though no movement or rotation occurs.

Torque consists of a force (lb) acting upon a length of a lever arm (ft). The product of these two factors produces the term lb-ft, which is the unit of measurement for torque (see Figure 8). Mathematically, it is expressed as:

Torque (lb-ft) = Force (lbs) x Distance (ft).

Example:
Torque = Force x Distance
Torque = 50 lbs x 1 ft
Torque = 50 lb-ft

Calculating Torque **Figure 8**



Because most power transmission is based upon rotating elements, torque is important as a measurement of the effort required to produce work.

Calculating Torque (Acceleration Torque Required for Rotating Motion)

Some machines must be accelerated to a given speed in a certain period of time. The torque rating of the motor may have to be increased to accomplish this objective. The following equation may be used to calculate the average torque required to accelerate a known inertia (WK^2). This torque must be added to all the other torque requirements of the driven machine when determining the motor's required peak torque output and the AFD rating.

$$T = \frac{(WK^2)(dN)}{308t}$$

Where:
T = Acceleration Torque (lb-ft)

WK^2 = Total system inertia (lb-ft^2) that the motor must accelerate. This value includes motor rotor, speed reducer and load.

dN = Change in speed required (rpm)

t = Time to accelerate total system load (seconds)

Note – The number substituted for (WK^2) in this equation must be in units of lb-ft^2.

The same formula can also be rearranged to determine the minimum acceleration time of a given drive system, or if a drive system can accomplish the desired change in speed within the required time period.

Rearranged Equation:

$$t = \frac{(WK)^2(dN)}{308T}$$

Most drives have either a 110% or 150% load capability for 1 minute. Therefore, additional acceleration torque will be available without increasing the drive horsepower rating.

General Rules (for drives with 150% current limit)

If the running torque is equal to or less than the accelerating torque divided by 1.5, use the accelerating torque divided by 1.5 as the full load torque required to determine the motor horsepower.

If the running torque is greater than the accelerating torque divided by 1.5, use the running torque as the full load rated torque required to determine the motor horsepower.

Calculating Horsepower

Note – The following equations for calculating horsepower are meant to be used for estimating purposes only. These equations do not include any allowance for machine friction, windage or other factors. These factors must be considered when selecting a drive for a machine application.

Once the machine torque is determined, the required horsepower is calculated using the formula:

$$hp = \frac{TxN}{5250}$$

Where:
hp = Horsepower
T = Torque (lb-ft)
N = Speed of motor at rated load (rpm)

If the calculated horsepower falls between standard available motor ratings, select the higher available horsepower rating. It is good practice to allow some margin when selecting the motor horsepower.

For many applications, it is possible to calculate the horsepower required without actually measuring the torque. The following equations will be helpful:

Conveyors

$$hp(\text{Vertical}) = \frac{F(\text{lbs}) \times V(\text{fpm})}{33{,}000 \times \text{Efficiency}}$$

$$hp(\text{Horizontal}) = \frac{F(\text{lbs}) \times V(\text{fpm}) \times \text{Coef.}}{33{,}000 \times \text{Efficiency}}$$

Where:
F = force (weight) in lbs
V = Velocity in feet per minute
Coef. = Coefficient of friction

Fans and Blowers

$$hp = \frac{\text{cfm} \times \text{psi}}{33{,}000 \times \text{Efficiency of Fan}}$$

$$hp = \frac{\text{cfm} \times \text{Pressure (lb/ft}^2)}{229 \times \text{Efficiency of Fan}}$$

$$hp = \frac{\text{cfm} \times \text{Inches of Water Gauge}}{6356 \times \text{Efficiency of Fan}}$$

Pumps

$$hp = \frac{\text{gpm} \times \text{Head (ft)} \times \text{Specific Gravity}}{3960 \times \text{Efficiency of Pump}}$$

Where:
psi = pounds per square inch
cfm = cubic feet per minute
gpm = gallons per minute

Specific gravity of water = 1.0

1 cubic foot per second = 448 gpm

1 psi = a head of 2.309 ft for water weighing 62.36 lbs per cu. foot at 62°F.

Efficiency of fan or pump = % efficiency/100

Displacement pump efficiency:
Displacement pumps vary between 85 and 90% efficiency depending on size of pumps.

Centrifugal pump efficiency (at design point):
500 to 1000 gal. per min. = 70 to 75%
1000 to 1500 gal. per min. = 75 to 80%
Larger than 1500 gal. per min. = 80 to 85%

Inertia

Inertia is a measure of a body's resistance to changes in velocity, whether the body is at rest or moving at a constant velocity. The velocity can be either linear or rotational.

The moment of Inertia (WK^2) is the product of the weight (W) of an object and the square of the radius of gyration (K^2). The radius of gyration is a measure of how the mass of the object is distributed about the axis or rotation. Because of the distribution of mass, a small diameter cylindrical part has a much lower inertia than a large diameter part.

The inertia calculations for typical shapes follow.

WK^2 or WR^2

WR^2 refers to the inertia of a rotating member that was calculated by assuming the weight of the object was concentrated around its rim at a distance R (radius) from the center.

WK^2 refers to the inertia of a rotating member that was calculated by assuming the weight of the object was concentrated at some smaller radius, K (termed the radius of gyration). To determine the WK^2 of a part, the weight is normally required.

Calculations

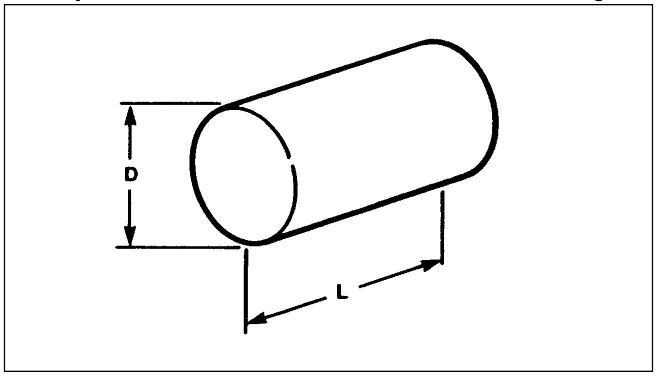
When performing calculations, be consistent with the formulae and units used. Common mistakes are substituting inches for feet, etc.

The following formulas WK^2 and WR^2 are interchangeable.

Cylinders

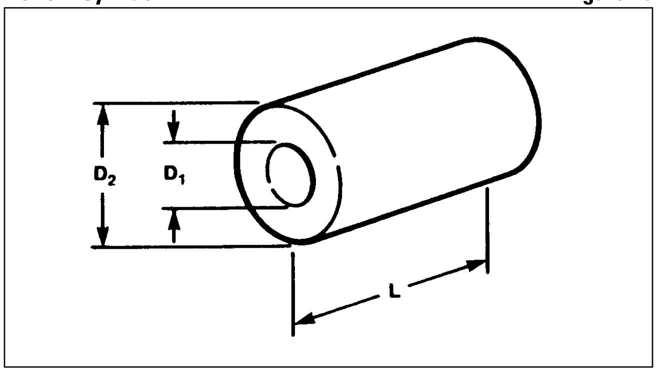
$WK^2 = .000681 \times p \times L \times (D)^4$

Solid Cylinder **Figure 9**



$WK^2 = .000681 \times p \times L \times (D_2^4 - D_1^4)$

Hollow Cylinder **Figure 10**



WK2 = inertia of a cylinder (lb-ft^2)

p = density of cylinder material in lb/in^3
(see density chart below)

D_1 = inside diameter of cylinder (inches)

D_2 = outside diameter of cylinder (inches)

L = Length of cylinder (inches)

Common Material Densities (p)

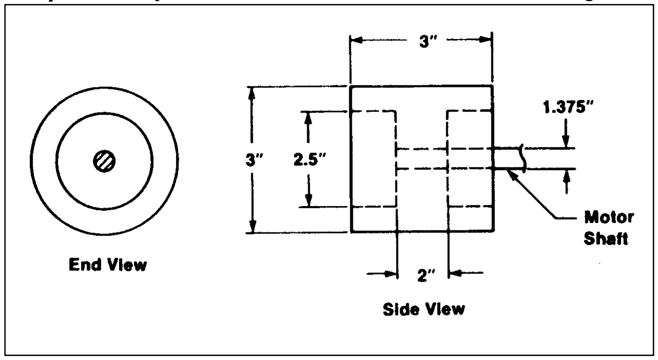
Aluminum	0.0977
Brass	0.3110
Cast iron	0.2816
Steel	0.2816
Rubber	0.0341
Paper	0.0250 to 0.0420

Pulley/Gear

To calculate the inertia of a pulley or gear, divide up the piece (shown in Figure 11) as shown in Figure 12. Using the same equation for calculating hollow cylinders, perform the calculations of each separate part and add them together for a total inertia.

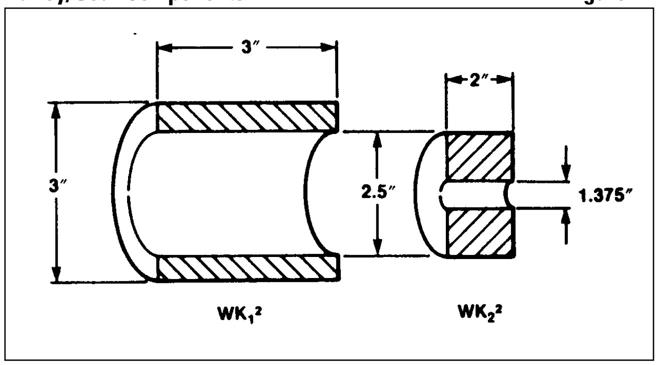
Note: WK_1^2 and WK_2^2 are the separate inertia calculations.

Complete Pulley/Gear **Figure 11**



Pulley is made of steel.
Divide up as shown.

Pulley/Gear Components **Figure 12**



Equations:
$WK^2 = 0.000681 \times p \times L\ (D_2^4 - D_1^4)$

Calculations:
$WK_1^2 = 0.000681 \times 0.2816 \times 3 \times (3^4 - 2.5^4)$
$= 0.0241$ lb-ft^2

$WK_2^2 = 0.000681 \times 0.2816 \times 2 \times (2.5^4 - 1.375^4)$
$= 0.0136$ lb-ft^2

Total Inertia $= WK_1^2 + WK_2^2 = 0.0241 + 0.0136$
$= 0.0377$ lb-ft^2

WK^2 Reflected to the Motor Shaft

In most mechanical systems, not all the moving parts operate at the same speed. If speeds of the various parts have a continuous fixed relationship to the motor speed, the equation can be used to convert all of the various inertia values to an equivalent WK^2 applied to the motor shaft.

WK^2 of Rotating Parts

$$\text{Equivalent } WK^2 = WK^2 \left[\frac{N}{N_M}\right]^2$$

Where:
WK^2 = inertia of the moving part
N = speed of the moving part (rpm)
N_M = speed of the driving motor (rpm)

When using speed reducers, and the machine inertia is reflected back to the motor shaft, the equivalent inertia is equal to the machine inertia divided by the square of the drive reduction ratio.

$$\text{Equivalent } WK^2 = \frac{WK^2}{(DR)^2}$$

Where:

$$DR = \text{drive reduction ratio} = \frac{N_M}{N}$$

WK^2 of Linear Motion

Not all driven systems involve rotating motion. The equivalent WK^2 of linearly moving parts can also be reduced to the motor shaft speed as follows:

$$\text{Equivalent } WK^2 = \frac{W(V)^2}{39.5\,(N_M)^2}$$

Where:
W = weight of load (lbs)
V = linear velocity of rack and load or conveyor and load (fpm)

N_M = Speed of the driving motor (rpm)

This equation can only be used where the linear speed bears a continuous fixed relationship to the motor speed, such as a conveyor.

Speed Reducer Selection

Note – Adjustable speed drive motors can be damaged by continuous operation at low speed and rated torque. The motor's cooling ability diminishes as speed is reduced.

If the driven machine will always be operated at speeds below the motor's rated speed, the motor should always be coupled to the driven machine by a power transmission device that will permit maximum motor rpm at maximum machine speed. The power transmission may be a simple belt-sheave or sprocket-chain arrangement or a compact gear reducer. In most applications requiring seed reductions greater than 5:1, the gear reducer may be the most economical choice.

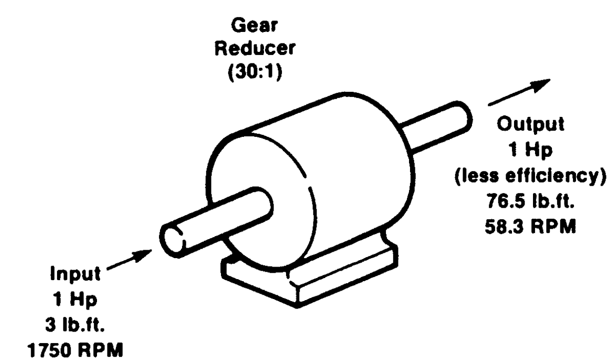
Gear Reducer Selection

A gear reducer transmits power by an arrangement of various forms of gears. It provides an efficient, positive method to change speed, direction and torque. This may mean a change of speed with a corresponding change in torque, or a change in output direction or position. A common result is a combination of the above.

The gear reducer serves as a torque amplifier, increasing the torque by a factor proportional to the reducer ratio, less an efficiency factor. See Figure 13.

A 1 hp, 1750 rpm motor has an output torque of 3 lb-ft. If a 30:1 ratio reducer with 85% efficiency is used, the reducer output torque will be 3 x 30 x 0.85 = 76.5 lb-ft.

Gear Reducer Characteristics **Figure 13**



A typical application involves selecting a gear reducer that permits the drive motor to operate at nameplate speed when the driven machine is at maximum speed. The gear reducer should also provide adequate torque to drive the machine.

Application Example:

A 1750 rpm motor is selected for a machine which is to operate at 57.5 rpm maximum speed and requires 70 lb-ft of torque.

To find the answer, the following two steps must be accomplished.

1. Determine the required ratio:

$$\text{Reducer Ratio} = \frac{\text{Maximum Motor rpm}}{\text{Maximum Driven Machine rpm}}$$

$$\text{Reducer Ratio} = \frac{1750}{57.5} = 30.4 \text{ or a } 30:1 \text{ standard ratio}$$

Note: When the calculated reducer ratio is not close to a standard speed reducer ratio, a chain, belt or additional gears with further reduction are necessary (located on the input or output side).

2. Determine the motor torque and horsepower:

A 30:1 gear reducer is selected which is capable of supplying 70 lb-ft of output torque. Since the machine torque requirement is known, this value is divided by the reduction ratio and an efficiency factor to arrive at the required motor torque (TM).

$$TM = \frac{\text{Required Torque (lb-ft)}}{\text{Reducer Ratio x Efficiency Factor}}$$

$$TM = \frac{70}{30 \times 0.85} = 2.75 \text{ lb-ft}$$

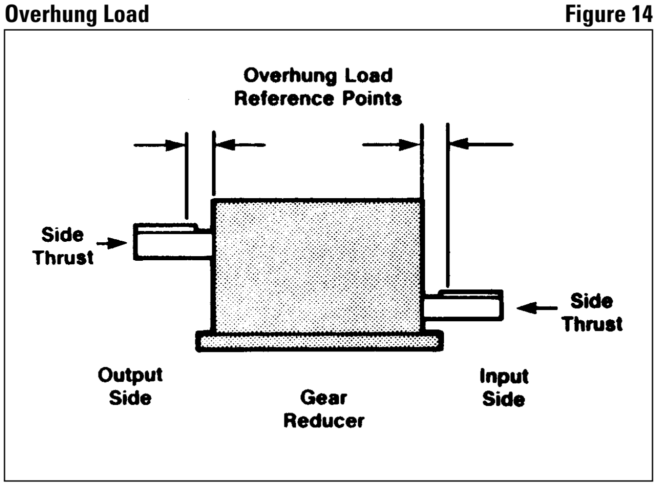
Since a 1 hp, 1750 rpm motor delivers 3 lb-ft of torque, it is chosen for this application along with a 30:1 gear reducer with a minimum of 70 lb-ft output torque rating.

Where the reduction ratio permits the use of a chain or belt, the same formulae are used as with the reducers.

Gear Reducer – Overhung Load

An overhung load (OHL) is defined as the dead weight the gear reducer bearings can support on an output shaft at a distance equal to the shaft diameter. This distance is measured from the outside end of the bearing housing along the shaft (see Figure 14). If the acting load is at a point different from the OHL point, it must be converted to the reference point and compared to the manufacturer's catalog value.

Overhung Load **Figure 14**



When a gear reducer is driven by a belt, chain or gear drive, or when the gear reducer drives a driven unit through a belt, chain or gear drive, an overhung load (side thrust) is produced. The overhung load must not exceed the rating of the gear reducer as listed by the manufacturer. The magnitude of the overhung load should always be kept to a minimum. Excessive loads could lead to fatigue failure of either the bearing or shaft. The sprocket or pulley should always be located as close to the gear housing as possible.

Increasing the sprocket or pulley diameter results in a reduced overhung load. Use the following equation to determine the overhung load:

$$OHL \text{ (lb)} = \frac{\text{2 x Shaft Torque (lb-in) x K}}{\text{Diameter (inch)}}$$

Where:
Diameter is of the sprocket, sheave, pulley or gear attached to the gear box shaft.

Note: K is a constant which is:
1.00 for chain drives
1.25 for gears or gear-belt drives
1.50 for V belt drives
2.50 for flat belt drives

No overhung loads are encountered when the gear reducer is directly coupled to the motor and/or driven machine shaft. However, care must be taken in aligning the shafts to avoid preloading bearings by misalignment.

Other Gear Issues

1. **Low speed operation** — When a variable speed gear motor is operated at low speed, its internal lubrication may not be adequate. In this circumstance, a lubrication pump may need to be added. Confirm with the gear manufacturer the intended operating speed range.
2. **Service Factor** — The application determines the amount of shock load the gearbox will be subjected to. Based on the operating time per day and the degree of shock loading, the gearbox may need to be oversized with a service factor of up to 250%.
3. **Thermal Rating** — It is possible that the gearbox will have a mechanical rating larger than its thermal rating. The gearbox manufacturer should advise under what situations this might occur.

AC Drive Theory and Application

Introduction

This section of your *Application Guide* discusses the following topics on AC Drive Theory and Application:

- Principles of Adjustable Frequency Motor Operation
- Motor Application and Performance
- AC Drive Application
- AC Drive Performance

Adjustable Frequency AC Drive System Description

An Adjustable Frequency AC drive system controls the speed of an AC motor by controlling the frequency of the power supplied to the motor. A basic AC drive system consists of an ordinary three-phase motor, an adjustable frequency drive (AFD), and operator's controls.

The motor is usually a standard NEMA design B squirrel cage induction motor rated for 230 or 460 volt, 3-phase, 60 Hz operation.

The adjustable frequency drive is a solid-state power conversion unit which typically receives 240 or 480 volt, 3-phase, 60 Hz input power and provides power to the motor which can be steplessly adjusted from 2 to 60 Hz or higher. The AFD drive also regulates the output voltage in proportion to the output frequency to provide a nominally constant ratio of voltage to frequency as required by the characteristics of the AC motor.

The operator's controls provide a means for starting and stopping the motor and for setting the motor speed. The operator's control functions can be performed by a wide variety of automatic control systems, as well as by the built-in keypad.

Benefits of Using AC Drives

AC drives have become very popular because they provide direct and efficient speed control using the most rugged and reliable of prime movers, the squirrel cage motor. Cutler-Hammer AC drives provide economic and performance advantages in a wide variety of adjustable speed applications.

