AC Drive Theory and Application

Application Guide AP04014005E

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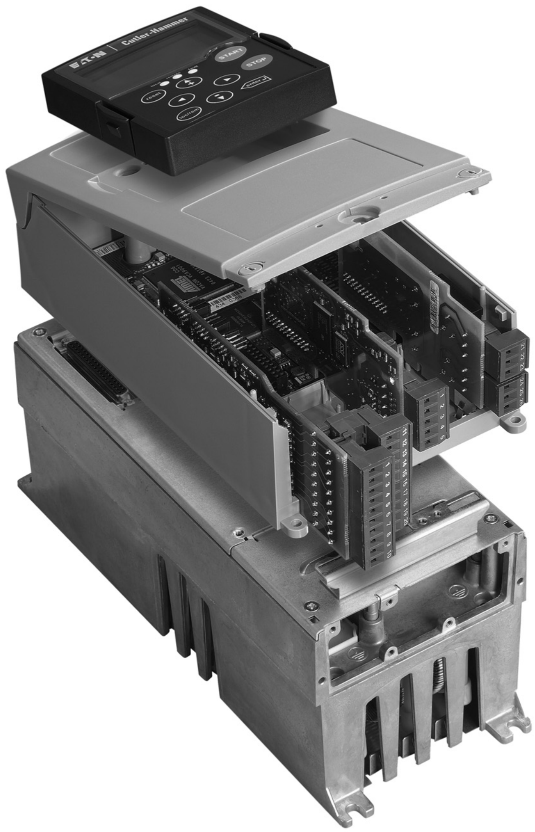

Introduction

Adjustable Frequency AC Drive System Description

An adjustable frequency AC drive system consists of an ordinary three-phase induction motor, an adjustable frequency drive to control the speed of the motor and an operator's control station.

The most common motor used with an AF drive system is a standard NEMA® design B squirrel cage induction motor, rated for 230 or 460 volt, 3-phase, 60 Hz operation.

The adjustable frequency controller is a solid-state power conversion unit. It receives 240 or 480 volt, 3-phase, 60 Hz power and converts it to a variable frequency supply which can be steplessly adjusted between 0 and 60 Hz. The controller also adjusts the output voltage in proportion to the frequency to provide a nominally constant ratio of voltage to frequency as required by the characteristics of the motor.

The operator's station provides the operator with the necessary controls for starting and stopping the motor and varying the motor speed. These functions can also be performed by a wide variety of automatic control systems.

Benefits of Using AC Drives

AC drives have become very popular in recent years as it is recognized that they provide a very efficient and direct method of controlling the speed of the most rugged and reliable of prime movers, the squirrel cage motor. Eaton's Cutler-Hammer® AC drives provide many economic and performance advantages in a wide variety of adjustable speed drive applications.

The following are some of the benefits provided:

- High efficiency and low operating cost
- Minimal motor maintenance
- Controlled linear acceleration and deceleration provide soft starting and stopping and smooth speed changes
- Multiple motor operation is easily accomplished
- Current limit provides for quick and accurate torque control
- Adjustable speed operation can be accomplished with existing AC motors
- Improved speed regulation can be accomplished by slip compensation
- AC motors are available in a wide variety of mechanical configurations
- Flexibility of machine design due to the light weight and compact size of AC motors
- IR compensation provides high starting torque easily and economically
- AC motors are available in enclosures suitable for hazardous or corrosive environments
- Fewer spare motors are required since the same motor can be used for both adjustable speed and constant speed operations.
- Cutler-Hammer rugged and reliable designs ensure minimum downtime expense
- High speed operation can be economically accomplished using extended frequency operation
- Reverse operation is accomplished electronically without the need for a reversing starter

Basic Principles of AC Drive Operation

There are several classifications of adjustable frequency AC drives. Some common types of drives are Variable Voltage Input (VVI) sometimes called Six Step drives, current source input (CSI), pulse width modulated (PWM) drives, Sensorless Vector drives, Field Oriented drives and Closed Loop Vector drives. The more common AC drives are PWM, Sensorless Vector and Closed Loop Vector drives.

Figure 1 is a block diagram of a typical VVI drive. The AC/DC converter is an SCR bridge, which receives ac power from the input line and provides adjustable voltage dc power to the dc bus. A voltage regulator is required to preset the dc bus voltage to the level needed to provide the required output voltage amplitude to the motor.

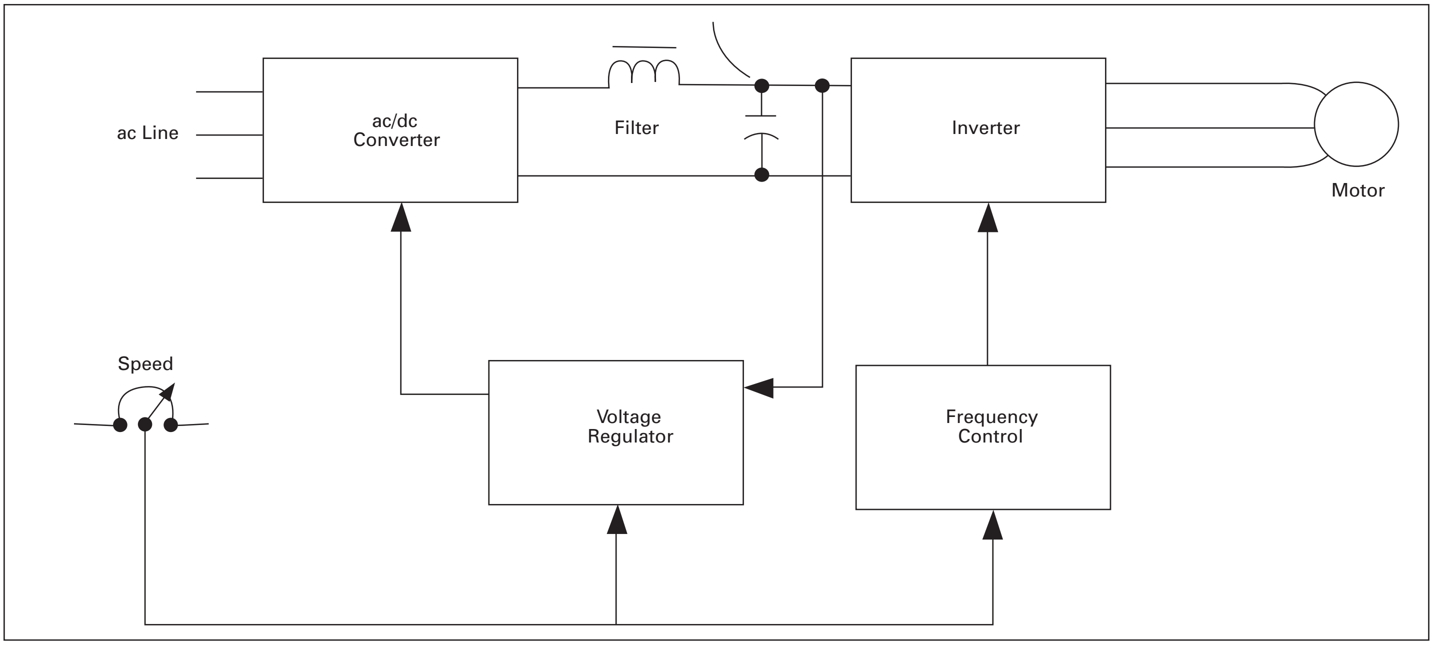

FIGURE 1. TYPICAL WI DRIVE BLOCK DIAGRAM

The inverter uses either SCRs or transistors as solid-state switches to convert the dc power to a stepped waveform output. The amplitude of the dc bus voltage determines the amplitude of the output voltage. **Figure 2** shows typical output voltage and current waveforms for a VVI inverter. The voltage waveform is normally referred to as a "six step" waveform.

Figure 3 is a block diagram of a typical PWM drive. It receives line voltage and converts it to a fixed dc voltage using a 3-phase full wave diode bridge. Since the dc bus is a fixed voltage level, the amplitude of the output voltage is fixed. Modulating the output waveform using IGBT inverter switches controls the effective value of the output voltage. **Figure 4** shows the output voltage and current waveforms for the PWM inverter.