The following are some of the benefits provided:

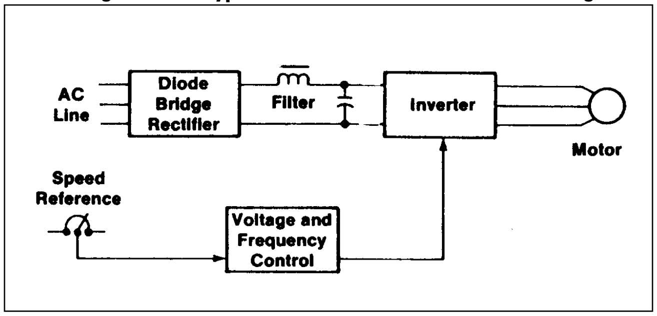
- Efficiency is high and operating cost is low.
- AC motors require minimal maintenance.
- Controlled linear acceleration & deceleration provide soft starting & stopping, and smooth speed changes.
- Multiple motor operation is easily provided.
- Current limit is available for quick and accurate torque control.
- Existing AC motors can be converted to adjustable speed.
- Close speed regulation can be provided by slip compensation without using a tachometer generator.
- AC motors are available in a wide variety of mechanical configurations.
- The light weight and compact size of AC motors allow flexibility of machine design.
- High starting torque can be provided easily and economically using IR compensation, voltage boost, or flux control.
- AC motors can be economically obtained in enclosures suitable for hazardous or corrosive environments.
- Fewer spare motors are required since spares can serve both constant speed and adjustable speed applications.
- Cutler-Hammer's very rugged and reliable drive designs assure minimum downtime expense.
- High speed operation is economically available.
- Reverse operation is provided electronically without contactors.

Basic Principles of AC Drive Operation

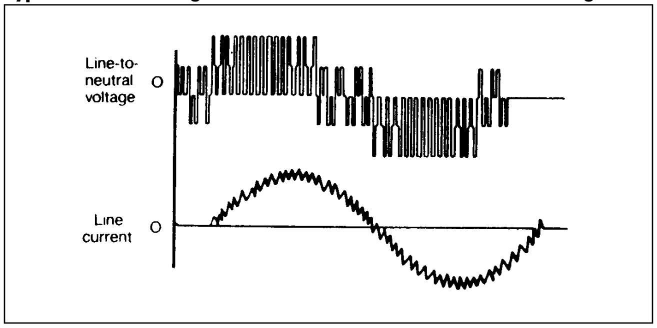
Standard AFDs are of the pulse width modulated (PWM) design type.

Figure 15 is a block diagram of a typical PWM drive. The diode bridge rectifier receives AC utility power and provides fixed voltage DC power to the DC bus. Since the inverter section is powered from a fixed voltage source, the amplitude of the output waveform is fixed. The effective value of the output voltage is controlled by using the solid-state inverter switches to modulate the width of zero voltage intervals in the output waveform. Figure 16 shows the output voltage and current waveforms for the PWM inverter.

Block Diagram for a Typical PWM Drive **Figure 15**



Typical PWM Voltage and Current Waveforms **Figure 16**



Principles of Adjustable Frequency Motor Operation

Torque-Speed Curves

The operating speed of an AC motor is determined by the frequency of the power source and the number of poles created by the stator windings. Figure 17 shows the torque-speed curve for a standard NEMA design B motor. The no-load, or synchronous speed is given by:

$$\text{Synchronous rpm} = \frac{120 \times \text{Frequency}}{\text{Number of Motor Poles}}$$

The actual operating speed is the synchronous speed minus slip. Slip is typically 3% of base speed for a design B motor.

NEMA Design B Motor Torque-Speed Curve **Figure 17**

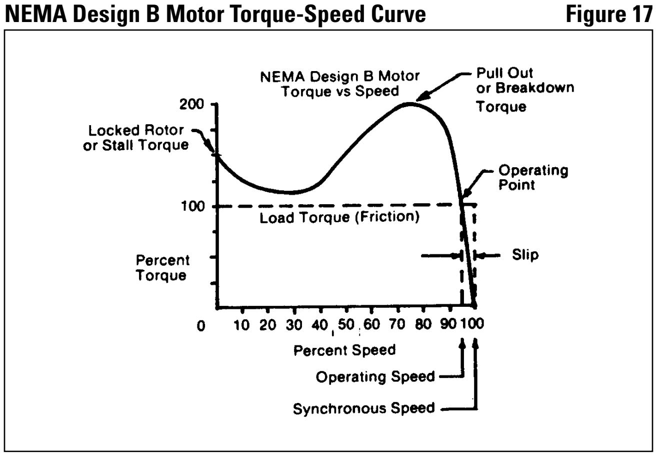
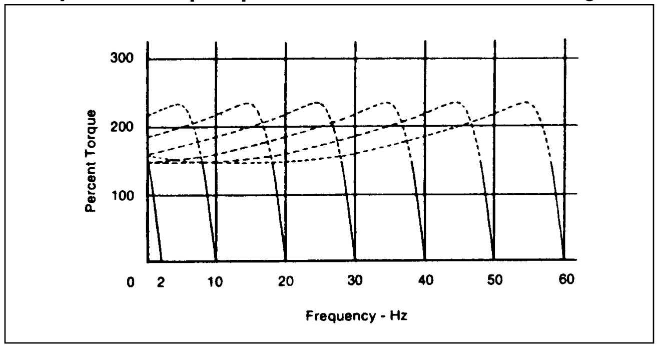


Figure 18 shows a family of ideal speed-torque curves for a motor powered from an adjustable frequency power source. The figure shows a series of identical curves with different synchronous speeds corresponding to various operating frequencies. Each curve has the same value of breakdown torque and the same value of slip rpm at any given operating torque level. The normal operating portions of the curves are shown as a series of parallel solid lines.

Motors operated from an AFD are normally never operated on the dotted portion of the curve.

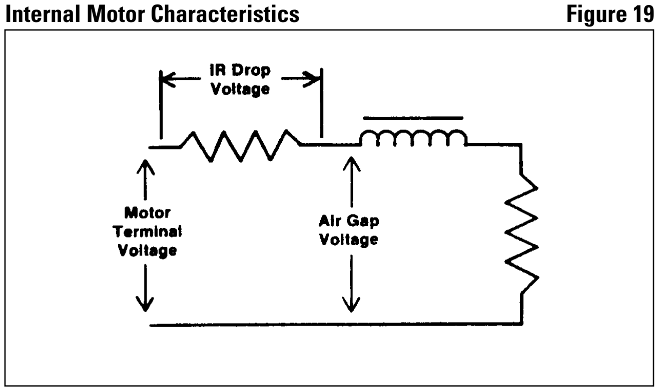
Family of Ideal Torque-Speed Curves **Figure 18**



Volts per Hertz Regulation

In order for the motor to operate with the desired torque vs. speed curve at each operating frequency, it is necessary to apply the optimum voltage to the motor at each frequency. As mentioned previously, the characteristics of the motor require the voltage to be regulated in proportion to the frequency to provide a constant ratio of voltage to frequency. However, the constant volts per hertz requirements applies not to the motor terminals, but to a theoretical point inside the motor. The voltage inside the motor is often called the air gap voltage. The difference between the air gap voltage and the terminal voltage is the IR voltage drop across the internal resistance as shown in Figure 19.

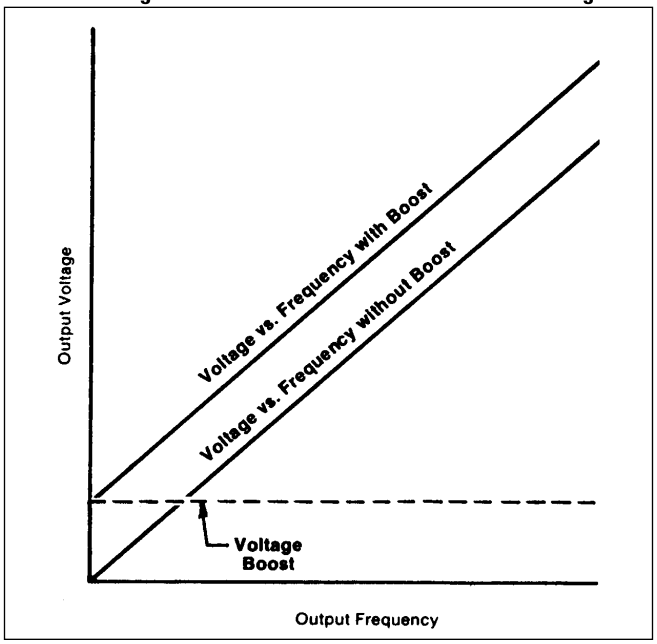
Internal Motor Characteristics **Figure 19**



Assume that the optimum motor terminal voltage is at 460 volts when the motor is operating at 60 Hz at full load. If the motor's full load current is 40 amps, and the internal resistance is 1 ohm, the IR drop is 40 volts and the air gap voltage is 420 volts, or 7 volts per hertz. If full torque is required when the motor is operating at 6 Hz, the motor current will be 40 amps since current is proportional to torque. This means that the voltage drop across the resistance will be 40 volts — the same as for 60 Hz operation. The voltage required at the air gap is 7 V/Hz, or 42 volts. The voltage required at the motor terminals is the sum of the air gap voltage and the IR drop, or 82 volts (13.67 V/Hz).

This means that a significant V/Hz "boost" is required if the motor is to produce full torque at low speed. Since the required boost voltage depends on individual motor and load characteristics, an adjustment is usually provided for setting the boost voltage. Figure 20 shows the inverter output voltage vs. frequency, and the effect of the boost adjustment. A high boost level can lead to an excessive motor current under light load conditions.

Effect of Voltage Boost **Figure 20**

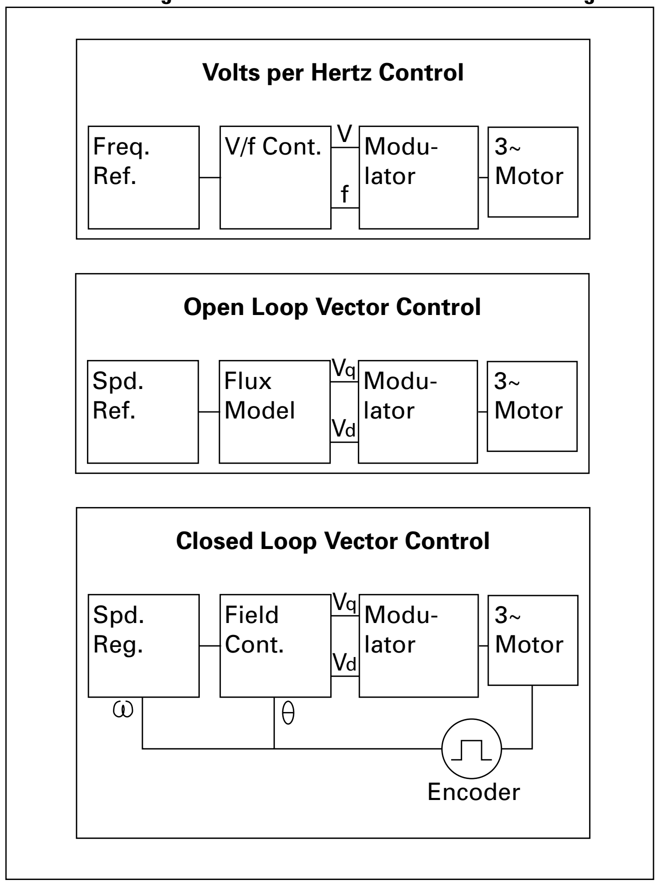


Vector Controlled Drives

Two other drive technologies are in use to provide precise control of motor speed and torque. The first is the flux or open loop vector drive, also known in the industry as a Sensorless Vector drive. The name refers to the increased performance without using a sensing device for motor rotor feedback. This drive models the motor's characteristics to estimate the motor's rotor flux and angular position between the flux and the stator current. See Figure 21. By dynamically regulating the magnitude of the stator current and its phase relationship with respect to the stator voltage, it improves both speed regulation and response by 10:1 over volts per Hertz control. While this drive has the advantage of not requiring a motor mounted encoder, its performance is reduced at or near zero speed.

The second type of drive is the field oriented or closed loop vector drive. This drive utilizes an encoder on the motor shaft for both speed and angular position feedback. The drive control also requires stator current sensing for accurate torque control. See Figure 21. This allows a 10:1 improvement in performance over the open loop vector drive. The performance is better than a six pulse DC drive with encoder feedback. The closed loop vector drive provides zero speed torque control and smooth transitions from forward to reverse operation under load.

AFD Control Diagrams **Figure 21**



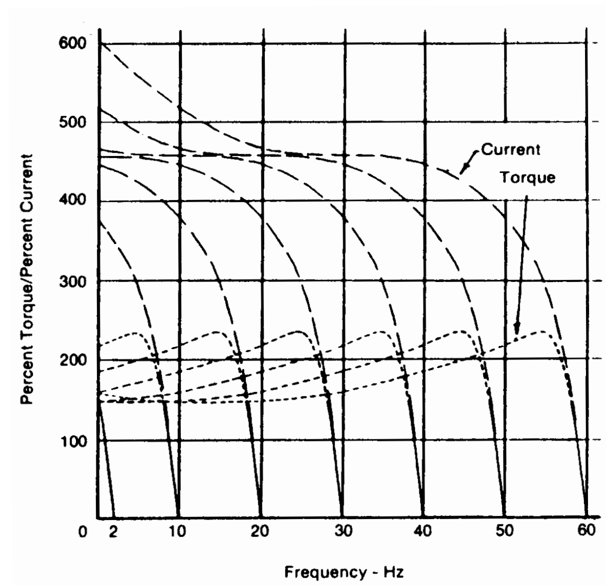
Summary of Adjustable Frequency Drive Control Variables **Table 1**

Volts per Hertz Control	Open Loop Vector Control	Closed Loop Vector Control
Voltage Frequency	Stator Current Current\Voltage Phase	Speed Torque

Soft Start

Torque vs. frequency and current vs. torque for various operating frequencies are shown in Figure 22 for a NEMA B motor. Note that the curves show that motor current is directly proportional to motor torque for operation on the normal operating portions of the curves (solid lines). The dotted portions of the curves show operation where the motor current is greater than 150% and the ratio of percent torque/percent current is significantly less than one.

Torque-Current Frequency Curves Figure 22



If the motor is started by connecting it to the power supply at full voltage and full frequency, the starting current inrush will be approximately 600% as shown in Figure 22. It is not economically feasible to provide this level of current from an AC drive. Note, that the 2 Hz curve contains only the solid portion; the dotted portion lies to the left of the zero speed axis. This means that the motor can be started at 2 Hz or less, without requiring a high starting current. If the motor is started at a low frequency, and then brought up to speed by slowly increasing the frequency, the motor will always operate on the solid portions of the torque-speed curves and never require more than 150% of rated current.

Note that some existing applications may intentionally or unintentionally exploit the torque capacity of a motor above the 150% level. If this is the case, and a drive is to be retrofitted to the application, oversizing of the drive may be required to start or operate the load.

Motor Application and Performance

Motor Sizing

The basic requirement of drive sizing is to match the torque vs. speed capability of the drive to the torque vs. speed requirement of the driven load. Refer to the other parts of this document for information explaining how to determine the torque vs. speed requirements of the load. In sizing an AC drive, it is usually sufficient to determine the motor size and then simply match the AFD to the motor. However, there are situations where a given horsepower motor will have inherently more short-term torque capacity then the same horsepower AFD. The AFD may need to be oversized to take advantage of the motor's short-term torque capacity.

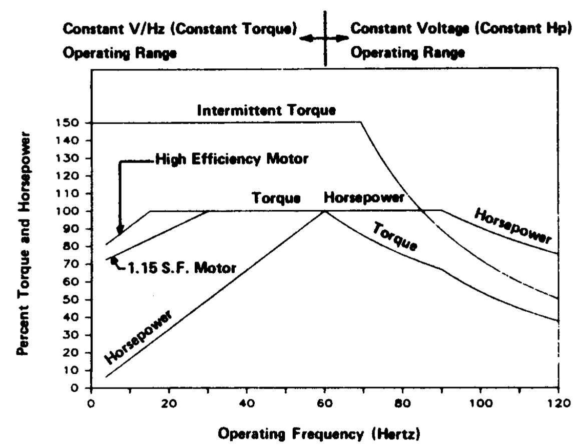
AC Drive Motor Torque vs. Speed Capability

As the speed of a motor is reduced below its 60 Hz base speed, motor cooling becomes less effective because of the reduced speed of the self-cooling fan. This limitation determines the minimum allowable motor speed for continuous constant torque operation (see Figure 23).

Low speed motor cooling does not limit the speed range with a variable torque load since the load requires less torque at lower speeds.

Typical motor performance curves are shown in Figure 23. These curves can be used with a reasonable level of confidence for most quality motors furnished in NEMA standard cast iron frames with copper windings. The curves show that a wider constant torque speed range can be obtained by using a high efficiency motor or by oversizing the motor so that it can always be operated at less than rated torque. Operation above 60 Hz can also provide a wider speed range. For further information, refer to the paragraphs under the heading "Extended Motor Performance".

Typical Motor Performance Curves Figure 23



In some applications, a special motor may be required to provide the required speed range. Motor vendors can provide information on special motors, such as motors cooled by separate blowers, or oversized models.

Operation Above 60 Hz

Figure 23 shows the motor performance which results when the AFD reaches its maximum output voltage at 60 Hz. Above 60 Hz, the output voltage is held constant as the frequency increases. This results in a reduced volts per hertz ratio as the frequency increases. The final result is a torque capability which decreases as frequency increases. The capability is approximately equivalent to constant horsepower up to 90 Hz, and reduced horsepower above 90 Hz.

Constant torque operation can be provided up to 120 Hz by applying constant V/Hz to the motor. This mode of operation requires an AFD with 460 volt output capability, and a motor connected for 230 volt, 60 Hz operation. The principle of constant V/Hz means that a 230V/60 Hz motor needs 460 volts at 120 Hz. At 460 volts and 120 Hz, the motor will be operating at twice its nameplate voltage and twice its nameplate frequency. Since the motor is at rated volts per hertz at this point, it can be operated at rated torque. At 120 Hz, the motor will be operating at twice its rated speed. Operation at rated torque at twice speed means that the motor will be operating at twice its rated horsepower. Since the motor will be operating within the limits of its normal torque and current ratings, operation at twice its rated horsepower may be permitted provided that due consideration is given to the following considerations:

1. Speed capability of the bearings.
2. Rotor balance.
3. Centrifugal stress on the motor.
4. Speed capability and windage losses of the cooling fan.
5. Increased acoustical noise produced at higher speed.
6. Critical speeds.

For operation of the motor at twice its rated horsepower, the AFD must be sized to a corresponding horsepower rating. The AFD must be sized to provide the motor current required for operation at the required torque with the motor connected for 230 volt operation.

Motor vendor and Application Engineering assistance should be requested to assure safe and successful application of the drive and motor above 60 hertz.

AFD Output Harmonics

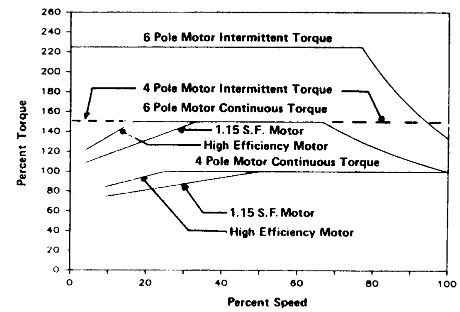
For the purpose of performance evaluation, the non-sinusoidal output waveforms produced by AFDs are represented by their mathematically equivalent component parts. All such waveforms consist of an infinite number of sinusoidal components of different amplitudes and frequencies. The fundamental component is the “good” part of the waveform, which provides power to the motor at the desired operating frequencies. The harmonics are unwanted components, which provide unusable voltages and currents to the motor at frequencies which are multiples of the fundamental.

State-of-the-art designs for pulse width modulated AFDs provide a sine weighted modulation strategy with a high switching frequency, and reduced output harmonic content as compared to other types of drives. A motor operating on a PWM drive will have an additional heat loss due the harmonic content as compared to utility line operation. For this reason, standard motors with a 1.15 service factor or energy efficient motors are recommended for use with drives.

Extended Motor Performance

Extended motor performance can be obtained by operating the motor above base speed to 90 Hz. If the drive is sized using an 1800 rpm motor, use a 1200 rpm motor of the same horsepower, and operate it at 1800 rpm by increasing the maximum frequency from 60 Hz to 90 Hz (see Figure 28). Note that the percent torque ratings shown in Figure 24 are based on 100% torque equal to the rated torque of a 4-pole motor. The rated torque of a 6-pole motor is 150% of the rated torque of a 4-pole motor of the same horsepower.

Torque-Speed Characteristics for Extended Motor Performance **Figure 24**



The motor voltage is held constant between 60 Hz and 90 Hz. Therefore, the available torque follows a constant horsepower curve.

This mode of operation increases the continuous and intermittent torque available over most of the speed range. Breakaway torque is increased from 150% to 225%. The continuous constant torque speed range is also increased.

Since the operating horsepower is not increased, it is usually not necessary to oversize the AFD to obtain extended motor performance. Check to ensure that the motor nameplate current is less than or equal to the AFD nameplate current.

Multiple Motor Operation

Any number of motors can be connected in parallel and controlled by a single AFD. A closed loop vector controlled drive cannot be used with multiple motors.

Although the basic principles of multiple motor operation are not difficult to understand, Application Engineering assistance should be requested to make certain that the application is successful.

Since the frequency of the power supplied by the AFD is the same for all motors, the motors will always operate at relatively the same speed. With NEMA design B motors, the speeds will be matched within 3% or less, depending on the load variation among the motors and their rated slip. Exact speed matching between motors is not possible. If an adjustable speed ratio is required between motors, each motor must be connected to its own individual AFD.

The simplest multiple motor application is one in which all the motors are permanently connected to the AFD, and always started and stopped simultaneously by starting and stopping the AFD. In this case, the AFD is simply sized to provide an output current equal to the sum of the maximum continuous running currents required by the motors.

If the motors must be started and stopped individually, it is necessary to determine the maximum intermittent current which will be required for the worst case combination of motors running plus motors starting. Stopping individual motors may cause difficulty in some situations.

If the motors are mechanically coupled together through the load, load sharing requirements must be considered. High slip, NEMA design D motors may be required.

Individual overload protection must be provided for each motor in a multiple motor application per the appropriate code requirements.

Special Types of Motors

This section deals exclusively with the use of standard NEMA design A or B motors, which are used in the majority of applications. In some applications, NEMA design D, high slip motors may be recommended. Design C motors, wound rotor motors and other types of motors are occasionally used with AFDs. The application of these types of motors involves considerations not covered in this section. If the existing motor or the motor proposed for use with the AFD is a type other than NEMA design A or B, application engineering assistance must be requested to make certain that the drive is properly applied.

AC Drive Application

Matching the AFD to the Motor

Voltage source AFDs are designed for use with any standard three-phase induction motor. AFD sizing and motor matching are often simply a matter of matching the AFD output voltage, frequency, and current ratings to the requirements of the motor. If the load torque exceeds 150% for Constant Torque (CT) drives or 110% for Variable Torque (VT) drives during starting or intermittently while running the drive, oversizing may be required. Refer to Table 5 for typical load requirements.

Output Voltage and Frequency

For AFDs rated at 480 volts, motors are connected for 460 volts at 60 Hz. 380V/50 Hz motors can also be used since the V/Hz ratio, 380/50, is 7.6V/Hz, the same as a 460V/60 Hz motor. 415 volt motors can be operated if the AFD V/Hz adjustment is reset. With proper V/Hz adjustment, 575 volt motors can be operated at constant V/Hz up to 80% speed and at constant voltage from 80% to 100% speed. Maximum motor torque and hp for this mode of operation is limited above 80% speed because of the reduced V/Hz levels. For AFDs rated at 240 volts, the motor will be connected for 230 volts.

Output Current

The full load current ratings of typical AFDs are matched to typical full load motor current ratings as listed in National Electric Code Table 430-150. Generally, an AFD of a given horsepower rating will be adequate for a motor of the same rating, but the actual motor current required under operating conditions is the determining factor for AFD sizing. If the motor will be run at full load, the AFD output current rating must be equal to or greater than the motor nameplate current. If the motor is oversized to provide a wide speed range, the AFD should be sized to provide the current required by the motor at the maximum operating torque. Motor oversizing should generally be limited to one horsepower size increase.

Motor Protection

Motor overload protection must be provided as required by applicable codes. Direct motor protection is not automatically provided as part of the AC drive.

AFDs are equipped with electronic protection circuits with an inverse time or I^2T characteristic equivalent to a conventional overload relay. Conventional overload relays are also used with AFDs equipped with bypass. If these current sensing protective devices are used with motors driving constant torque loads, the minimum speed should be adjusted to prevent the motor from running at speeds at which overheating could occur, unless the I^2T circuit provides a speed and load calibrated trip. The best means of AC drive motor protection is direct winding overtemperature sensing, such as an overtemperature switch or thermistor imbedded in the motor windings. Overtemperature switches are more convenient because they can normally be connected directly to the AC drive control circuit. Thermistors generally require a special sensing relay. Direct overtemperature protection is preferred over overcurrent sensing protective devices because motor overheating can occur with normal operating current at low operating speeds.

Motor short circuit protection is not required since the AC drive protection circuits nearly always adequately protect the motor in this respect.

When a single AFD provides power to multiple motors connected in parallel, special considerations must be given to motor protection. Individual overload protection must be provided for each motor. Short circuit protection may be required for some applications.

Bearing and DV/DT Protection

The high switching frequency present in today's PWM drives may cause current to flow in the motor bearings due to shaft voltage caused by capacitive coupling. This current flow can result in minute electrical discharges within the bearing, potentially damaging the bearing over time. There are several techniques for use in reducing this effect:

a) Use a lower voltage motor and control if possible, i.e., 230 volts instead of 460 volts.

b) Run the AFD at the lowest carrier frequency that satisfies any audible noise and temperature requirements.

c) Add a shaft grounding device to the motor. This device has a brush that rides on the motor shaft. Current does not go through the bearing but is instead conducted directly to ground through the brush. These brushes are specially selected to tolerate misalignment and maintain rotating contact throughout the motor's life.

d) Use a motor with both bearings insulated. This approach will avoid damage to the motor's bearings. **Caution:** Other noninsulated bearings in the mechanical system which are connected to the shaft with a conductive coupling (such as tachometers or gearboxes), may be damaged by the shaft voltage.

e) Use non-conductive couplings for the mechanical system, loads or devices, which may be damaged by bearing currents.

f) Ensure that the AFD is grounded per the manufacturers' instructions.

g) Use a filter that reduces common mode voltage.

The high switching frequency can also lead to large voltage overshoots at the motor terminals. See *Output DV/DT Issues* in the following **AC Drive Performance** section.

AC Drive Performance

Operator Control and Interface

Operator controls are often via the drive keypad. In other situations, an operator station or remote control may be desired. If these requirements cannot be achieved by remotely mounting the keypad, terminal blocks with digital and analog interface capability are provided.

Acceleration and Deceleration

AFDs are always equipped with adjustable acceleration and deceleration control. Acceleration and deceleration rates must be adjusted to suit the characteristics of the load to prevent shutdown due to overcurrent or overvoltage. Increasing acceleration or deceleration times will proportionally decrease the torque requirement.

Speed Range

The characteristics of the motor usually determine the speed range of an AC drive. The AFD output frequency range is usually wider than the range that can be effectively utilized by the motor.

Speed Regulation

The open loop speed regulation of an AC drive is determined by the motor slip. Since NEMA design B motors usually have 3% slip or less, at 60 Hz and rated load the speed regulation of the drive is 3%.

AFDs equipped with slip compensation or flux or vector control can provide speed regulation which is better than the open loop regulation of the motor. Slip compensation and flux or vector control improves speed regulation by increasing and decreasing the operating frequency by a small amount as the load increases and decreases.

Further improvement in steady state speed regulation can be obtained by using a tachometer generator to provide speed feedback to a closed loop speed regulator option, or an external device such as the Durant Strider.

Service Deviation

Speed regulation specifies only that portion of the drive speed change which is directly caused by a change in load. Several other factors can cause unintended changes in the drive operating speed. These factors contribute to the drive's service deviation. Table 2 lists some of these factors and the typical effect they have on drive speed.

Factors Affecting Service Deviation **Table 2**

Influencing Factor	Typical Speed Change
Line voltage variations within rated tolerance.	0.0%
Ambient temperature variations of controller within rated tolerance after warmup.	0.25%
Motor temperature variations. Cold to maximum operating temperature.	0.5%

Current Limit

If an AC drive was not equipped with current limit, the overcurrent trip circuits would shut down the drive should the motor draw excessive current due to an overload or too rapid an acceleration rate. Current limit provides a means of maintaining control of the drive under these conditions.

If the output current reaches the current limit setting while the drive is running at set speed, the drive will decelerate to a lower speed. If possible, the speed will decrease to whatever operating speed is required to prevent exceeding the current limit setting.

If the output current reaches the current limit setting while the drive is accelerating, the drive will deviate from the programmed acceleration ramp and accelerate at a rate which will prevent the current from exceeding the set limit.

If the drive reaches the negative current limit setting (if applicable) while the drive is decelerating, the drive will deviate from the programmed deceleration ramp, and decelerate at a rate which will try to prevent the current from exceeding the limit.

Regeneration Limit and Braking

The AC drive will inherently develop braking torque when the frequency is reduced to decelerate the motor, or when there is an overhauling load.

When the motor is producing braking torque, it is operating as an induction generator. This means that the motor is receiving power from the load and returning the power to the source. If a drive receives energy regenerated by the motor, the energy appears as a reversal of the DC bus current. Since the standard input converter can not accept reverse current, the current flows into the DC bus filter capacitors. This charging current causes the DC bus voltage to increase. If this process is allowed to proceed, the AC drive will be damaged by DC bus overvoltage. AFDs must be protected from DC bus overvoltage due to regeneration. The minimum protection is a DC bus overvoltage trip.

If the AC drive is equipped with regeneration limit circuitry, control of the drive can be maintained during regeneration, and DC overvoltage shutdown can be prevented. If regeneration causes the DC bus voltage to rise during deceleration, the drive will deviate from the programmed deceleration ramp and decelerate at whatever rate is possible without generating excess bus voltage. If an overhauling load causes regeneration, the drive will allow the motor speed to increase above the set speed as required to prevent excess regeneration.

Regeneration limit prevents the motor from developing braking torque above a limit which corresponds to the normal losses which are inherent in the motor and controller.

When the drive is equipped with dynamic braking, the motor is allowed to develop a higher level of braking torque. The regenerated braking energy is dissipated in the dynamic braking resistors. A fully regenerative drive includes circuitry which returns the regenerated braking energy to the power lines.

IR Compensation

A V/Hz AC drive can provide improved starting torque and low speed overload capability if the lower speed voltage boost is changed automatically to compensate for changing load conditions. This feature is called IR compensation. Without IR compensation, it is difficult to achieve the maximum possible motor torque because the voltage boost required for maximum torque can cause the motor to saturate and draw excessive current when it is lightly loaded. The IR compensation circuit senses the motor load and reduces the voltage boost when the motor is lightly loaded.

A flux control AC drive provides a similar result by modifying its instantaneous voltage and frequency to allow the motor to develop the required torque for the load.

Installation Compatibility

The successful application of an AC drive requires the assurance that the drive will be compatible with the environment in which it will be installed. The following are some of the aspects of compatibility which should be considered.

Cooling Air

Even though AFDs are very efficient, the heat produced in the controller cabinet can be substantial. The electronic circuitry is subject to immediate failure if its operating temperature limits are exceeded. Junction temperatures of transistors, SCRs and IGBTs typically can only increase 20 – 25°C from full load to failure. It is important to remove heat through the usual mechanisms of radiation, conduction (heat sinks) or convection (fans). The enclosure must be located away from direct sunlight and hot surfaces. The room temperature must be kept within the specified limits and adequate cooling air must be allowed to flow around the enclosure. Excessively moist, corrosive or dirty air must be prevented from entering the enclosure.

Acoustical Noise

In some installations, it may be necessary to use sound abatement measures to prevent the drive from producing excessive acoustical noise. In a factory environment, noise will probably not be a problem unless the motor is operated above its normal base speed. In an office environment, the noise may be of greater concern. With PWM drives, the motor produces the majority of the noise. The noise may be noticeable because of the frequencies involved and the sudden shifts in pitch which may occur at certain operating points. The use of carrier frequencies of 6 kHz and above can limit motor noise to levels comparable to across-the-line operation.

Motor noise can also be reduced by adding a 3% output reactor to the drive. The reactor smoothes the output voltage, reducing the components responsible for the motor noise. A third approach for a motor which is not fully loaded, is to slightly reduce the AFD's output voltage. The reduced voltage provides less motor air gap flux, reducing the noise level.

Electromagnetic Compatibility

Electromagnetic compatibility may be of concern both from the standpoint of outside sources interfering with the AC drive and from the standpoint of the drive interfering with other equipment. Cutler-Hammer drives are designed to avoid problems of either type. Cutler-Hammer drives have been installed in a wide variety of environments with very little difficulty. Electromagnetic compatibility is by no means assured by the product alone. Installation methods and power distribution system design are also very important. Even the most extensive protection designed into the drive will be defeated if the drive is not properly installed.

Typical means of reducing the radio frequency effects of the drive on other equipment include the use of an input EMC filter and shielded output power wiring. The EMC filter will reduce the high frequencies which can be transmitted on the input power wiring. The use of shielded wire, wiring run in a well bonded, grounded metallic conduit, or continuous armored cable, will help prevent high frequency radiation from the three-phase power output wiring. Signal leads should be isolated from 120V control leads and both should be isolated from the input and output power leads.

If cable trays are used, there should be 1 foot of separation between the drive input and motor power leads for every 10 feet of length. Output leads from multiple units must be likewise separated. Long parallel runs should be avoided.

A single conduit containing both the input and output leads is not recommended. Separate conduits will reduce radio frequency coupling. Input or output power leads from multiple drives should not be run in the same conduit. The resultant radio frequency coupling may cause nuisance drive trips.

See the EMC application note for further information.

Output DV/DT Issues

PWM drives use fast transistors or IGBTs to provide the pulses required to control the voltage and frequency output. The property of these devices to turn on and off quickly results in a high switching DV/DT. High DV/DT levels when combined with long cable runs result in high peak voltages at the motor terminals. These high peak voltages can create a potential for motor insulation stress and damage due to the peak voltage magnitude or marginal motor insulation. The motor vendor can provide information on the insulation peak voltage and DV/DT capability of his particular motor design. Drive and motor mounted filters are available for small motors with cable runs greater than 33 feet and for larger motors with runs exceeding 100 feet. These consist of peak energy recovery filters, output line reactors and motor terminal reflective wave traps. For additional information on this topic, contact Cutler-Hammer.

Power from Engine-Generator Sets

Engine-generator sets have high output impedance and poor regulation in comparison to utility power lines. Cutler-Hammer assistance should be requested to avoid problems which might be encountered when applying AFDs with this type of power source.

Isolation Transformers

Drive isolation transformers are sometimes recommended or specified by others for various reasons. Cutler-Hammer does not require the use of isolation transformers because Cutler-Hammer drives are designed to operate directly from plant power distribution systems without using isolation transformers. The benefits sought through the use of isolation transformers are generally provided more economically, efficiently and reliably by features which are designed into the drive and power options such as line reactors. However, in some situations isolation transformers may be required to provide suitable input power.

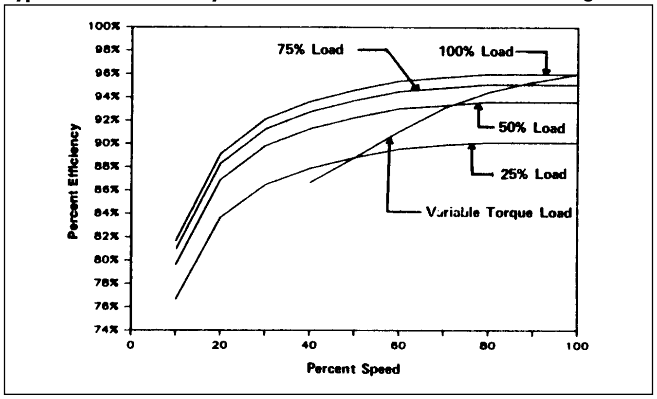
Cutler-Hammer AFDs are designed to withstand line voltage transients and noise generated by other equipment in a typical installation environment when applied to systems with the required minimum impedance levels. They are also designed to prevent nuisance levels of noise from being reflected back to the power lines. Electronic protection circuits fully protect the drives from output short circuits and ground faults regardless of available fault current without requiring isolation or external impedance. Isolation transformers are generally not recommended as a preventative or curative measure for suspected difficulties of these types.

Efficiency

Figure 25 shows typical efficiency curves for an IGBT AFD. The efficiency of an AC drive can be accurately determined only for a particular set of operating conditions. The characteristics of the motor and controller are interrelated in such a way that a change in the characteristics of either component will cause a change in the efficiency of the other.

The efficiency of the total AC drive system cannot be accurately determined from just the controller efficiency curves and the manufacturer's published motor data. Table 3 provides adjustment factors which can be used to estimate the total drive system efficiency. The adjustment factors take into account efficiency variations due to a typical range of different motor characteristics and operating conditions. The factors include data from the controller efficiency curves and adjust for motor characteristics at various speed and load points.

Typical AFD Efficiency **Figure 25**



To calculate total AC drive system efficiency, multiply the published motor efficiency by the adjustment factors listed in Table 3. Use the published motor efficiency for full load 60 Hz operation only. The adjustment factors account for changes in motor efficiency due to changing the speed and load.

Example:

Suppose you wish to estimate AC drive efficiency for a 50 hp drive on a centrifugal pump. Efficiency is to be estimated for operation at full speed and 70% speed. The motor is nameplated 94.5% NEMA nominal efficiency.

From the variable torque columns in Table 3, the adjustment factors for full speed operation range from 0.93 to 0.95 and the adjustment factors for 70% speed range from 0.874 to 0.895.

For 100% speed:
Eff.=94.5 x 0.93 = 87.9% (low estimate)
Eff.=94.5 x 0.95 = 89.8% (high estimate)

For 70% speed:
Eff.=94.5 x 0.874 = 82.6% (low estimate)
Eff.=94.5 x 0.895 = 84.6% (high estimate)

Adjustment Factors for Calculating Total AC Drive System Efficiency **Table 3**

Percent Speed	Constant Torque Load Load: Percent of Rated Torque				Variable Torque Load	
	100	75	50	25	Adjustment Factor	Percent Torque
100	0.930 – 0.950	0.912 – 0.932	0.878 – 0.899	0.800 – 0.820	0.930 – 0.950	100
90	0.931 – 0.951	0.912 – 0.933	0.879 – 0.900	0.800 – 0.821	0.919 – 0.940	81
80	0.930 – 0.951	0.912 – 0.933	0.878 – 0.900	0.800 – 0.821	0.900 – 0.921	64
70	0.928 – 0.949	0.909 – 0.931	0.876 – 0.898	0.798 – 0.820	0.874 – 0.895	49
60	0.924 – 0.946	0.906 – 0.928	0.872 – 0.895	0.794 – 0.817	0.836 – 0.859	36
50	0.910 – 0.934	0.892 – 0.916	0.859 – 0.883	0.782 – 0.806	0.782 – 0.806	25
40	0.889 – 0.915	0.872 – 0.897	0.839 – 0.864	0.763 – 0.788	0.689 – 0.714	16
30	0.855 – 0.883	0.838 – 0.866	0.805 – 0.833	0.732 – 0.760		
20	0.793 – 0.826	0.766 – 0.810	0.746 – 0.780	0.675 – 0.709		
10	0.625 – 0.675	0.610 – 0.660	0.584 – 0.634	0.522 – 0.572		

Power Factor

The power factor typically specified for AFDs is displacement power factor, which is defined as the cosine of the angle between the fundamental voltage and current. Many instruments used for utility billing purposes give readings equivalent to displacement power factor. Another definition and measurement method combines the effects of power and harmonic content to define total power factor. Newer utility instrumentation is capable of recording total power factor, resulting in potential power factor penalty billing.