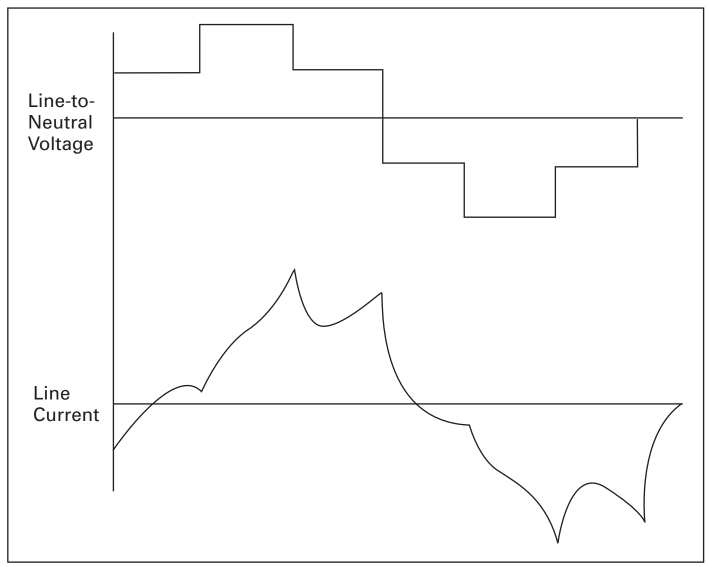

FIGURE 2. TYPICAL VVI VOLTAGE AND CURRENT WAVEFORMS

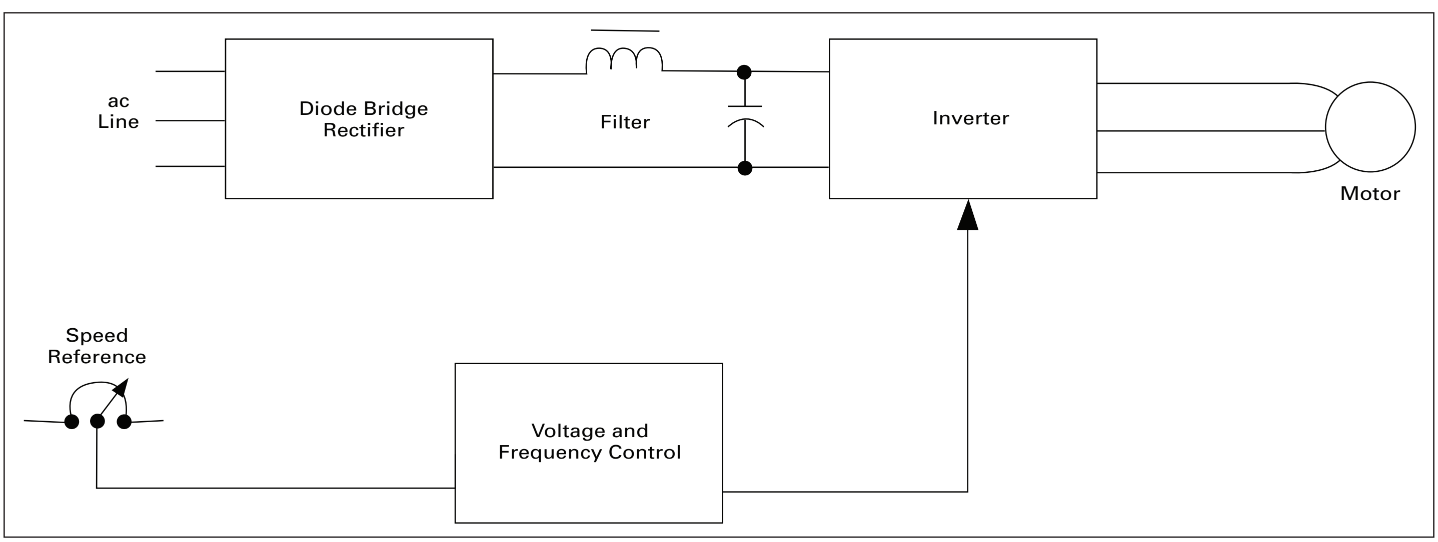

FIGURE 3. BLOCK DIAGRAM OF A TYPICAL PWM DRIVE

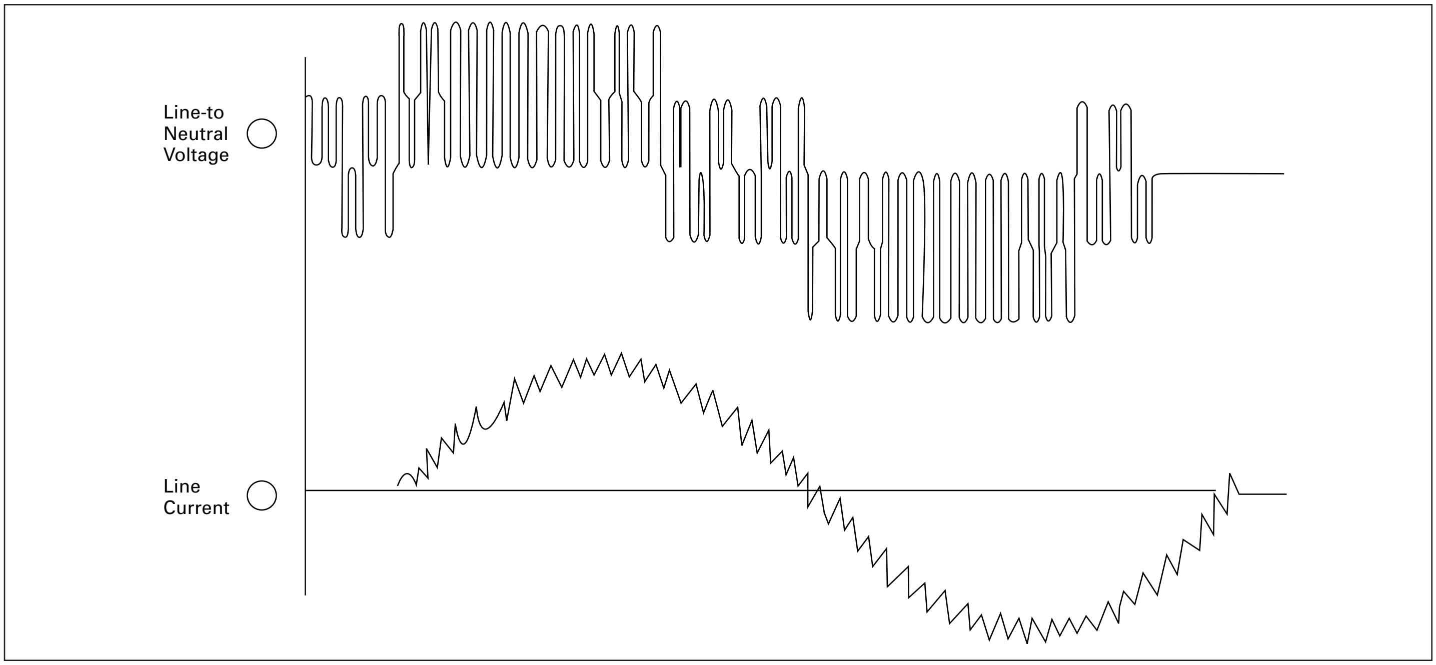

FIGURE 4. TYPICAL PWM VOLTAGE AND CURRENT WAVEFORMS

Principles of Adjustable Frequency Motor Operation

Torque Speed Curves

The operating speed of an AC induction motor can be determined by the frequency of the applied power and the number of poles created by the stator windings. Synchronous speed is the speed of the magnetic field created in the stator windings. It is given by:

N = 120f / p

where:

n = speed in RPM
f = operating frequency
p = number of poles

When the frequency is changed, the voltage must also be changed, based on the formula for reactance and Ohm's Law.

$$X_L = 2 \cdot \pi \cdot f \cdot L$$

Where L = inductance
X_L = reactance
V = voltage
I_m = magnetizing current

$$I_m = \frac{V}{X_L}$$

Combining the above equations yields:

$$I_m = \frac{1}{2 \cdot \pi \cdot f \cdot L} \cdot \frac{V}{f}$$

For steady-state operation, a constant volts per hertz ratio must be maintained. This is equal to the motor rated voltage divided by the rated frequency.

Example: 460 volt motor
60 hertz
7.67 volts per hertz

For the magnetizing current to remain constant, the V/f ratio, or the volts per hertz ratio, must remain constant. Therefore, the voltage must increase and decrease as the frequency increases and decreases.

If the voltage is held constant and the frequency is decreased, the magnetic field strength would increase. This increases the iron losses and would cause the motor to burn out.

The operating speed of the motor is synchronous speed minus slip. For a design B motor, slip is typically 3%.

Figure 5 is a speed/torque curve for a typical NEMA® design B motor. There are several important points indicated on the curve.

Locked rotor or stall torque is the amount of torque necessary to start the motor under full load conditions.

Pull out or breakdown torque is the amount of torque that will cause the motor to pull out or stall.

Full load torque is the amount of torque the motor is designed to develop.

The operating point is the point where the actual load is causing the motor to operate.