Displacement power factor for a PWM drive is approximately 0.95 at all operating points. The displacement power factor is not significantly affected by the motor speed, the motor load or the motor power factor. Total power factor will vary with line voltage, utility feeder size and total system and drive load.

Power factor correction capacitors should not be connected at the AC drive power input. Correction should be done on a plantwide basis. If capacitors are located too close to the drive, or if drives represent a high percentage of the total plant electrical load, there may be an undesirable interaction between the capacitors and the drives, leading to a failure of either or both.

If the capacitors must be located near the drive, a line reactor should be used on the drive input to reduce the possibility of interaction. Note that adding this reactor does not eliminate the potential for harmonic resonance.

To be assured of a solution that will improve power factor and avoid resonance, a system study must be performed to determine the optimum selection of capacitance and inductive reactance.

Power factor correction capacitors must never, under any circumstances, be connected at the AC drive controller output. They would serve no useful purpose, and they may damage the drive.

AC Drive Input Harmonics

AFDs utilize a rectifier to convert AC line voltage to the DC levels required by the inverter section. Rectifiers are non-linear devices which cause a current to be drawn from the line which includes many harmonics. These harmonic currents will cause harmonic voltages to be created in the line which may affect sensitive devices on the same line. IEEE519-1992 provides recommendations for the harmonic current levels reflected to the utility by any user, where his feeder ties into the utility grid. For difficult installations where the levels of IEEE519 cannot be met, or those utilizing on-site generated power, a "Clean Power" rectifier can be used. The "Clean Power" rectifier utilizes phase shifted semiconductors to significantly reduce harmonics to levels well within the IEEE guidelines. For more specific information contact Cutler-Hammer.

Motor Load Types and Characteristics

Introduction

This section of your *Application Guide* discusses the following topics on Motor Load Types and Characteristics:

- Motor Load Types
- Other Functional Considerations

The process of selecting an electrical adjustable speed drive is one where the load is of primary consideration. It is important to understand the speed and torque characteristics as well as horsepower requirements of the type of load to be considered.

When considering load characteristics, the following should be evaluated:

- What type of load is associated with the application?
- Does the load have a shock component?
- What is the size of the load?
- Are large inertial loads involved?
- What are the motor considerations?
- Over what speed range are heavy loads encountered?
- How fast is the load to be accelerated or decelerated?

Motor loads are classified into three main groups, depending on how their torque and horsepower vary with operating speed. The following paragraphs deal with the various motor load types usually found in process, manufacturing, machining and commercial applications.

Motor Load Types

Constant Torque Load

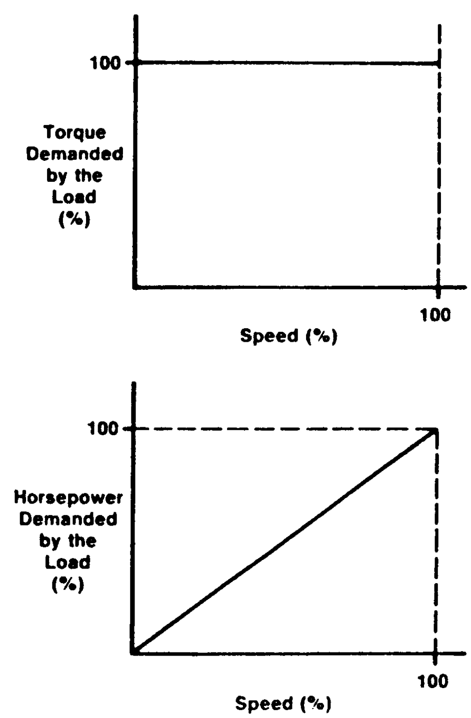
This type of load is frequently encountered. In this group, the torque demanded by the load is constant throughout the speed range. The load requires the same amount of torque at low speeds as at high speeds. Loads of this type are essentially friction loads. In other words, the constant torque characteristic is needed to overcome friction. Figure 26 shows the constant torque and variable horsepower demanded by the load.

As seen in Figure 26, torque remains constant while horsepower is directly proportional to speed. A look at the basic horsepower equation also verifies this fact:

$$hp = \frac{\text{Torque x Speed}}{5250}$$

Where:
Torque is measured in lb-ft
Speed is measured in rpm.
5250 is proportionality constant.

Constant Torque Load **Figure 26**



Examples of this type of load are conveyors, extruders and surface winders. Constant torque capability may also be used when shock loads, overloads or high inertia loads require special drive sizing.

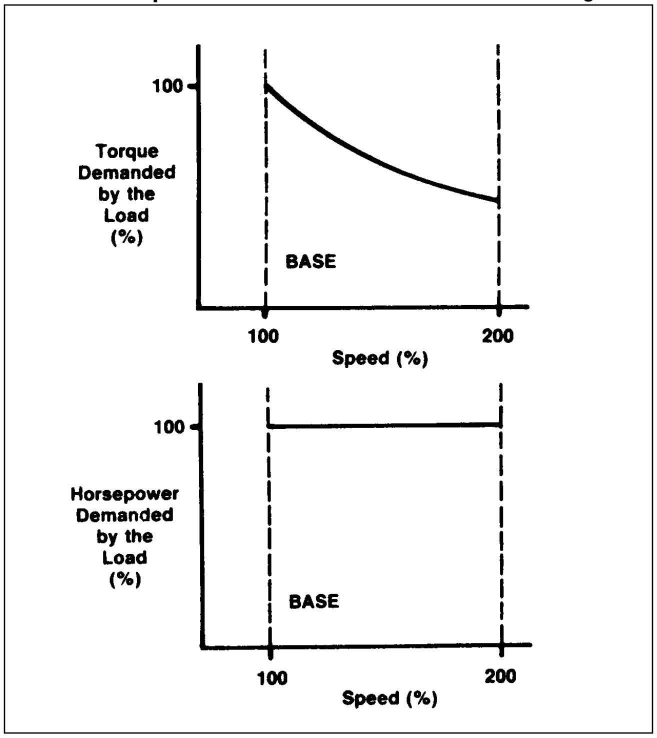
Constant Horsepower Load

In this type of load, the horsepower demanded by the load is constant over the speed range. The load requires high torque at low speeds. From the previous formula, you can see that with the horsepower held constant, the torque will decrease as the speed increases. Put another way, the speed and torque are inversely proportional to each other. Figure 27 shows the constant horsepower and variable torque demanded by the load.

Motor Load Types and Characteristics

Examples of this type of load are center-driven winders and machine tool spindles. A specific example of this application would be a lathe that requires slow speeds for rough cuts where large amounts of material are removed, and high speeds for fine cuts where little material is removed. Usually very high starting torques are required for quick acceleration. Constant horsepower range is usually limited on an AC drive from base speed to 1.5 – 2 times base speed.

Constant Horsepower Load **Figure 27**



Variable Torque Load (Cubed Exponential)

With this type of load, the torque is directly proportional to some mathematical power of speed, usually speed squared (Speed^2). Mathematically:

$$\text{Torque} = \text{Constant}\left(\frac{\text{operating speed}}{\text{nameplate speed}}\right)^2$$

Horsepower is typically proportional to speed cubed (Speed^3). Figure 28 shows the variable torque and variable horsepower demanded by the load.

Examples of loads that exhibit variable load torque characteristics are centrifugal fans, pumps and blowers. This type of load requires much lower torque at low speeds than at high speeds.

Variable Torque Load **Figure 28**

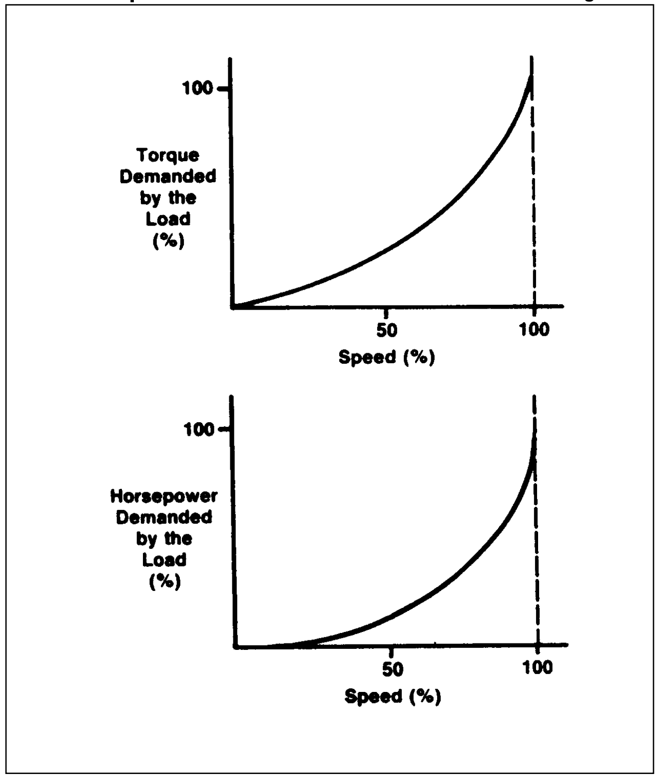


Table 4 summarizes load types, torque and horsepower characteristics.

Load Types **Table 4**

Horsepower and Torque Characteristics	Application Examples
Constant hp; torque varies inversely with speed.	Metal-cutting tools operating over wide speed range. Some extruders, mixers and center driven winders.
Constant torque; hp varies as the speed.	General machinery, hoists, conveyors, printing press, etc. Positive displacement pumps, some mixers, some extruders.
Cubed exponential; hp varies as cube of speed. Torque varies as square of speed. High inertia loads.	Machines using flywheels to supply most of operating energy, punch presses, etc. All centrifugal pumps and some fans.

Other Functional Considerations

Shock Loads

Drives for crushers, separators, grinders, conveyors, winches, cranes and vehicular systems often must manage loads which range from a small fraction of the rated load to several hundred percent.

Under these conditions, a drive has two fundamental tasks: move the load, and protect the prime mover and driven equipment. If the prime mover is an electric motor, as is the case with a large number of industrial drives, shock loads can damage components such as bearings and speed changers, as well as components of the drive control circuitry, by inducing signal irregularities and electrical overloads in the power converter.

Size of the Load

The size of the load determines the type of drive chosen. Adjustable speed drives (AC, DC, Eddy-Current, fluid, traction, etc.) range from fractional horsepower to many thousand horsepower. However, not all types of drives can be manufactured in the full range. Generally, power semiconductor technology is the limiting factor in what is practical or economical to manufacture for any given type of electrical drive.

Duty Cycle

Certain applications may require continuous reversals, long acceleration times at high torque due to inertia loads, frequent high rate acceleration, or cyclic overloads which may result in severe motor heating if not considered in the selection of the drive.

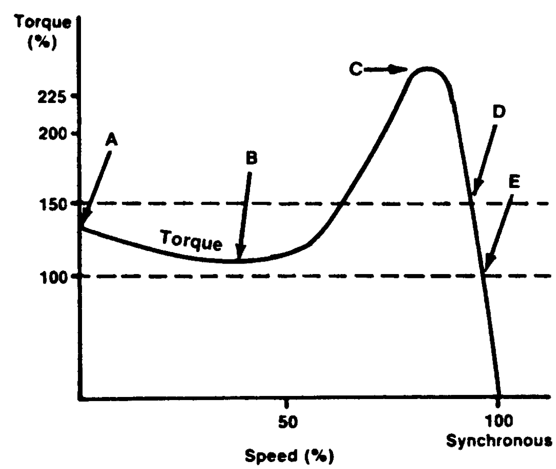
Most drives with 150% overload capability will operate successfully if there are compensating periods of operation where motor temperatures can be normalized.

AC Motor Torque

In an AC induction motor, torque results from the magnetic attraction between the rotor and stator. In essence, the stator (stationary case) has a rotating magnetic field at a frequency delivered by the inverter. The rotor (rotating piece) is attracted to the stator, producing a twisting motion called torque. Figure 29 shows an AC induction motor curve with the various torque ratings marked.

Point A in Figure 29 is torque produced at locked rotor — when rotor slip frequency is highest and inductive reactance is greatest (breakaway torque). As the motor begins to accelerate, the torque drops off, reaching a minimum value called pull-up torque. This is between 25 – 40% of synchronous speed. As acceleration continues, rotor slip frequency and inductive reactance decrease. The rotor flux moves more in-phase with stator flux, and consequently torque increases. Maximum torque is developed where inductive reactance becomes equal to the motor resistance. Beyond the maximum torque point, the inductive reactance continues to drop off along with the current through the rotor. The torque capabilities of the motor therefore also decrease.

AC Motor Torque Curve **Figure 29**



Torque Curve Points:

A-Breakaway or Starting Torque
B-Pull-Up Torque
C-Maximum or Break-Down Torque
D-150% Torque
E-Rated Torque

Motor Load Types and Characteristics

Typical Load Torque Requirements **Table 5**

Name of Application	Load Torque as Percent of Full-Load Drive Torque		
	Breakaway	Accelerating	Peak Running
Actuators:			
Screw-down (rolling mills)	200	150	125
Positioning	150	110	100
Agitators:			
Liquid	100	100	100
Slurry	150	100	100
Blowers, centifugal:			
Valve closed	30	50	40
Valve open	40	110	100
Blowers, positive-displacement, rotary, bypassed	40	40	100
Calendars, textile or paper	75	110	100
Card machines, textile	100	110	100
Centifuges (extractors)	40	60	125
Chippers, wood, starting empty	50	40	200
Compressors, axial-vane, loaded	40	100	100
Compressors, reciprocating, start unloaded	100	50	100
Conveyors, belt (loaded)	150	130	100
Conveyors, drag (or apron)	175	150	100
Conveyors, screw (loaded)	200	100	100
Conveyors, Shaker-type (vibrating)	150	150	75
Coolers, hot solids, rotary (loaded)	175	140	100
Cranes, traveling:			
Bridge motion	100	300	100
Trolley motion	100	200	100
Hoist motion	50	200	190
Draw presses (flywheel)	50	50	200
Drill presses	25	50	150
Edgers (starting unloaded)	40	30	200
Elevators, bucket (starting loaded)	150	175	150
Elevators, freight (loaded)	100	125	100
Elevators, man lift	50	125	100
Elevators, personnel (loaded)	110	150	100
Escalators, stairways (starting unloaded)	50	75	100
Extruders (rubber or plastic)	150	150	100
Fans, centrifugal, ambient:			
Valve closed	25	60	50
Valve open	25	110	100
Fans, centrifugal, hot gases:			
Valve closed	25	60	100
Valve open	25	200	175
Fans, propeller, axial-flow	40	110	100
Feeders, belt (loaded)	100	120	100
Feeders, distributing, oscillating drive	150	150	100
Feeders, screw compacting rolls	150	100	100
Feeders, screw, filter-cake	150	100	100
Feeders, screw, dry	175	100	100
Feeders, vibration motor-driven	150	150	100
Frames, spinning, textile	50	125	100
Grinders, metal	25	50	100
Hoists, skip	100	150	100
Indexers	150	200	150
Ironer, laundry (mangles)	50	50	125
Jointers, woodworking	50	125	125
Kilns, rotary (loaded)	250	125	125
Looms, textile, without clutch	125	125	150
Machines, boring (loaded)	150	150	100
Machines, bottling	150	50	100
Machines, buffing, automatic	50	75	100
Machines, cinder-block, vibrating	150	150	70
Machines, keyseating	25	50	100
Machines, polishing	50	75	100
Mills, flour, grinding	50	75	100
Mills, rolling metal:			
Billet, skelp and sheet, bar	50	30	200
Brass and copper finishing	120	100	200
Brass and copper roughing	40	30	200

Motor Load Types and Characteristics

Typical Load Torque Requirements *(continued)* **Table 5**

Name of Application	Load Torque as Percent of Full-Load Drive Torque		
	Breakaway	Accelerating	Peak Running
Mills, rolling metal (continued):			
Merchant mill trains	50	30	200
Plate	40	30	250
Reels, wire or strip	100	100	100
Rod	90	50	200
Sheet and tin (cold rolling)	150	110	200
Strip, hot	40	30	200
Structural and rail finishing	40	30	200
Structural and rail roughing	40	30	250
Tube	50	30	200
Tube piercing and expanding	50	30	250
Tube reeling	50	30	200
Mills, rubber	100	100	200
Mills, saw, band	50	75	200
Mixers, chemical	175	75	100
Mixers, concrete	40	50	100
Mixers, dough	175	125	100
Mixers, liquid	100	100	100
Mixers, sand, centrifugal	50	100	100
Mixers, sand, screw	175	100	100
Mixes, slurry	150	125	100
Mixers, solids	175	125	175
Planers, metalworking	50	150	150
Planers, woodworking	50	125	150
Plows, conveyor, belt (ore)	150	150	200
Positioners, indexing (machine tool)	50	200	100
Presses, pellet (flywheel)	150	75	150
Presses, printing, production type	100	150	150
Presses, punch (flywheel)	150	75	100
Puller, car	150	110	100
Pumps, adjustable-blade, vertical	50	40	125
Pumps, centrifugal, discharge open	40	100	100
Pumps, oil-field, flywheel	150	200	200
Pumps, oil, lubricating	40	150	150
Pumps, oil fuel	40	150	150
Pumps, propeller	40	100	100
Pumps, reciprocating, positive-displacement	175	30	175
Pumps, screw-type, started dry	75	30	100
Pumps, screw-type, primed, discharge open	150	100	100
Pumps, slurry-handling, discharge open	150	100	100
Pumps, turbine, centrifugal, deep-well	50	100	100
Pumps, vacuum (paper-mill service)	60	100	150
Pumps, vacuum (other applications)	40	60	100
Pumps, vacuum, reciprocating	150	60	150
Pumps, vane-type, positive-displacement	150	150	175
Rolls, bending	150	150	100
Rolls, crushing (sugarcane)	50	110	125
Rolls, flaking	30	50	100
Sanders, woodworking, disk or belt	30	50	100
Saws, band, metalworking	30	50	100
Saws, circular, metal, cutoff	25	50	150
Saws, circular, wood, production	50	30	150
Saws, edger (see Edgers)			
Saws, gang	60	30	150
Screens, centrifugal (centrifuges)	40	60	125
Screens, vibrating	50	150	70
Separators, air (fan-type)	40	100	100
Shakers, foundry or car	50	150	70
Shears, flywheel-type	50	50	120
Shovels, dragline, hoisting motion	50	150	100
Shovels, dragline, platform motion	50	100	100
Shovels, large, digging motion	50	200	200
Shovels, large, platform motion	50	100	100
Tension-maintaining drives	100	100	100
Textile machinery	150	100	90
Tools, machine	100	150	100

Motor Load Types and Characteristics

Typical Load Torque Requirements *(continued)* **Table 5**

Name of Application	Load Torque as Percent of Full-Load Drive Torque		
	Breakaway	Accelerating	Peak Running
Tools, machine, broaching, automatic	50	150	150
Tools, machine, lathe, metal production	50	200	200
Tools, machine, mill, boring production metal	100	125	100
Tools, machine, milling, production	100	100	100
Tools, machine, planer, production, metal (see Planers, metalworking)			
Tools, machine, shaper, metal, automatic	50	75	150
Vehicles, freight	200	200	200
Vehicles, passenger	100	400	200
Walkways, mechanized	50	50	100
Washers, laundry	25	75	100
Winches	125	150	100

Drive Selection

Introduction

This section of your *Application Guide* discusses the following topics on selecting the appropriate drive:

- Selection Considerations
- Selecting a Drive for a Machine
- Drive Application Questions

Selection Considerations

When selecting a drive and associated equipment for an application, the following points should be considered:

Environment

The environment in which the motor and power conversion equipment operates is of prime concern. Conditions such as ambient temperature, cooling air supply and the presence of gas, moisture, and dust should all be considered when choosing a drive, its enclosures and protective features.

Speed Range

The minimum and maximum motor speeds for the application will determine the drive's base speed.

Speed Regulation

The allowable amount of speed variation should be considered. Does the application require unvarying speed at all torque values or will variations be tolerated?

Torque Requirements

The starting, peak and running torques should be considered when selecting a drive. Starting torque requirements can vary from a small percentage of the full load to a value several times full load torque. The peak torque varies because of a change in load conditions or mechanical nature of the machine. The motor torque available to the driven machine must be more than that required by the machine from start to full speed. The greater the excess torque, the more rapid the acceleration potential.

Acceleration

The necessary acceleration time should be considered. Acceleration time is directly proportional to the total inertia and inversely proportional to the torque available.

Duty Cycle

Selecting the proper drive depends on whether the load is steady, varies, follows a repetitive cycle of variation or has pulsating torques. The duty cycle, which is defined as a fixed repetitive load pattern over a given period of time, is expressed as the ratio of on-time to the cycle period. When the operating cycle is such that the drive operates at idle, or a reduced load for more than 25% of the time, the duty cycle becomes a factor in selecting the proper drive.

Heating

The temperature of a motor or controller is a function of ventilation and losses. Operating self-ventilated motors at reduced speeds may cause above normal temperature rises. Derating or forced ventilation may be necessary to achieve the rated motor torque output at reduced speeds.

Drive Type

Does the application require performance elements such as quick speed response or torque control? These may require the use of a flux vector or closed loop vector drive, instead of a volts per hertz drive.

Selecting a Drive for a Machine

The application of an adjustable speed drive to power a machine is a mechanical, rather than an electrical problem. When applying the drive, the speed-torque-horsepower characteristics developed at the motor's shaft must be considered, and how well these characteristics suit the machine.

Four essential parameters are:

1. Breakaway Torque
2. Process Torque
3. Accelerating Torque
4. Running Torque

Breakaway Torque

This is the torque required to start the machine in motion. It is usually greater (except for centrifugal pumps and fans) than the torque required to maintain motion (running torque). Breakaway torque combined with process torque frequently determines drive selection. Typical breakaway torques for various machine types are given in Table 5.

Process Torque

This is the torque required to pull, push, compress, stretch or otherwise process or act upon the material being transported by or through the machine. On some machines, process torque may be so significant as to determine the drive power rating. On other machines, this load may be insignificant. The process torque load is superimposed on all other static and dynamic torque requirements of the machine.

Accelerating Torque

This is the torque required to bring the machine to an operating speed within a given time. With most machines, the load is largely friction and a standard drive rating may have adequate torque for satisfactory acceleration. However, certain machines classified as "high inertia" with flywheel, bull gears or other large rotating masses may require drive selection based upon the power required to accelerate the load within a given time.

Running Torque

This is the torque required to maintain the drive process or machine after it accelerates to the desired operating speed. The characteristics of the speed and torque curves of various machines are very important to the proper drive selection. All machines generally can be classified into load types as follows:

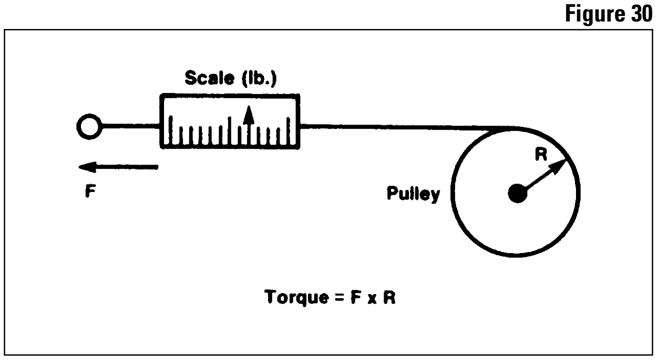
Constant Torque (e.g., conveyors)
Constant Horsepower (e.g., machine tools)
Squared Exponential Horsepower (e.g., mixers)
Cubed Exponential Horsepower (e.g., fans)

Additional load application information is given in Table 5.

Measuring Machine Torque

To measure the torque required to drive a machine, fasten a pulley securely to the shaft which the motor is to drive. Fasten one end of a cord to the outer surface of the pulley and wrap a few turns of the cord around the pulley. Tie the other end of the cord to a spring scale. See Figure 30.

Figure 30



Pull gently on the scale until the shaft turns. Do not yank. The force in pounds or ounces, indicated on the scale, multiplied by the radius of the pulley (measured from the centerline of the machine shaft) in inches gives the torque value in lb-in or oz-in. On some machines, this torque may vary as the shaft rotates. The highest value of torque must be used when selecting a motor. Note that the torque requirement may be dependent upon temperature and bad conditions.

The running torque required by a machine will be less than the starting torque if the load is composed almost entirely of friction. If the load is primarily inertia or windage, the characteristics of the inertia or windage producing elements must be determined.

Most machines require a higher torque value to break it away, but once running, the torque requirement will decrease. Many drives have 150% load capacity for 1 minute, which may allow the required additional breakaway torque to be obtained without increasing the drive horsepower rating.

If the running torque is equal to or less than the breakaway torque divided by 1.5, use the breakaway torque divided by 1.5 as the full load torque required to determine the drive horsepower.

If the running torque is greater than breakaway torque, divided by 1.5, use the running torque as the full load rated torque required to determine the drive horsepower.

Refer to specific controller drive specifications in the product sections of the Cutler-Hammer product guide to match the AFD with the driven machine requirements.

Drive Application Questions

1. **What is the maximum output speed of the drive in RPM** — Because the AC motor is a slip device, the synchronous rpm derived from calculations will always be greater than the actual operating rpm. As an example, a 4-pole AC motor with a synchronous speed of 1800 rpm will typically operate at 1750 rpm at full load. Therefore, if the maximum output speed required of the drive is greater than the synchronous rpm of the motor, then either an adjustable frequency drive running above base speed must be used, or some type of belting or gearing is necessary.
2. **Does the environment have an explosive atmosphere** — If the atmosphere is classified by the NEC to be hazardous or semi-hazardous (Division I or Division II), the drive must be selected with caution. Using adjustable frequency is not an easy matter. An AC motor in a hazardous environment powered by an AFD can only be purchased from vendors having UL labels for motors designed for AFD operation. Even then, the AFD must be located in a separate room away from the explosive environment. Contact Cutler-Hammer for additional information.
3. **Does the environment have any magnetic dust present** — Use of a protected AC motor with an adjustable frequency drive is a way to solve this problem. However, the AFD must again be placed away from the magnetic dust, which is likely to be conductive and could cause short circuits on the drive's printed circuit boards and power components.

4. **Will the drive be subject to harsh chemicals or washdown** — If the drive will be subject to washdown or harsh chemicals, the AC motor will require protection, such as epoxy coating. An AC motor enclosure, such as a TEFC, can be purchased to preclude any intrusion of washdown by-products or chemicals. The AFD portion, once again, must be located in a clean, dry environment.
5. **What is the required dynamic response** — Dynamic response pertains to the drive's ability to respond to a given speed or load change. Given this need, the drive will cause the load to accelerate or decelerate as required.
6. **How often is the drive required to reverse** — Reversing with an adjustable frequency drive does not require the use of a reversing starter, as the drive itself acts as a starter. When reversing is commanded, the output frequency ramps down to zero, or minimum frequency. At this point, the firing sequence of the output semiconductors is changed, causing reverse motor rotation. The output frequency then ramps up until it matches the reference commanded. If frequent reversing is required (more than once per minute) for an application, a duty cycle calculation should be made.
7. **What is the type of drive load** — Variable torque loads are typically exhibited by pumps and fans. The torque varies with the square of speed of the motor. The horsepower varies with the cube of speed of the motor. Constant torque loads are typically employed by conveyors, stamping presses and extruders. The torque required by the load remains constant regardless of motor speed. The horsepower of the load varies directly with the speed of the motor. Adjustable frequency drives are suitable for both variable and constant torque loads.

Additional Questions

After running through the above "traps", you will find that a high percentage of applications can be satisfied by using an adjustable frequency drive. There are some additional questions which need to be answered to properly apply the drive.

1. **What is the input power that will be connected to the drive** — The input voltage, frequency, and voltage and frequency variations must be identified in order to properly select the drive.
2. **What is the speed range required for the application** — If an inverter duty motor is not used, a speed range in excess of 2:1 most likely will require motor oversizing or external cooling in order to prevent damage to the motor insulation. The cooling properties of an AC motor fan are reduced as it slows down.
3. **What is the nameplate current rating of the AC motor** — AFDs are both current and horsepower rated. As such, the AFD's output current rating must be in excess of the motor's full load current rating, plus 5% to cover for harmonic content of the AFD's output current waveform. The AFD's horsepower rating must exceed the motor's horsepower rating at base speed. When applying an adjustable frequency drive to input power, other than its rated value, care must be exercised to ensure that the current rating of the AC motor remains less than the current rating of the AFD.

AFD Application Checklist

The "AFD Application Checklist" on the following pages can be used to record the answers to the "Drive Application Questions."

AFD Application Checklist

This "AFD Application Checklist" is for your use when you collect the information necessary to select the proper AFD for your project. If you have more questions, contact your Cutler-Hammer representative.

Motor

New ____________ Existing ___________ Horsepower ______ Base Speed ______ Voltage ___________

FLA ______________ LRA ______________ NEMA Design _____ Gearbox/Pulley Ratio ____________________

Service Factor _________________________

Load

Application: ____

Load Type: Constant Torque _______ Variable Torque ________ Constant Horsepower______________

Load inertia reflected to motor: ____ $lb\text{-}ft^2$

Required breakaway torque from motor: ____ lb-ft ①

Running load on motor: ____ lb-ft ①

Peak torques (above 100% running): ____ lb-ft ①

Shortest/longest required accel. time: _______ / _______ secs up to __________ Hz from zero speed

Shortest/longest required decel. time: _______ / _______ secs down to _______ Hz from max. speed

Operating speed range: _______ Hz to _______ Hz

Time for motor/load to coast to stop: _________ secs

① Very Important

AFD

Source of start/stop commands: ____

Source of speed adjustment: ____

Other operating requirements: ____

Will the motor ever be spinning when the AFD is started? ____

Is the load considered to be high inertia? ____

Is the load considered to be hard to start?____

Distance from AFD to the motor: _________________ feet

Type of AFD (V/Hz, Flux Vector, Closed Loop Vector): ____

Options desired: ____

____

____

Other Special Requirements/Conditions: ____

Drive Selection

Power Supply

Supply Transformer: ________ KVA and ________ % Z or Short Circuit current at drive input: ________ amps

(If the drive does not include a built-in line reactor and the available feeder short circuit current is more than 100 times the drive FLA rating, a 1% line reactor or a drive isolation transformer is required.)

Total horsepower of all drives connected to supply transformer or feeder: ________ hp

Is a drive transformer or line reactor desired? ____

Any harmonic requirements? __________ % Voltage THD: __________ % Current THD: _________ IEEE519: _________

Total non-drive load connected to the same feeder as drive(s): ________ amps

Service

Start-up assistance: ______________________________ Customer Training: ______________________________

Preventative maintenance: ___________________________ Spare Parts: ______________________________

Additional Issues

(If any of the following are answered yes, consult your Cutler-Hammer sales office with details.)

Will the AFD operate more than one motor? ____

Will the power supply source ever be switched with AFD running? ________________________________

Is starting or stopping time critical? ____

Are there any peak torques or impact loads? ____

Will user supplied contactors be used on the input or output of the AFD? __________________________

Does the user or utility system have PF capacitors that are being switched? _________________________

Will the AFD be in a harsh environment or high altitude? ____________________________________

Does the utility system experience surges, spikes or other fluctuations? ___________________________

Formulae, Conversions and Tables

Introduction

This section of your *Application Guide* provides a rich resource of formulae, conversions and tables:

- How to Calculate Torque
- How to Calculate Horsepower
- How to Calculate Surface Speed
- How to Calculate Horsepower for Pumps
- How to Calculate Horsepower for Fans and Blowers
- How to Calculate Horsepower for Conveyors
- How to Calculate Accelerating Torque
- How to Calculate Maximum Motor Torque
- How to Calculate WK^2
- How to Calculate Equivalent WK^2 at Motor Shaft
- Electrical Formulae
- Induction Motor Formulae
- Tables of Conversions and Abbreviations

How to Calculate Torque

$$\text{Torque (lb-ft)} = \frac{\text{hp} \times 5250}{\text{Speed (rpm)}}$$

How to Calculate Horsepower

Definition: 1 horsepower = 550 ft-lb per second.

For rotating objects:

$$\text{hp} = \frac{\text{Torque (lb-ft)} \times \text{Speed (rpm)}}{5250}$$

$$\text{hp} = \frac{\text{Torque (lb-ft)} \times \text{Speed (rpm)}}{63{,}000}$$

For object or material in linear motion:

$$\text{hp} = \frac{\text{Force (lb-ft)} \times \text{Velocity (in/min)}}{396{,}000}$$

$$\text{hp} = \frac{\text{Force (lb-ft)} \times \text{Velocity (ft/min)}}{33{,}000}$$

Tension may be substituted for force in the above formulae.

How to Calculate Surface Speed

Surface speed (ft/min) = rpm x Radius (ft) x 6.283

How to Calculate Horsepower for Pumps

$$\text{hp} = \frac{\text{Flow} \times \text{Head} \times \text{Specific Gravity}}{3960 \times \text{Efficiency of Pump}}$$

Where:
(Flow in gal/min; Head in ft)
Head in feet is pressure (lb/in^2) x 2.307.

$$\text{Specific Gravity} = \frac{\text{Density of Fluid}}{\text{Density of Water}}$$

Where:
Density of water =
62.43 lb/ft^3 at 39.2°F (4°C)
Specific Gravity of Water = 1.0

Efficiency is expressed as a decimal.
(Efficiency of 0.85 is 85% efficient).

Typical Values of Efficiency for Centrifugal Pump **Table 6**

Gallons per Minute	Efficiency
500 to 1000	0.70 to 0.75
1000 to 1500	0.75 to 0.80
over 1500	0.80 to 0.85

Typical values of efficiency for positive displacement pumps:
Efficiency = 85 to 90

Effects of Changing Pump Speed; for Centrifugal Pumps:
$hp = K_1(rpm)^3$
Horsepower is proportional to cube of speed.

$Torque = K_2(head)$
Torque is constant at all speeds with a constant head.

$Flow = K_3(rpm)$
Flow is directly proportional to speed.

How to Calculate Horsepower for Fans and Blowers

$$\text{hp} = \frac{\text{Flow} \times \text{Pressure}}{229 \times \text{Efficiency of Fan}}$$

(Flow in ft^3/min; Pressure in lbs/in^2)

$$hp = \frac{\text{Flow x Pressure}}{\text{6356 x Efficiency of Fan}}$$

(Flow in ft^3/min; Pressure in inches of water gauge)

Efficiency is expressed as a decimal (efficiency of 0.85 is 85% efficient).

How to Calculate Horsepower for Conveyors

$$hp\ (\text{Vertical}) = \frac{\text{F x V}}{\text{33,000 x Efficiency}}$$

$$hp\ (\text{Horizontal}) = \frac{\text{F x V x Coef. of Friction}}{\text{33,000 x Efficiency}}$$

Where:
F = Force (lbs)
V = Velocity (ft/min)
Coef. of Friction:
Ball or Roller Slide = 0.02
Dovetail Slide = 0.20
Hydrostatic Ways = 0.01
Rectangle Ways with Gib = 0.1 – 0.25

How to Calculate Accelerating Torque

In addition to the torque required to drive a load at a steady speed, torque is required to accelerate the load inertia from standstill to operating speed. The torque required for acceleration is determined by the inertia and the required rate of acceleration.

The following formula is used to calculate acceleration torque (torque required above load torque) of a rotating member:

$$T = \frac{(WK^2)(dN)}{308t}$$

Where:
T = acceleration torque (lb-ft)

WK^2 = total system inertia (lb-ft^2) that the motor must accelerate. This value includes motor rotor, reducer and load. See "How to Calculate WK^2" that follows.

dN = change in speed required (rpm)

t = time to accelerate total system load (seconds)

The formula can also be arranged to calculate acceleration time given inertia, available torque and required speed change.

$$t = \frac{(WK)^2(dN)}{308T}$$

The accelerating force required for linear motion is given by:

$$\text{Accelerating Force (F)} = \frac{W\ (dV)}{1933t}$$

Where:
W = weight (lbs)
dV = change in velocity (fpm)
t = time (seconds) to accelerate weight

For motor selection, this force must be converted to motor torque and added to the torque required for accelerating the rotating parts of the machine. See also "How to Calculate WK^2" that follows. The weight of the linear moving parts can be converted to an equivalent WK^2 at the motor shaft, eliminating the force calculations.

How to Calculate Maximum Motor Torque

Maximum Motor Torque	=	Running Torque	+	Accelerating Torque

How to Calculate WK^2

The factor WK^2 (inertia) is the weight of a rotating object multiplied by the square of the radius of gyration K. For weight in pounds and radius of gyration in feet, WK^2 is in lb-ft^2.

For a solid cylinder:

$$WK^2 = \frac{\text{Density x Length x Diameter}^4}{1467}$$

Where:
Density of material is in pounds per cubic inch.
Length and diameter are in inches.
Given weight in pounds and diameter in feet:

$$WK^2 = \frac{\text{Weight x Diameter}^2}{8}$$

For a hollow cylinder:

$$WK^2 = \frac{\text{Density x Length x } (OD^4 - ID^4)}{1467}$$

Where:
Density of materials is in pounds per cubic inch.
Length and diameter are in inches.
Given weight in pounds and diameter in feet:

$$WK^2 = \frac{\text{Weight x } (OD^2 + ID^2)}{8}$$

Density Values for Common Materials **Table 7**

Material	Density lb/in^3
Aluminum	0.0924
Bronze	0.3200
Cast Iron	0.2600
Nylon	0.0510
Paper	0.0250 to 0.0420
Steel	0.2820
Rubber	0.0341

WK^2 of Solid Steel Cylinders One Inch Long

Table 8 lists values of WK^2 in lb-ft^2 for one inch long solid steel cylinders of various diameters. For cylinders longer or shorter than one inch, multiply the value given by the actual length in inches. Values can be determined for diameters not listed by moving the decimal point in the diameter in either direction and moving the decimal point in the corresponding value of WK^2 four places in the same direction for every one place the decimal is moved in the diameter.

For hollow cylinders, subtract the WK^2 given for the inside diameter from the WK^2 given from the outside diameter.

The WK^2 are for steel with a density of 0.2820 lbs per in^3. For other materials, multiply the WK^2 by the density from the table:

$$\frac{\text{lbs per in}^3 \text{ of material}}{0.2820}$$

How to Calculate Equivalent WK^2 at the Motor Shaft

In most mechanical systems not all of the moving parts operate at the same speed. If the speeds of the various parts have a continuous fixed relationship to the motor speed, the following formulae can be used to convert all of the various inertia values to an equivalent WK^2 applied to the motor shaft.