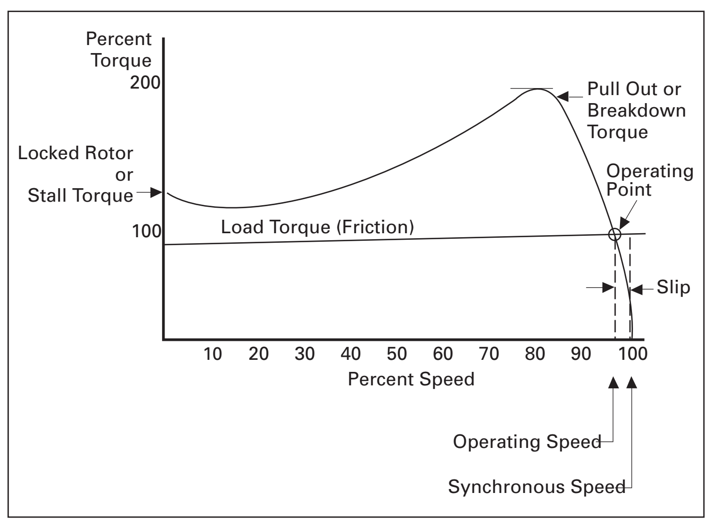

FIGURE 5. NEMA DESIGN B MOTOR SPEED/TORQUE CURVE

Induction Motor Speed Control

Standard induction motors (NEMA design B) have approximately 3% slip at full load.

If the drive only controls the output frequency, the motor speed will deviate from the set speed due to slip.

For many fan and pump applications, precise speed control is not needed. The motor slip can be:

- Ignored
- Compensated for by the drive based on motor current and a programmed speed-torque characteristic of the motor
- Compensated for by a control loop external to the drive. An example would be a pump where a certain flow rate is desired. The “flow control loop” tells the drive to either speed up or slow down to reach the desired flow. The actual speed of the pump has no importance.

Vector controlled drives need speed feedback of the rotor. For Sensorless Vector, the rotor speed is calculated based on a model of the motor stored in the drive. For Closed Loop Vector, a digital encoder is added to the motor to provide actual rotor speed.

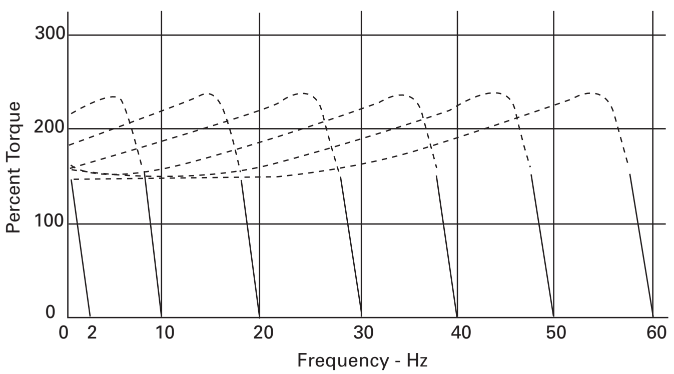

FIGURE 6. FAMILY OF IDEAL SPEED/TORQUE CURVES

This curve is drawn for a motor operating at a fixed frequency. Changing the frequency of the power applied to the motor changes the slip/torque curve.

Figure 6 shows a family of ideal speed/torque curves drawn for a motor operating from an adjustable frequency power source. As can be seen, the value of slip is constant at any given operating torque level, and the normal operating portions of the curves are a series of parallel lines. When a motor is operated from an AC drive, it normally never enters the dotted portion of the curve.

Volts per Hertz Regulation

In order to operate the motor with the desired speed/torque curve, we must apply the proper voltage to the motor at each frequency. As we have already seen, it is necessary to regulate motor voltage in proportion to the frequency at a constant ratio. In reality, this requirement for constant volts/hertz does not apply to the motor terminals, but to a hypothetical point inside the motor. The voltage at this point is called the air gap voltage. The difference between air gap voltage and motor terminal voltage is the IR voltage drop as shown in **Figure 7**.