For rotating parts:

$$\text{Equivalent } WK^2 = WK^2 \left[\frac{N}{N_m}\right]^2$$

Where:
WK2 = inertia of the moving part (lb-ft^2)
N = speed of the moving part (rpm)
N_m = speed of the driving motor (rpm)

When using speed reducers, and the machine inertia is reflected back to the motor shaft, the equivalent inertia is equal to the machine inertia divided by the square of the drive reduction ratio.

$$\text{Equivalent } WK^2 = \frac{WK^2}{(DR)^2}$$

Where:
DR = drive reduction ratio N_m/N

For linear motion:

Not all driven systems involve rotating motion. The equivalent WK^2 of linearly moving parts can also be reduced to the motor shaft speed as follows:

$$\text{Equivalent } WK^2 = \frac{W(V)^2}{39.5\,(N_m)^2}$$

Where:
W = weight of load (lbs)
V = linear velocity of moving parts (feet per minute)
N_m = speed of the driving motor (rpm)

Electrical Formulae

Ohms Law

Amperes = Volts/Ohms, or I = E/R
Ohms = Volts/Amperes, or R = E/I
Volts = Amperes x Ohms, or E = IR

Power in DC Circuits

Watts = Volts x Amperes, or W = EI

$$\text{Horsepower (hp)} = \frac{\text{Volts x Amperes}}{746}$$

$$\text{Kilowatts (kW)} = \frac{\text{Volts x Amperes}}{1000}$$

$$\text{Kilowatts Hours (kWH)} = \frac{\text{Volts x Amperes x Hours}}{1000}$$

Power in AC Circuits

Kilovolt-Amperes(kVA)

$$\text{kVA (1-ph)} = \frac{\text{Volts x Amperes}}{1000}$$

$$\text{kVA (3-ph)} = \frac{\text{Volts x Amperes x 1.73}}{1000}$$

Kilowatts (kW)

$$\text{kW (1-ph)} = \frac{\text{Volts x Amperes x PF}}{1000}$$

$$\text{kW (3-ph)} = \frac{\text{Volts x Amperes x PF x 1.73}}{1000}$$

Kilowatt Hours (kWH)

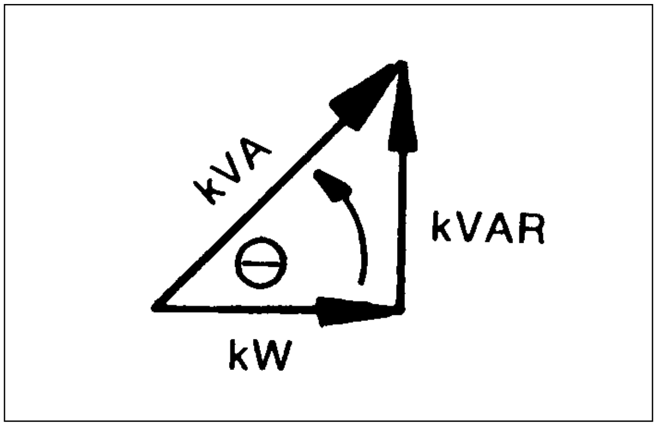
kWH = kW x Hours

Kilovolt-Amperes Reactive (kVAR)

kVAR = kVA SIN Θ

Power Factor

$$PF = \Delta \, COS\Theta = \frac{kW\ (input)}{kVA\ (input)}$$



Induction Motor Formulae

Synchronous Speed

$$\text{Sync. rpm} = \frac{120f}{p}$$

Where:
p = number of poles
f = frequency (Hz)

Operating Speed

rpm = Sync rpm - Slip rpm

$$\text{Slip rpm} \approx \frac{2 \times \text{percent load}}{p} \quad \text{(approx.)}$$

For 3-Phase Motors

$$\text{Current (Amps)} = \frac{hp \times 746}{\sqrt{3} \times \text{Volts} \times \text{Efficiency} \times PF}$$

$$= \frac{hp \times 431}{\text{Volts} \times \text{Efficiency} \times PF}$$

$$\text{Locked Rotor Current (Amps)} = \frac{hp \times \text{start kVA/hp} \times 1000}{\text{Volts} \times \sqrt{3}}$$

At frequencies other than 60 Hz, LRA can be estimated by:

$$LRA = LRA \text{ at } 60\ Hz \times \frac{f}{60}$$

Calculating Power for Any Motor

$$kW\ (input) = \frac{hp \times 0.746}{efficiency}$$

kW (output) = hp x 0.746

WK^2 of Solid Steel Cylinders One Inch Long — Table 8

Diameter in Inches	WK^2	Diameter in Inches	WK^2	Diameter in Inches	WK^2	Diameter in Inches	WK^2	Diameter in Inches	WK^2
1	0.000192	41	543.9	81	8286	121	41262	161	129336
2	0.00308	42	598.8	82	8703	122	42643	162	132579
3	0.01559	43	658.1	83	9135	123	44059	163	135883
4	0.049278	44	721.4	84	9584	124	45510	164	139249
5	0.12030	45	789.3	85	10048	125	46995	165	142676
6	0.2494	46	861.8	86	10529	126	48517	166	146166
7	0.46217	47	939.3	87	11028	127	50076	167	149720
8	0.78814	48	1021.8	88	11544	128	51672	168	153339
9	1.262	49	1109.6	89	12077	129	53305	169	157022
10	1.924	50	1203.07	90	12629	130	54978	170	160772
11	2.818	51	1302.2	91	13200	131	56689	171	164588
12	3.991	52	1407.4	92	13790	132	58440	172	168472
13	5.497	53	1518.8	93	14399	133	60231	173	172424
14	7.395	54	1636.7	94	15029	134	62063	174	176446
15	9.745	55	1761.4	95	15679	135	63936	175	180537
16	12.61	56	1893.1	96	16349	136	65852	176	184699
17	16.07	57	2031.9	97	17041	137	67811	177	188933
18	20.21	58	2178.3	98	17755	138	69812	178	193239
19	25.08	59	2332.5	99	18490	139	71858	179	197618
20	30.79	60	2494.7	100	19249	140	73948	180	202071
21	37.43	61	2665.2	101	20031	141	76083	181	206599
22	45.09	62	2844.3	102	20836	142	78265	182	211203
23	53.87	63	3032.3	103	21665	143	80493	183	215883
24	63.86	64	3229.5	104	22519	144	82768	184	220640
25	75.19	65	3436.1	105	23397	145	85091	185	225476
26	87.96	66	3652.5	106	24302	146	87463	186	230391
27	102.30	67	3879.0	107	25232	147	89884	187	235386
28	118.31	68	4115.7	108	26188	148	92355	188	240461
29	136.14	69	4363.2	109	27173	149	94876	189	245619
30	155.92	70	4621.7	110	28183	150	97449	190	250858
31	177.77	71	4891.5	111	29222	151	100075	191	256182
32	201.8	72	5172	112	30289	152	102750	192	261589
33	228.2	73	5466	113	31385	153	105482	193	267081
34	257.2	74	5772	114	32511	154	108268	194	272660
35	288.8	75	6090	115	33667	155	111107	195	278325
36	323.2	76	6422	116	34853	156	114002	196	284078
37	360.7	77	6767	117	36071	157	116954	197	289920
38	401.3	78	7125	118	37320	158	119962	198	295852
39	445.3	79	7498	119	28601	159	123028	199	301874
40	492.78	80	7885	120	39914	160	126152	200	307988

Standard Abbreviation Descriptions **Table 8**

Temperature	deg. = degrees C = Celsius (Centigrade) F = Fahrenheit Btu = British Thermal Unit	**Work/Inertia**	ft-lb = foot pound WK^2 = moment of inertia $N•m^2$ = Newton meters^2 r = radius k = radius of gyration
Length	yd = yard m = meter mm = millimeter (1/1000 of a meter) cm = centimeter (1/100 of a meter) in = inch ft = feet km = kilometer	**Area**	ft^2 = square foot sq. m = square meter mil = unit of length of angular measurement mm^2 = square millimeter in^2 = square inch
Weight	oz = ounce lb = pound kg = kilogram gm = gram	**Rotation/Rate**	FPM = feet per minute FPS = feet per second m/s = meters per seconds mph = miles per hour cfm = cubic feet per minute
Electrical	Ω = Ohms ϕ = Phase V = Volts A = Amperes mA = milliamperes μA = microamperes mV = millivolts kV = kilovolts kVA = kilovolts-amps kVAR = kilovolt-amps reactive Hz = Hertz, cycle per second	**Mathematic** **Pressure**	π = "pi" rad. = radians ρ = Density Σ = Summation Δ = Change kg per sq. cm = kilograms per square centimeter Hg = Mercury symbol PSI = pounds per square inch PSF = pounds per square foot
Power/Energy	hp = horsepower W = watt kW = kilowatt kWH = kilowatt-hours J = Joule	**Volume**	cu. = cubic in^3 = cubic inch gal. = gallon ft^3 = cubic foot ml = milliliter fl. oz = fluid ounce (U.S.)

Useful Conversion Constants **Table 10**

	To Convert From	To	Multiply By
AREA	in^2	cm^2	6.4516
	ft^2	m^2*	9.2903 x 10^{-2}
	yd^2	m^2*	0.83613
	ft^2	yd^2	0.11111
ENERGY	Btu (thermochemcial)	Joule (J)*	1054.4
	Btu (thermochemical)	kWH	2.9288 x 10^{-4}
	calorie (thermochemical)	Joule (J)*	4.184
	hp-hr	kWH	1.341
	ft-lb	Joule (J)*	1.3558
	ft-lb	Btu	1.2859 x 10^{-3}
	ft-lb	kWH	3.7662 x 10^{-7}
	kWH	Joule (J)*	3.6 x 10^{6}
FLOW Mass	lb/hp-hr**	kg/Joule*	1.6897 x 10^{-7}
	**Specific fuel consumption (SFC)		
	lb-hr	kg/hr	45359
	lb/min	kg/sec*	7.5599 x 10^{-3}
	lb/sec	kg/sec*	0.45359
	oz/min	g/min	28.35
FLOW Vol.	gpm	liter/min	3.7854
	gpm	m^3/sec*	6.309 x 10^{-5}
	in^3/sec	cm^3/sec	16.387
	gal/hp-hr***	m^3/Joule*	1.4101 x 10^{-9}
	***Specific fuel consumption (SFC)		
	ft^3/sec	m^3/sec*	2.8317 x 10^{-2}
	cfm	m^3/hr	1.699
FORCE	kg	Newtons (N)*	9.8067
	oz (avoirdupois)	Newtons (N)*	0.27801
	lb (avoirdupois)	Newtons (N)*	4.4482
	gm	Newtons (N)*	9.8067 x 10^{-3}
	kg	lb (avoirdupois)	2.2046
	ton (2000 lb)	Newton*	8896.4
	ton (2000 lb)	kg	907.18
	oz (avoirdupois)	gm	28.35
	lb (avoirdupois)	gm	453.59
LENGTH	ft	meter (m)*	0.3048
	in	cm	2.54
	mile (statute)	km	1.6093
	mil	mm	2.54 x 10^{-2}
	To	**To Convert From**	**Divide By**

	To Convert From	To	Multiply By
MASS	lb (avoirdupois)	kg*	0.45359
	lb (avoirdupois)	gm	453.59
	oz (avoirdupois)	gm	28.35
	slug	kg*	14.594
	ton (2000 lb)	kg*	907.18
	ton (metric)	kg*	1000
POWER	hp (550 ft-lb/sec)	watt*	745.7
	ton (refrigeration)	watt	3516.8
	ton (refrigeration)	hp	4.7161
	hp (550 ft-lb/sec)	hp (metric)	1.0139
	Btu/min (thermochemical)	watt	17.573
	Btu/sec (thermochemical)	hp (550 ft-lb/sec)	1.4139
	calorie/sec (thermochemical)	watt*	4.184
PRESSURE	PSI	kPa	6.8948
	ft of water (39.2°F)	kPa	2.989
	gm/cm^2	Pa*	98.067
	in Hg (32°F)	kPa	3.3864
	atmosphere	kPa	101.33
	atmosphere	PSI	14.696
	in Hg (32°F)	PSI	0.49115
	ft of water (39.2°F)	PSI	0.43351
	in of water (39.2°F)	PSI	3.6126 x 10^{-2}
	in of water (39.2°F)	kPa	0.24908
	mm Hg @ 0°C (= Torr)	kPa	0.13332
	mm Hg @ 0°C (= Torr)	PSI	1.9337 x 10^{-2}
TEMP.	°F	°C*	t°$_c$ = (t°$_f$ - 32)/1.8
	°C*	°F	t°$_f$ = (1.8)(t°$_c$) + 32
	°C*	°K*	t°$_k$ = t°$_c$ + 273.15
	°F	°R	t°$_r$ = t°$_f$ + 459.67
TORQUE	lb-in	N-m*	0.11298
	lb-ft	N-m*	1.3558
	oz-ft	N-m*	8.4739 x 10^{-2}
	oz-ft	lb-in	0.75
	kg-m	N-m*	9.8067
	oz-in	gm-cm	72.008
	kg-m	lb-in	86.796
	dyne-cm	oz-in	1.4161 x 10^{-5}
	dyne-cm	N-m*	1 x 10^{-7}
	To	**To Convert From**	**Divide By**

*Indicates Standard International (S) Unit

Formulae, Conversions and Tables

Useful Conversion Constants

Table 11

	To Convert From	To	Multiply By
VELOCITY	ft/min	mph	1.1364×10^{-2}
	mph	kWH	1.6093
	mph	meter/sec*	0.44704
	ft/sec	meter/sec*	0.3048
	rpm	radians/sec	0.10472
	revolutions/sec	radians/sec	6.2832
VOLUME	barrel (oil, 42 gal)	$meter^3$	15699
	barrel (oil, 42 gal)	gallon (U.S. liquid)	42
	barrel (42 gal)	liter	158.99
	barrel (42 gal)	ft^3	5.6146
	gallon (U.S. liquid)	liter	3.7854
	gallon (U.S. liquid)	in^3	231
	gallon (U.S. liquid)	$meter^3$	3.7854×10^{-3}
	quart (U.S. liquid)	in^3	57.75
	quart (U.S. liquid)	liter	0.94635
	fluid oz (U.S. liquid)	in^3	1.8047
	fluid oz (U.S. liquid)	cm^3	29.571
	liter	$meter^3$	1×10^{-3}
	liter	cm^3	1000
	liter	in^3	61.024
	in^3	cm^3	16.387
	ft^3	in^3	1728
	ft^3	liter	28.317
	To	**To Convert From**	**Divide By**

HOW TO USE

Direct Conversion

Multiply known value by conversion factor to obtain equivalent value in desired units. For example, 203 in^2 is converted to cm^2, as follows:

$$203 \text{ in}^2 \times 6.4516 = 1309.67 \text{ cm}^2$$

Inverse Conversion

Divide known value by conversion factor to obtain equivalent value in desired units. For example, 10.82 N-m converted to oz-ft, as follows:

$$\frac{10.82 \text{ N-m}}{8.4739 \times 10^{-2}} = 127.69 \text{ oz-ft}$$

Formulae, Conversions and Tables

Fractional Inch to Equivalent Millimeters and Decimals **Table 12**

Inch	Equivalent		Inch	Equivalent	
	mm	Decimal		mm	Decimal
1/64	0.3969	0.0156	33/64	13.0969	0.5156
1/32	0.7938	0.0313	17/32	13.4938	0.5313
3/64	1.1906	0.0469	35/64	13.8906	0.5469
1/16	1.5875	0.0625	9/16	14.2875	0.5625
5/64	1.9844	0.0781	37/64	14.6844	0.5781
3/32	2.3813	0.0938	19/32	15.0813	0.5938
7/64	2.7781	0.1094	39/64	15.4781	0.6094
1/8	3.1750	0.1250	5/8	15.8750	0.6250
9/64	3.5719	0.1406	41/64	16.2719	0.6406
5/32	3.9688	0.1563	21/32	16.6688	0.6563
11/64	4.3656	0.1719	43/64	17.0656	0.6719
3/16	4.7625	0.1875	11/16	17.4625	0.6875
13/64	5.1594	0.2031	45/64	17.8594	0.7031
7/32	5.5563	0.2188	23/32	18.2563	0.7188
15/64	5.9531	0.2344	47/64	18.6531	0.7344
1/4	6.3500	0.2500	3/4	19.0500	0.7500
17/64	6.7469	0.2656	49/64	19.4469	0.7656
9/32	7.1438	0.2813	25/32	19.8438	0.7813
19/64	7.5406	0.2969	51/64	20.2406	0.7969
5/16	7.9375	0.3125	13/16	20.6375	0.8125
21/64	8.3344	0.3181	53/64	21.0344	0.8281
11/32	8.7313	0.3438	27/32	21.4313	0.8438
23/64	9.1281	0.3594	55/64	21.8281	0.8594
3/8	9.5250	0.3750	7/8	22.2250	0.8750
25/64	9.9219	0.3906	57/64	22.6219	0.8906
13/32	10.3188	0.4063	29/32	23.0188	0.9063
27/64	10.7156	0.4219	59/64	23.4156	0.9219
7/16	11.1125	0.4375	15/16	23.8125	0.9375
29/64	11.5094	0.4513	61/64	24.2094	0.9531
15/32	11.9063	0.4688	31/32	24.6063	0.9688
31/64	12.3031	0.4844	63/64	25.0031	0.9844
1/2	12.700	0.5000	—	—	—

Glossary

AC Contactor
An alternating current (AC) contactor is designed for the specific purpose of establishing or interrupting an AC power circuit. Also see *Contactor*.

Adjustable Speed
The concept of varying the speed of a motor, either manually or automatically. The desired operating speed (set speed) is relatively constant regardless of load.

Adjustable Frequency Drive (AFD)
The adjustable frequency drive is composed of the motor, drive controller and operator's controls (either manual or automatic).

Ambient Temperature
Ambient temperature is the temperature of the medium, such as air, water or earth, into which the heat of the equipment is dissipated.

For self-ventilated equipment, the ambient temperature is the average temperature of the air in the immediate neighborhood of the equipment.

For air or gas cooled equipment with forced ventilation, or secondary water cooling, the ambient temperature is taken as that of the ingoing air or cooling gas.

For self-ventilated enclosed (including oil immersed) equipment, considered as a complete unit, the ambient temperature is the average temperature of the air outside of the enclosure in the immediate neighborhood of the equipment.

Antihunt
Antihunt is the means of reducing or suppressing the oscillation of a system.

Antiplug Protection
The effect of a control function, or a device that operates to prevent application of counter torque, by the motor until the motor speed has been reduced to an acceptable value.

Armature
The laminated iron core with wire wound around it, in which electromotive force is produced by magnetic induction in a motor or generator; usually the stator of an AC motor.

Auxiliary Contacts
Auxiliary contacts of a switching device are contacts in addition to the main circuit contacts and operate with the movement of the latter.

Axis
A principal direction along which movement of the tool or workpiece occurs. The term "axis" also refers to one of the reference lines of a coordinate system.

Back of a Motor
The back of a motor is the end which carries the coupling or driving pulley (NEMA). This is sometimes called the drive end (D.E.) or pulley end (P.E.).

Bandwidth
Generally, this is the frequency range of a sinusoidally changing reference signal which can be accurately followed by a regulator. Speed loop bandwidth and torque loop bandwidth are measures of the performance of high performance or servo drives. This measure of performance usually involves reference signal changes with an amplitude on the order of 10% of the total control range, and is termed "small signal bandwidth."

Base Speed
Base speed is the manufacturer's nameplate rating where the motor will develop rated horsepower at rated load and voltage. With AC systems, it is commonly the point where 60 Hz is applied to the induction motor.

Bearing (Ball)
A "ball" shaped component that is used to reduce friction and wear while supporting rotating elements. For a motor, this type of bearing provides a relatively rigid support for the output shaft.

Bearing (Roller)
A special bearing system with cylindrical rollers capable of handling belted load applications that are too large for standard ball bearings.

Bipolar Transistor
Ordinary NPN or PNP transistors with emitter, base and collector are called bipolar since they operate through the flow of both holes and electrons. The most typical type is the Darlington, made up of several transistors, where a smaller transistor provides the large drive current required by the power transistor. Unipolar devices, such as FET transistors, operate through the flow of minority carriers only; i.e., electron flow.

Braking

Braking provides a means of stopping an AC motor and can be accomplished in several ways:

A. Dynamic Braking (AC Drives) — Since AC motors do not have separate field excitation, dynamic braking is accomplished by continuing to excite the motor from the drive. This causes a regenerative current to the drive's DC intermediate bus circuit. The dynamic brake resistors are then placed across the DC bus to dissipate the power returned. The brake resistor is usually switched by a transistor or other power switch controlled by the drive.

B. Regenerative Braking — This is similar to dynamic braking, but is accomplished electronically. The generated power is returned to the line through the power converter.

C. Motor Mounted or Separately Mounted Spring Set Brake — This is a positive action, mechanical, friction device. Normal configuration is such that when the power is removed, the brake is set. This can be used as a holding brake. (Note: a separately mounted brake is one which is located on some part of the mechanical drive train other than the motor).

D. Eddy-Current Brake — Eddy currents are generated in the brake drum to produce braking torque for retarding or stopping shaft rotation. Braking torque is transmitted by the eddy-current principle when voltage is applied to the brake coil, with the rate of shaft deceleration being determined by the amount of excitation applied to the coil. Braking torque, which is a function of speed and brake coil excitation, is provided throughout most of the speed range, but drops to zero as the shaft approaches zero rpm. Therefore, this brake cannot serve as a holding brake.

E. Friction Brake — An electromagnetic field is established between the brake coil and armature assemblies only while the brake coil is energized. Upon energizing the brake coil, these two assemblies are drawn together and stop shaft rotation by friction. The rate of shaft deceleration is determined by the amount of excitation applied to the coil. As long as excitation is applied to the brake coil, the two assemblies will remain locked together, thereby servicing as a holding brake.

F. DC Dynamic Braking – A low DC voltage is applied to the AC motor stator at low speed. A braking torque is developed which will slow the motor down quickly. No braking torque exists if the shaft is at zero speed.

Breakaway Torque

The torque required to start a machine from standstill.

Breakdown Torque

The breakdown torque of an AC motor is the maximum torque which it will develop with rated voltage applied at rated frequency.

Bridge Rectifier

A full wave rectifier that conducts current in only one direction of the input current. AC applied to the input results in pulsating DC at the output.

Bridge Rectifier (Diode, SCR)

A diode bridge rectifier is a non-controlled full wave rectifier that produces a constant, rectified DC voltage. An SCR bridge rectifier is a full wave rectifier with an output that can be varied by switching of the gate control element.

Cascade Drive System

Two or more drives connected to a master speed setting potentiometer. The master speed setting potentiometer sets the speed of the master drive. Each of the slave drives has a potentiometer for trimming the speed reference from the master speed setting potentiometer.

C-Face (Motor/Drive Mounting)

This type of motor mounting is used to closely couple pumps and similar applications where the mounting holes in the face are threaded to receive bolts from the pump. Normally, the C-Face is used where a pump or similar item is to be overhung on the motor. This type of mounting is a NEMA standard design and available with or without feet.

Closed Loop

Closed loop refers to a regulator circuit in which the actual value of the controlled variable (e.g., speed) is sensed, and a signal proportional to this value (feedback signal), is compared with a signal proportional to the desired value (reference signal). The difference between these signals (error signal) causes the actual value to change in the direction that will reduce the difference in signals to zero.

Closed Loop Vector

See *Field Oriented Control*.

Cogging

A condition in which a motor does not rotate smoothly, but "steps" or "jerks" from one position to another during shaft revolution. Cogging is most pronounced at low motor speeds and can cause objectionable vibrations in the driven machine.

Commutation

The process by which forward current is interrupted or transferred from one switching device to the other. In most circuits where power is supplied from an AC source, turn-on control is adequate and turn-off occurs naturally when the AC cycle causes the polarity across a given device to reverse.

Glossary

Comparator
A device that compares one signal to another, usually the process signal compared to the set point or command signal.

Computerized Numerical Control (CNC)
A numerical control system where a computer is used to perform some or all of the basic numerical control functions on a machine tool.

Constant Horsepower Range
A range of motor operation where constant voltage is applied to the motor. In this range, motor torque decreases as speed increases. Since horsepower is speed times torque (divided by a constant), the value of horsepower developed by the motor in this range is constant.

Constant Torque Range
A speed range in which the motor is capable of delivering a constant torque, subject to cooling limitations of the motor.

Constant Voltage Range (AC Drives)
The range of motor operation where the drive's output voltage is held constant as output frequency is varied. This speed range produces motor performance similar to constant horsepower.

Constant Volts per Hertz (V/Hz)
This relationship exists in AC drives where the output voltage is varied directly proportional to frequency. This type of operation is required to allow the motor to produce constant rated torque as speed is varied.

Contactor
A contactor is a two-state (ON/OFF) device for repeatedly establishing and interrupting an electric power circuit. Interruption is obtained by introducing a gap or a very large impedance.

Contactor Reversing
A method of reversing motor rotation by the use of two separate contactors, one of which produces rotation in one direction and the other produces rotation in the opposite direction. The contactors are electrically (and mechanically) interlocked so that both cannot be energized at the same time.

Continuous Duty
Operation of a motor within the insulation temperature limits after it has reached normal operating (equilibrium) temperature.

Continuous Rating
The continuous rating is the maximum constant load that can be carried continuously without exceeding established temperature rise limitations under prescribed conditions of load and within the limitations of established standards.

Control Circuit
The control circuit of a control apparatus or system is the circuit which carries the electric signals directing the performance of the controller, but does not carry the main circuit power.

Control Device
A control device is an individual device used to control functions.

Control Transformer
A control transformer is a voltage transformer utilized to supply voltage suitable for the operation of control devices.

Converter
The device for changing AC to DC. This is accomplished through use of a diode rectifier or thyristor rectifier circuit. The term "converter" may also refer to the device for changing AC to DC to AC (e.g., adjustable frequency drive). A "frequency controller," such as that found in an adjustable frequency drive, consists of a rectifier, a DC intermediate circuit, an inverter and a control unit.

Critical Frequency or Speed
Any frequency or speed at which mechanical resonance occurs in the mechanical drive train or the driven equipment. To avoid damage due to vibration, the drive must not operate at this speed except during acceleration or deceleration.

Current Limit
An electronic method of limiting the maximum current available to the motor. This is adjustable so that the motor's maximum current can be controlled. It can also be preset as a protective device to protect both the motor and controller from extended overloads.

Current Limit Acceleration
A system of control in which acceleration is governed so that the motor current does not exceed an adjustable maximum value.

Current Limiting Fuse
A fuse that, when it is melted by a current within its specified current limiting range, abruptly introduces a high impedance to end the current flow.

Current Relay

A current relay functions at a predetermined value of current. It may be an overcurrent relay, an undercurrent relay or a combination of both.

Damping

Damping is the reduction in amplitude of an oscillation in the system.

DC Contactor

A contactor specifically designed to establish or interrupt a direct current power circuit.

Definite Purpose Motor

A definite purpose motor is any motor design, listed and offered in standard ratings with standard operating characteristics and mechanical construction, for use under service conditions other than usual or for use on a particular type of application (NEMA).

Dead Band

The range of values through which a system input can be changed without causing a corresponding change in system output.

Deviation

Difference between an instantaneous value of a controlled variable, and the desired value of the controlled variable corresponding to the set point. Also called "error."

D-Flange (Motor Mounting)

This type of motor mounting is used when the motor is to be built as part of the machine. The mounting holes of the flange are not threaded. The bolts protrude through the flange from the motor side. Normally D-Flange motors are supplied without feet since the motor is mounted directly to the driven machine.

di/dt

The rate of change in current versus time. Line reactors and isolation transformers can be used to provide the impedance necessary to reduce the harmful effects that unlimited current sources can have on phase controlled rectifiers (SCRs).

Dimension Drawing

A dimensioned or outline drawing (base plan, floor plan, etc.) is one which shows the physical space and mounting requirements of a piece of equipment. It may also indicate ventilation requirements and space provided for connections or the location to which connections are to be made.

Diode

A device that passes current in one direction, but blocks current in the reverse direction.

Drift

Drift is the deviation from the initial set speed with no load change over a specific time period. Normally, the drive must be operated for a specified warm-up time at a specified ambient temperature before drift specifications apply. Drift is normally caused by random changes in operating characteristics of various controller components.

Drive Controller (also Variable Speed Drive)

An electronic device that can control the speed, torque, horsepower and direction of a AC motor.

dv/dt — Converter Input

The rate of change in voltage versus time. Specially designed resistor-capacitor networks can help protect the SCRs from excessive dv/dt which can result form line voltage spikes, line disturbances and circuit configurations with extreme forward conducting or reverse blocking requirements.

dv/dt — Drive Output

The use of high speed switching semiconductors in the drive output results in high dv/dt levels being impressed on the motor windings. Combined with long motor leads, this can cause early motor insulation failure. The use of output filters will reduce the dv/dt to safer levels. See *Peak Voltage*.

Duty Cycle

The relationship between the operating and resting times or repeatable operation at different loads.

Dwell

The time spent in one state before moving to the next. In motion control applications for example, a dwell time may be programmed to allow time for a tool change or part clamping operation.

Dynamic Braking

A system of electric braking in which the motor, when used as a generator, converts the kinetic energy of the load into electric energy dissipated in resistors, and in doing so, exerts a retarding force on the load.

Eddy-Current

The electrical current induced in metallic components from the change in magnetic fields. Motor stators are often laminated to reduce the eddy-current effect.

Eddy-Current Brake

An eddy-current brake consists of a rotating member keyed to a straight-through, double extension shaft and a field coil assembly. The brake rotor rotates at the speed of the prime mover until the field coil is energized. Rotation of the rotor is retarded by controlling the current in the field coil.

Efficiency

Ratio of power output to power input indicated as a percent. In motors, it is the effectiveness of which a motor converts electrical power into mechanical power.

Electronic Reversing

The method of changing the motor's rotational direction by changing the phase rotation of the drive output by modifying the output gating sequence.

EMF

The acronym for electromotive force, which is another term for voltage or potential difference.

Enable

To allow an action or acceptance of data by applying an appropriate signal to the appropriate input.

Enclosure

Enclosure refers to the housing in which the controller is mounted. Enclosures are available in designs for various environmental conditions:

A. NEMA Type 1 — A general purpose enclosure of either a ventilated or a nonventilated variety. It is used for most indoor applications and is intended to protect limited amounts of falling dirt and accidental human contact with the electrical circuit.

B. NEMA Type 4 — A watertight enclosure, required whenever the unit is subjected to a great amount of water from any angle. It is normally used in areas that are repeatedly hosed down. These enclosures are not designed to be submerged.

C. NEMA Type 7 — An enclosure designed for an indoor hazardous location, Class I (air), Group A, B, C or D, per the National Electrical Code. This hazardous environment is one in which flammable gases or vapors are or may be present in the air in quantities sufficient to produce explosive or ignitable mixtures. This explosion-proof enclosure shall be of such substantial construction that is will withstand the internal pressures resulting from explosions without bursting, permanently distorting or loosening its joints.

D. NEMA Type 9 — An enclosure designed for hazardous locations, Class II, Groups E, F and G per the National Electrical Code. The atmosphere in which this controller must operate may contain carbon black, coal or coke dust, flour, starch or grain dust.

E. NEMA Type 12 — Designed for industrial use. This enclosure is intended for use in applications where it is desirable to exclude such materials as cooling oil, seepage, dust, lint, fibers and filings. This is a nonventilated enclosure with an oil resistant, synthetic gasket between the case and the cover. The cover is hinged to swing horizontally and is held in place with suitable fasteners which require the use of a tool.

F. JIC — Joint Industry Conference enclosures are similar in specifications to the NEMA Type 4 and Type 12 enclosures. The most obvious difference is the way the seal is obtained. They are suitable for the same environments of the standard NEMA Type 4 and NEMA Type 12 enclosures.

G. Explosion-proof enclosures normally meet some, or all of the following specifications: Class I, Group D; Class II, Groups E, F and G; NEMA Type 7 and NEMA Type 9.

   1. Class I, Group D is designed to meet the application requirements of the NEC and is in accordance with the latest specifications of Underwriters Laboratories, Inc., for locations having atmospheres containing gasoline, hexane, naphtha, benzene, butane, propane, alcohol, acetone, benzol, lacquer solvent vapors or natural gas.

   2. Class II, Groups E, F and G is designed to meet the application requirements of the NEC and is in accordance with UL requirements for atmospheres containing metal dust, including aluminum, magnesium and their commercial alloys; and other metals or similar hazardous characteristics, such as carbon black, coal or coke dust, flour, starch or grain dusts.

Encoder

An electromechanical transducer that produces a serial or parallel digital indication of mechanical angle or displacement. Essentially, an encoder provides high resolution feedback data related to shaft position and is used with other circuitry to indicate velocity and direction. The encoder produces discrete electrical pulses during each increment of shaft rotation.

Error

Difference between the set point signal and the feedback signal. An error is necessary before a correction can be made in a controlled system.

Fault Current

Fault current is a current which results from a short between conductors or between a conductor and ground.

Feedback

The element of a control system that provides an actual operation signal for comparison with the set point to establish an error signal used by the regulator circuit.

Field Oriented Control

A method of adjustable frequency AC motor control which controls the instantaneous angular relationship between the motor stator current and the rotor flux in order to control motor torque. This is done by instantaneously regulating both the amplitude of the stator current and the phase relationship between the stator voltage and current. Motor torque is determined from slip, using speed feedback to determine slip. Zero speed torque control and smooth transition from one direction to the other is possible. This method of regulation provides performance equivalent to DC drive performance.

Field Range

The range of motor speed from base speed to the maximum rated speed.

Filter

A device that passes a signal or a range of signals and eliminates all others.

Flux Vector Control

A method of adjustable frequency AC motor control by which the drive models the motor to estimate motor flux and the angular relationship between flux and the stator current. Motor torque is controlled by instantaneously regulating both the amplitude of the stator current, and the phase relationship between the stator voltage and current. Because no direct measurement of speed or rotor position occurs, the performance of this type of drive is less than the Field Oriented Control. Zero speed torque control is not available.

Floating Ground

A circuit whose electrical common point is not at earth ground potential or the same ground potential as circuitry it is associated with. A voltage difference can exist between the floating ground and earth ground.

Follower Drive

A drive in which the reference input and operation are direct functions of another drive, called the master drive.

Force

The tendency to change the motion or position of an object with a push or pull. Force is measured in ounces or pounds.

Form Factor

A figure of merit which indicates how much a waveform deviates from a pure sinewave. A large departure from unity form factor means that energy is being used to produce heat instead of intended work.

Four-Quadrant Operation

The four combinations of forward and reverse rotation and forward and reverse torque of which a regenerative drive is capable. The four combinations are:

1. Forward rotation/forward torque (motoring)
2. Forward rotation/reverse torque (regeneration)
3. Reverse rotation/reverse torque (motoring)
4. Reverse rotation/forward torque (regeneration)

Frame Size

The physical size of motor, usually consisting of NEMA defined "D" and "F" dimensions at a minimum. The "D" dimension is the distance in quarter inches from the center of the motor shaft to the bottom of the mounting feet. The "F" dimension relates to the distance between the centers of the mounting feet holes.

Front of a Motor

The end opposite the coupling or driving pulley (NEMA). This is sometimes called the opposite pulley end (O.P.E.).

Full Load Current

The input current to a motor operated at its full load torque and nameplate voltage and frequency.

Full Load Speed

The speed that the output shaft of the motor attains with rated load connected and with nameplate voltage and frequency.

Full Load Torque

The full load torque of a motor is the torque necessary to produce rated horsepower at full load speed.

Full Wave Rectification

Full wave rectification passes the positive half and inverts the negative half cycle of the input sinusoid so that the output contains two half sine pulses for each input cycle.

Gain

The ratio of system output signal to system input signal.

Gate

The control element of an SCR (silicon controlled rectifier) commonly referred to as a thyristor. When a small positive voltage is applied to the gate momentarily, the SCR will conduct current (when the anode is positive with respect to the cathode of the SCR). Current conduction will continue even after the gate signal is removed as long as the anode/cathode voltage relationship is maintained.

GTO
Gate turn-off power semiconductor device.

General Purpose Motor
This motor has a continuous Class B insulation rating and NEMA B design, listed and offered in standard ratings with standard operating characteristics and mechanical construction, for use under usual service conditions without restriction to a particular application or type of application (NEMA).

Half Wave Rectification
In the rectifying process, half wave rectification passes only one-half of each incoming sinusoid, and does not pass the opposite half cycle. The output contains a single half sine pulse for each input cycle. A single semiconductor rectifier provides half wave rectification.

Head
A measurement of pressure, usually in feet of water. A 30 foot head is the pressure equivalent to the pressure found at the base of a column of water 30 feet high.

Heater Coil (Thermal Overload Relay)
A heater coil is a part of a thermal overload relay that is intended to produce heat when conducting current. Heater coils are sometimes referred to as heaters, thermal units, current elements or heater elements.

Horsepower
A measure of the amount of work that a motor can perform in a given period of time.

Hunting
Undesirable fluctuations in motor speed that can occur after a step change in speed reference (either acceleration or deceleration) or load.

Hysteresis Loss
The resistance offered by materials to becoming magnetized results in energy being expended and a corresponding loss. Hysteresis loss in a magnetic circuit is the energy expended to magnetize and demagnetize the core.

IGBT Transistor
Insulated **G**ate **B**ipolar **T**ransistor; a type of transistor that has low losses and low drive requirements. It can be operated at a higher switching frequency than a bipolar Darlington transistor.

Induction Motor
An alternating current motor in which the primary winding on one member (usually the stator) is connected to the power source. A secondary on the other member (usually the rotor) carries the induced current. There is no physical electrical connection to the secondary winding; its current is induced.

Inertia
A measure of a body's resistance to changes in velocity, whether the body is at rest or moving at a constant velocity. The velocity can be either linear or rotational. The moment of inertia (WK^2) is the product of the weight (W) of an object and the square of the radius of gyration (K^2). The radius of gyration is a measure of how the mass of the object is distributed about the axis of rotation. WK^2 is usually expressed in units of lb-ft^2.

Instability
The state or property of a system where there is an output but no corresponding input.

Integral Horsepower Motor
A motor built in a frame having a continuous rating of 1 hp or more.

Interconnection Diagram
An interconnection diagram is a diagram which shows only the external connections between controllers and associated machinery and equipment.

Intermittent Duty
A motor that never reaches equilibrium temperature, but is permitted to cool down between operations. For example, a crane, hoist or machine tool motor is often rated for 15 or 30 minute duty.

Interrupting Capacity
The interrupting capacity is the maximum value of current that a contact assembly is required to successfully interrupt at a specified voltage for a limited number of operations under specified conditions.

Inverter
A term commonly used for an AC adjustable frequency drive. An inverter is also a term used to describe a particular section of an AC drive. This section uses the DC voltage from a previous circuit stage (intermediate DC circuit) to produce an AC current or voltage having the desired frequency and voltage.

IR Compensation
A way to compensate for the voltage drop across the resistance of the AC motor circuit which causes a reduction in speed when load is increased. This compensation helps to improve the speed regulation characteristics of the motor, especially at low speeds.

Isolation Transformer

A transformer that electrically separates the drive from the AC power line. An isolation transformer provides the following functions:

A. Enhances protection of semiconductors from line voltage transients.

B. Reduces disturbances from other solid-state control equipment such as drives without isolation transformers, time clock systems, electronic counters, etc.

C. Reduces harmonic levels caused by the connected drive.

D. Provides isolation from the power line ground as required by the application.

Jogging

Jogging is a means of accomplishing momentary motor movement by repetitive application of power.

Kinetic Energy

The energy of motion possessed by a body.

Linear Acceleration/Deceleration (LAD)

A circuit that controls the rate at which the motor or drive is allowed to accelerate or decelerate upon a speed command change. On most drives, this circuit is adjustable and can be set to accommodate a particular application.

Linearity

The measure of the maximum deviation between the actual speed and the set speed, expressed as a percentage of set speed.

Locked Rotor Current

Steady state current taken from the line with the rotor at standstill (at rated voltage and frequency). This is the current when starting the motor and load.

Locked Rotor Torque

The minimum torque that a motor will develop at rest for all angular positions of the rotor with application of rated voltage and frequency.

Master Drive

A drive that sets the reference for one or more follower drives.