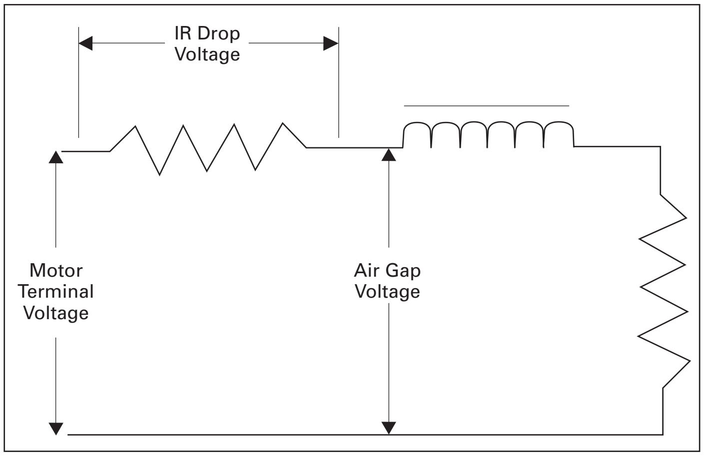

FIGURE 7. MOTOR EQUIVALENT CIRCUIT

In a hypothetical example, lets assume that the optimum motor terminal voltage is 460 V when we are operating at 60 Hz. If the motor has a full load current of 40 amps and the internal resistance is 1 ohm, then the IR drop would be 40 volts and voltage at the air gap would be 420 V, or 7 V/Hz. If we then operate the motor at 6 Hz and still require full load torque, the current must still be 40 amps since current is proportional to torque. In this condition, if we require 7 V/Hz at the air gap, or 42 V and we still have an IR drop of 40 V, we must have a motor terminal voltage of 82 V (13.67 V/Hz).

This means that if we are required to produce full torque at low speeds, we must have a significant V/Hz “boost” at low speeds. Since the required boost voltage depends on individual motor and load characteristics, some type of voltage boost adjustment is usually provided.

In many cases, this voltage boost adjustment provides us with a fixed voltage boost. If our motor load is always constant, this is no problem. However, if we have a varying load, using a fixed boost can produce undesirable results. In the example above, assume we are using a fixed voltage boost to 13.67 V/Hz. If load is now cut in half, IR drop, which is a purely resistive load, will also be cut in half. If we are operating at 6 Hz and are applying 82 V to the motor terminals, we now have an air gap voltage of 62 V (10.33 V/Hz). Because of this, we must set a fixed boost at some point that will give us adequate starting torque without saturating the motor. This means that the motor is not producing optimum torque at low speeds. By using IR compensation instead of a fixed boost, we can provide improved torque during low speed operations. This is accomplished by sensing motor current and automatically adjusting the voltage boost in proportion to motor current.

Soft Start

Figure 8 shows torque/frequency and current/frequency at various operating frequencies. From these curves, we can see that when the motor is operating in the normal operating portions (solid lines) of the curves, motor current is directly proportional to motor torque. However, when we operate above 150% current, we can see the ratio of torque to current is significantly less than one.

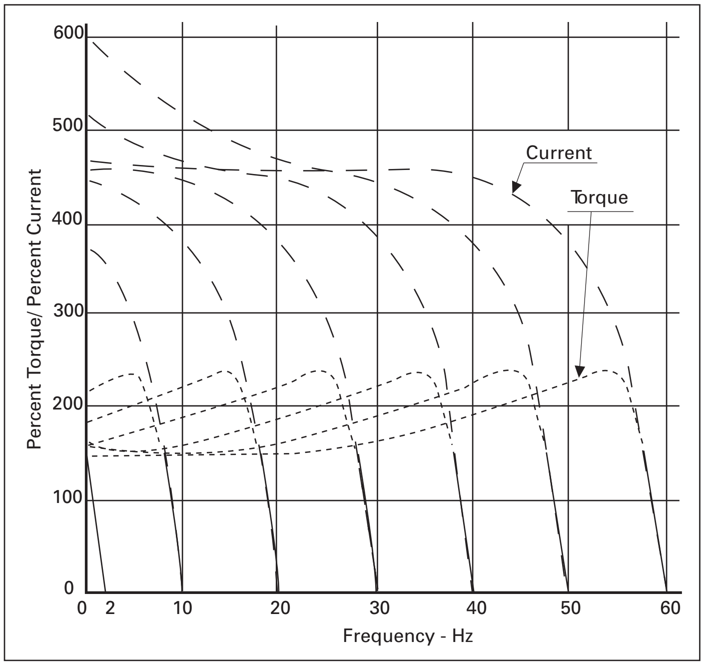

FIGURE 8. SPEED/TORQUE AND SPEED/CURRENT CURVES

If the motor is line started, we can see from **Figure 8** that the current inrush will be approximately 600% of full load current. We can also see that at the 2 Hz curve we are already on the solid portion of the curve at start. This means that if a motor is started at 2 Hz or less we will not require a high starting current. If we start at a low frequency and then increase speed by increasing frequency, the motor will always operate on the solid portion of the curves and never require more than 150% of rated current.

Motor Application and Performance

Motor Sizing

In sizing a drive, we must first match the torque/speed capabilities of the motor to the requirements of the driven load. We can then match the inverter to the motor.

AC Drive Motor Torque vs. Speed Capability

When a drive is being used in a constant torque application, we must remember that as motor speed is reduced below base speed, motor cooling will become less effective. The minimum speed allowable for continuous operation under constant torque conditions is effected by this limitation.

In a variable speed application, we do not have this limitation, as motor load is lower at low speeds.

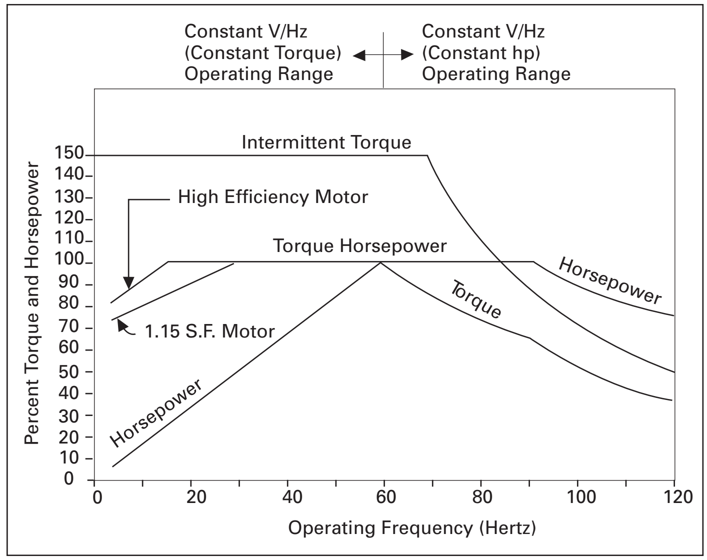

FIGURE 9. TYPICAL MOTOR PERFORMANCE CURVES

Figure 9 shows typical motor performance curves. These curves show that by using a high efficiency motor or by oversizing the motor, a wider constant torque speed range can be realized. Operation above 60 Hz will also give us a wider speed range.

Load Characteristics

Most loads are divided into two categories:

- Variable Torque — centrifugal fans and pumps
- Constant Torque — conveyors, hoists, etc.

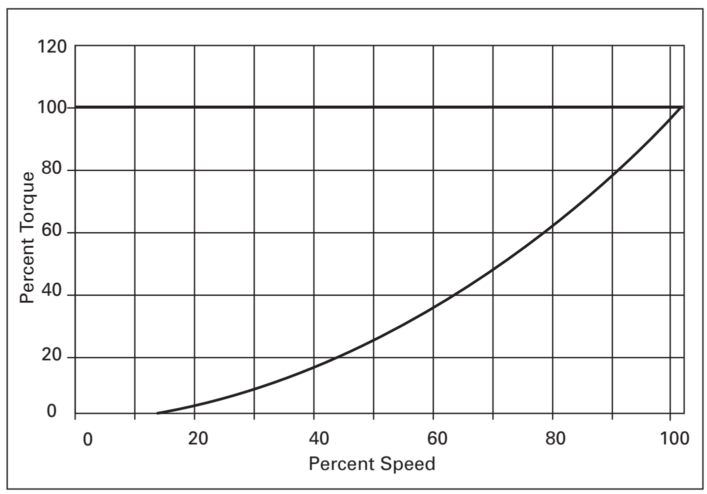

FIGURE 10. SPEED VS. TORQUE CONSTANT AND VARIABLE TORQUE

The current drawn by an AC motor is proportional to the load torque. The above curves can also represent the motor load current versus speed (when supplied by an AC drive).