Megohm Meter

A device used to measure an insulation system's resistance. This is usually measured in megohms and tested by passing a low current at high voltage through the motor windings and measuring the resistance of the various insulation systems.

Modular Construction

The major circuit elements are mounted in replaceable modules which can readily be removed and replaced. Equipment can be serviced without delay.

Module

A unit of circuit elements usually packaged so it can be readily replaced.

Multi Motor Operation

A system in which one controller operates two or more motors simultaneously, maintaining a relative ratio between the speeds of the motors.

Multi Speed Motor

An induction motor that can operate at two, three or four discrete (fixed) speeds by the selection of various stator winding configurations.

NEC

The National Electrical Code is the recommendation of the National Fire Protection Association for electrical safety and property protection and is revised every three years. City, county or state regulations may differ from these code regulations and take precedence over NEC rules.

Negative Feedback

A condition where feedback is subtractive to the input reference signal. Negative feedback forms the basis for automatic control systems.

NEMA

The National Electrical Manufacturers Association is a non-profit organization, organized and supported by manufacturers of electrical equipment and supplies. Some of the standards NEMA promulgates cover: horsepower ratings, speeds, frame sizes and dimensions, torques and enclosures.

No Load

The state of machine rotating at normal speed under rated conditions, but when no output is required from it.

OFF-Delay

OFF-delay signifies that the timing period of a time delay relay is initiated upon de-energization of its coil.

Offset

The steady state deviation of a controlled variable from a fixed set point.

ON-Delay

ON-delay signifies that the timing period of a time delay relay is initiated upon energization of its coil.

Open Loop
A control system that lacks feedback.

Operating Overload
Operating overload is the overcurrent to which an electric apparatus is subjected in the course of the normal operating conditions that it may encounter. For example, those currents in excess of running current which occur for a short time as a motor is started or jogged, are considered normal operating overloads for a control apparatus.

Op Amp
An operational amplifier is usually a high gain DC amplifier that is designed to be used with external circuit elements to perform a specified computating operation.

Open Machine (Motors)
A machine having ventilating openings which permit passage of external cooling air over and around the windings of the machine.

A. Dripproof is an open machine in which the ventilating openings are so constructed that successful operation is not interfered with when drops of liquid or solid particles strike or enter the enclosure at any angle from 0 to 15 degrees downward from vertical.

B. Splashproof is an open machine in which the ventilating openings are so constructed that successful operation is not interfered with when drops of liquid or solid particles strike or enter the enclosure at any angle not greater than 100 degrees downward from the vertical.

C. Guarded (NEMA) is an open machine in which all openings giving direct access to live metal or rotating parts (except smooth rotating surfaces) are limited in size by the structural parts of by the screens, baffles, grilles, expanded metal or other means to prevent accidental contact with hazardous parts. Openings giving direct access to such live or rotating parts shall not permit the passage of a cylindrical rod 0.75 inch in diameter.

D. Semiguarded is an open machine in which part of the ventilating openings in the machine, normally in the top half, are guarded, as in the case of a "guarded machine", while the other parts are left open.

E. Dripproof Guarded is a dripproof machine whose ventilating openings are guarded in accordance with the definition of a guarded machine.

F. Open Externally Ventilated is one which is ventilated by means of a separate motor driven blower mounted machine enclosure. This machine is sometimes known as a blower-ventilated or a force-ventilated machine.

G. Open Pipe Ventilated is basically an open machine except that openings for admission of ventilating air are so arranged that inlet ducts or pipes can be connected to them. Air may be circulated by means integral with the machine or by means external to the machine (separately or forced ventilated).

H. Weather Protected is an open enclosure divided into two types:

   1. Type 1 enclosures have ventilating passages constructed to minimize the entrance of rain, snow, airborne particles and prevent passage of a 0.75 in. diameter cylindrical rod.

   2. Type 2 enclosures provide additional protection through the design of their intake and exhaust ventilating passages. The passages are so arranged that wind and airborne particles blown into the machine can be discharged without entering directly into the electrical parts of the machine. Additional baffling is provided to minimize the possibility of moisture or dirt being carried inside the machine.

Operating/Service Deviation
A means of specifying the speed regulating performance of a drive's controller, generally in percent of base speed.

Operating Deviation defines speed change due to load change and typically assumes:

A. A change from one steady state load value to another (not transient).

B. A 95% maximum load change.

Service Deviation defines speed change due to changes in ambient conditions greater than these typical variations:

Condition	Change
AC Line Voltage	±10%
AC Line Frequency	±3%
Ambient Temperature	15°C

Overcurrent Relay
An overcurrent relay operates when the current through the relay, during its operating period, is equal to or greater than its setting.

Overload Capacity
The ability of the drive to withstand currents beyond the system's continuous rating. It is normally specified as a percentage of full load current for a specified time period.

Overload Relay
An overload relay is an overcurrent relay which operates at a predetermined value of current vs. time in order to prevent overheating of the motor. A self-ventilated motor may not be protected below base speed.

Overshoot
The amount that a controlled variable exceeds a desired value after a change of input.

Peak Voltage
When a PWM drive is applied to a standard motor with long cable runs, the differences in the motor and cable impedance can cause voltage overshoots to be present at the motor terminals. These overshoots can approach 1600 volts, potentially damaging the motor insulation. For small motors this phenomenon occurs for cables 33 feet and longer. For larger drives, 100 foot or longer cable runs become a concern. Either a NEMA MG1 Part 31 motor can be used or a motor cable filter can be applied. Cutler-Hammer offers a complete line of drive output and motor input filters to eliminate these concerns.

Phase Control
The process of varying the point within the electrical cycle at which thyristor gating occurs, to begin forward conduction.

Pickup Voltage or Current
The pickup voltage or current of a magnetically operated device is the minimum voltage or current at which the device operates.

Plugging
Plugging refers to a type of motor braking provided by reversing phase sequence so that the motor develops a counter-torque which exerts a retarding force to brake the motor.

Position Transducer
An electronic device (e.g., encoder or resolver) that measures actual position and converts this measurement into an electrical signal convenient for transmission. This signal may then be used as an input to a programmable controller which controls the parameters of the positioning system.

Positive Feedback
Positive feedback is a condition where the feedback is additive to the input signal.

Potentiometer
A three terminal rheostat, or a resistor with one or more adjustable sliding contacts, that functions as an adjustable voltage divider.

Power
Work done per unit of time. Measured in horsepower or watts:

1 hp = 33,000 ft-lb/min. = 746 watts

Power Factor
Two different power factors are usually defined for drives. The first, displacement power factor, is the most frequently used. Displacement power factor is defined as the phase angle between the fundamental voltage and current. For PWM drives, displacement power factor is usually specified as 0.96. The second power factor definition is for total power factor. This takes into account any voltage and current harmonics. It is the ratio of the total input kW divided by the total input kVA. The total power factor is usually lower than the displacement power factor and depends upon the characteristics of the utility feeder and the drive type.

Preset Speed
Preset speed refers to one or more fixed speeds at which the drive will operate.

Printed Circuit Board
A board for mounting of separately manufactured components which has the connections made by printed circuitry.

Pull-Up Torque
The minimum torque available after initial motor start to accelerate the load to full speed (where breakdown torque occurs), expressed in percent of running torque.

Pulse
A pulse is a signal of relatively short duration.

Pushbutton
A pushbutton is a switch having a manually operable plunger, rocker or button for actuating the switch.

PWM
A type of AC adjustable frequency drive that accomplishes frequency and voltage control at the output section (inverter) of the drive. The drives DC bus voltage is always a constant amplitude and by “chopping” (pulse width modulating), the average voltage is controlled.

Rectification
The term used to designate the process by which electric energy is transformed from an alternating current circuit to a direct current circuit.

Reactance
The opposition to the flow of current made by an inductor or a capacitor.

Rectifier
A device that transforms alternating current to direct current.

Regeneration

The characteristic of a motor to act as a generator when the rotor's speed is greater than that corresponding to the applied frequency.

Regenerative Braking

The technique of slowing or stopping a drive by regeneration.

Regenerative Control

A regenerative drive contains the inherent capability and/or power semiconductors to control the flow of power to the motor and from the motor back to the power supply.

Regulation

The ability of a control system to hold a speed once it has been set. Regulation is given as a percentage of either base speed or set speed. Regulation is specified for two separate sets of conditions:

A. Speed Regulation is the percentage of speed change with a defined change in load, assuming all other parameters to be constant.

B. Line Regulation is the percentage of speed change with a given line voltage change, assuming all other parameters to be constant.

Relay

An electrically controlled device that causes electrical contacts to change status. Open contacts will close and closed contacts will open when rated voltage is applied to the coil of relay.

Remote Control

Remote control is a control function which provides for initiation or change or a control function from a remote point.

Reset

To reset is to restore a mechanism, stored characteristics or device to a prescribed state.

Resolution

The smallest distinguishable increment into which a quantity can be divided (e.g., position or shaft speed). It is also the degree to which nearly equal values of a quantity can be discriminated. For encoders, it is the number of unique electrically identified positions occurring in 360 degrees of input shaft rotation.

Response Time

Response time is the time required, following the initiation of a specified stimulus to a system, for an output going in the direction of necessary corrective action to first reach a specified value.

Reversing

Changing the direction of rotation of the motor rotor. An AC motor is reversed by reversing the connection of two legs on the three-phase power line.

Rotor

The rotating member of a machine with a shaft.

Rotor Time Constant

The inductance divided by the resistance of the motor rotor. This is a motor characteristic that is used in adjusting a field oriented control for optimum performance.

Schematic Diagram (Elementary Diagram)

A schematic or elementary diagram is one that shows all circuits and devices of a controller. The diagram does not show the physical arrangement of the devices or the actual wiring to the devices.

S-Curve Acceleration/Deceleration

Control of the rate of change of speed so that the graph of speed vs. time has an "S" shape. Speed begins to increase slowly, then changes more quickly until the rate change is reduced when approaching the final speed. This method of accel/decel control minimizes the "jerk" that occurs at the beginning and ending of the accel/decel period.

Service Deviation

See *Operating/Service Deviation.*

Service Factor

When used on a motor nameplate, a number which indicates how much above the nameplate rating a motor can be loaded without causing serious degradation (i.e., a motor with 1.15 S.F. can produce 15% greater torque than one with 1.0 S.F.).

Service of a Controller

The service of a controller is the specific application in which the controller is to be used; for example:

A. General Purpose

B. Definite Purpose

1. Crane and hoist
2. Elevator
3. Machine tool, etc.

Servo Drive

Any drive that is designed to closely follow the changes in a speed or position command. Servo drives can provide tight speed regulation, fast acceleration/deceleration, full torque at zero speed, and holding torque, or stiffness, to hold a position at zero speed.

Set Speed
The desired operating speed.

Shock Load
The load seen by a clutch, brake or motor in a system which transmits short duration, high peak loads. This type of load is present in crushers, separators, grinders, conveyors, winches and cranes.

Silicon Controlled Rectifier (SCR)
A solid-state switch, sometimes referred to as a thyristor. The SCR has an anode, cathode and control element called the gate. The device provides controlled rectification since it can be turned on at will. The SCR can rapidly switch large currents at high voltages. It is small in size and low in weight.

Skew
The arrangement of laminations on a rotor to provide a slight angular pattern of their slots with respect to the shaft axis. This pattern helps to eliminate low speed cogging and minimize induced vibration in a rotor as well as reduce associated noise.

Skewing
Refers to time delay or offset between any two signals in relation to each other.

Slaving
Method of connecting controllers in cascade (series) or parallel. A number of slave units can be utilized, each running a drive at a different speed. When the manually operated master controller calls for a speed change, the slave units will respond in proportion, maintaining the speed ratios between them.

Slewing
Slewing is an incremental motion of the motor shaft or machine table from one position to another at maximum speed without losing position control.

Slip
The difference between rotating magnetic field speed (synchronous speed) and rotor speed of AC induction motors. Usually expressed as a percentage of synchronous speed.

Slip Compensation
Method of changing the speed reference to the speed regulator circuit, based on the value of motor torque, to maintain motor speed as the load on the motor varies.

Special Purpose Motor
A motor with special operating characteristics, special mechanical construction or both, designed for a particular application and not falling within the definition of a general purpose of definite purpose motor (NEMA).

Speed Range
The minimum and maximum speeds at which a motor must operate under constant or variable torque load conditions. A 50:1 speed range for a motor with top speed of 1800 rpm means the motor must operate as low as 36 rpm and still maintain regulation within specifications.

Speed Regulation
The numerical measure in percent of how accurately the motor speed can be maintained. It is the percentage of change in speed between no load and full load as compared to base speed.

Stability
The ability of a drive to operate a motor at constant speed (under varying load) without “hunting” (alternately speeding up and slowing down). It is related to the characteristics of the load being driven and the electrical time constants of the drive’s regulator circuits.

Starting Torque
The torque exerted by the motor during the starting period (a function of speed or slip).

Stator
The stationary portion of the magnetic circuit and the associated windings and leads of a rotating machine.

Stiffness
The ability of a device to resist deviation due to load change.

Surge
A transient wave of current, voltage or power in the electric circuit. Note: A transient has a high rate of change of current or voltage in the system.

Surge Protection
The process of absorbing and clipping voltage transients on an incoming AC line or control circuit. MOVs (Metal Oxide Varistors) and specially designed RC (resistor-capacitor) networks are usually used to accomplish this.

Switch
A switch is a device for opening and closing, or for changing the connections of a circuit. Note: A switch is understood to be manually operated unless otherwise stated.

Synchronous Speed
The speed of an AC induction motor’s rotating magnetic field. It is determined by the frequency applied to the stator and the number of magnetic poles present in each phase of the stator windings. Mathematically, it is expressed as: Sync Speed (RPM) = 120 x Applied Frequency (Hz)/Number of Poles per Phase.

System Efficiency

System efficiency is the ratio of the mechanical power supplied to load to the total input power under specified operating conditions. The input power includes requirements for auxiliary functions, such as phase control, switching equipment, overload protection and fans.

Tachometer Generator (Tach)

A generator, mechanically coupled to a rotating machine whose function is to generate a voltage, the magnitude or frequency of which is used either to determine the speed of rotation of the common shaft or to supply a signal to a control circuit to provide speed regulation.

Thermal Overload Relay

A thermal overload relay functions (trips) by means of a thermal response to current.

Thermal Protector (Rotating Machinery)

A protective device assembled as an integral part of a machine that protects the machine against overheating due to an overload condition.

Notes:

1. It may consist of one or more temperature sensing elements integral with the machine and a control device external to the machine;
2. When a thermal protector is designed to perform its function by opening the circuit to the machine and then automatically closing the circuit after the machine cools to a satisfactory operating temperature, it is an automatic reset thermal protector;
3. When a thermal protector is designed to perform its function by opening the circuit to the machine but must be reset manually to close the circuit, it is a manual reset thermal protector.

Thread Speed

A fixed low speed, usually adjustable, supplied to provide a convenient method for loading and threading machines. May also be called a preset speed.

Thyristor

A three-junction semiconductor device that can be switched from the OFF-state to the ON-state by a logic signal. Also known as a silicon controlled rectifier (SCR).

Time Delay

Time delay means that a time interval is purposely introduced in the performance of a function.

Torque

A turning force applied to a shaft, tending to cause rotation. Torque is normally measured in pound feet and is equal to the force applied, times the radius through which it acts.

Torque Control

Motor torque is regulated instead of motor speed.

Totally Enclosed Machine (Motor)

A totally enclosed machine is one so enclosed as to prevent the free exchange of air between the inside and the outside of the case, but not sufficiently enclosed to be termed airtight.

A. Totally Enclosed Fan-Cooled is a totally enclosed machine equipped for exterior cooling by means of a fan or fans integral with the machine, but external to the enclosing parts.

B. Explosion-Proof is totally enclosed machine whose enclosure is designed and constructed to withstand an explosion of a specified gas or vapor which may occur within it and to prevent the ignition of the specified gas or vapor surrounding the machine by sparks, flashes or explosions of the specified gas or vapor, which may occur within the machine casing.

C. Dust-Ignition-Proof is a totally enclosed machine whose enclosure is designed and constructed in a manner which will exclude ignitable amounts of dust or amounts that might affect performance or rating, and will not permit arcs, sparks or heat, otherwise generated or liberated inside of the enclosure, to cause ignition of exterior accumulations or atmospheric suspensions of a specific dust on, or in the vicinity of the enclosure.

D. Waterproof is a totally enclosed machine constructed so that it will keep out water sprayed onto it. Leakage may occurred around the shaft, but will be prevented from entering the oil reservoir. Provision is made for automatically draining the machine. The means for automatic draining may be a check valve or a tapped hole at the lowest part of the frame which will serve for application of a drain pipe.

E. Totally Enclosed Water Cooled is a totally enclosed machine which is cooled by circulating water, the water or water conductors coming in direct contact with the machine parts.

F. Totally Enclosed Water-Air Cooled is a totally enclosed machine which is cooled by circulating air which, in turn, is cooled by circulating water. It is provided with a water cooled heat exchanger for cooling the internal air and a fan, or fans integral with the rotor shaft or separate, for circulating the internal air.

G. Totally Enclosed Air to Air Cooled is a totally enclosed machine which is cooled by circulating the internal air through a heat exchanger which, in turn, is cooled by circulating external air. It is provided with an air to air heat exchanger for cooling the internal air, a fan or fans integral with the rotor shaft, or separate for circulating the internal air and a separate fan for circulating the external air.

H. Totally Enclosed Fan Cooled Guarded is a totally enclosed fan cooled machine, in which all openings giving direct access to the fan are limited in size by the design of the structural parts of by screens, grilles, expanded metal, etc., to prevent accidental contact the with the fan. Such openings shall not permit the passage of a cylindrical rod, 0.75 inch in diameter, and a probe shall not contact the blades, spokes or other irregular surfaces of the fan.

I. Totally Enclosed Air-Over is a totally enclosed machine intended for exterior cooling by a ventilating means external to the machine.

Transducer

A device that converts one energy form to another (e.g., mechanical to electrical). Also, a device when actuated by signals from one or more systems or media, can supply related signals to one or more other systems or media.

Transient

A momentary deviation in an electrical or mechanical system.

Transistor

A solid-state, three-terminal device that allows amplification of signals and can be used for switching and control. The three terminals are called emitter, base and collector.

Trigger Circuit

The circuit used to gate a thyristor that causes it to conduct current.

Undervoltage Protection

Undervoltage or low voltage protection is the effect of a device, operative on the reduction or failure of voltage, to cause and maintain the interruption of power to the main circuit. The main objective of the device is to prevent restarting of the equipment on an undervoltage condition.

Vector

A quantity that has magnitude and direction. This quantity is commonly represented by a directed line segment whose length represents the magnitude, and whose orientation in space represents the direction.

Vector Control

See *Field Oriented Control.*

Ventilated Enclosure

A ventilated enclosure is provided with means to permit circulation of sufficient air to remove an excess of heat, fumes or vapors.

Voltage Relay

A voltage relay operates at a predetermined value of voltage. It may be an overvoltage relay, an undervoltage relay or a combination of both.

Volts per Hertz (V/Hz)

The basic measurement of proper AC motor excitation level for adjustable frequency AC drive operation.

VVI (Variable Voltage Inverter)

A type of AC adjustable frequency drive that controls the voltage and frequency to the motor to produce variable speed operation. A VVI type drive controls the voltage in a section other than the output section where frequency generation takes place. The frequency control is accomplished by an output bridge circuit which switches the variable voltage to the motor at the desired frequency.

Wiring (or Connection) Diagram

A wiring, or connection diagram is one which locates, and identifies electrical devices, terminals and interconnecting wiring in an assembly.

Work

A force moving an object over a distance. Measured in foot pounds (ft-lb).

Work = Force x Distance.

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Cutler-Hammer, a part of Eaton Corporation, is a worldwide leader providing customer-driven solutions. From power distribution and electrical control products to industrial automation, Cutler-Hammer utilizes advanced product development, world-class manufacturing, and offers global engineering services and support.

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