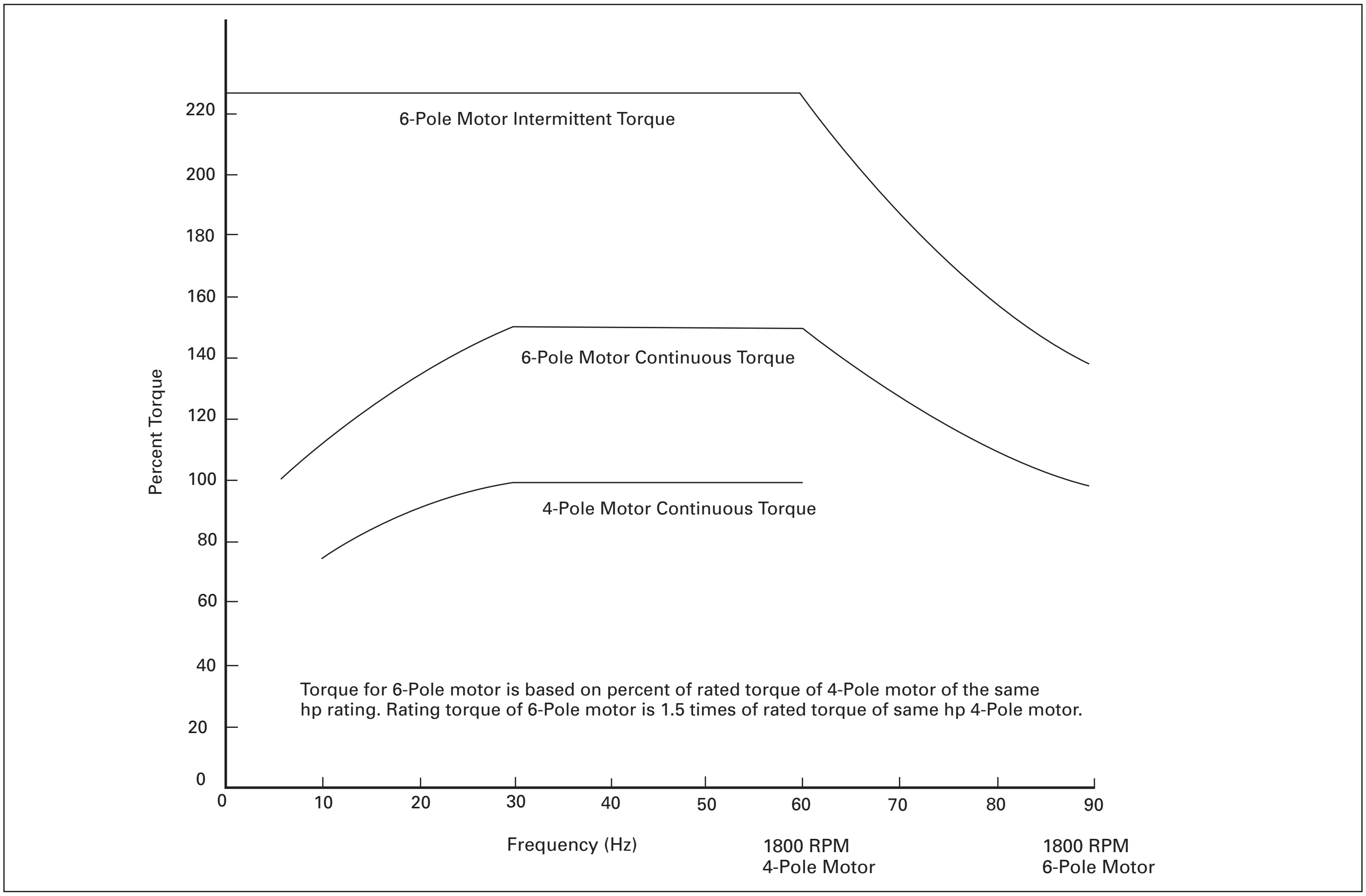

FIGURE 11. TORQUE SPEED CHARACTERISTICS FOR EXTENDED MOTOR PERFORMANCE

Extended Motor Performance

We can obtain extended motor performance by operating a motor above its base speed to 90 Hz. If an application was sized by using an 1800 RPM motor, we could use a 1200 RPM motor of the same size and operate the motor at 1800 RPM by increasing the maximum frequency to 90 Hz (see **Figure 11**). We can see that the% torque ratings 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 rated horsepower.

The motor voltage is held constant between 60 Hz and 90 Hz; therefore the available torque follows a constant hp curve.

This mode of operation increased the continuous and intermittent torque available over most of the speed range. It increases the breakaway torque to 225%. Continuous constant torque speed range is also increased. Because we have increased the frequency for any given speed by 50%, we have reduced the possibility of clogging.

Since we have not increased the operating hp, it is usually not necessary to oversize the drive to obtain extended motor performance. Check the motor current to be sure.

Operating Below Rated Motor Speed

Most motors have an internal cooling fan.

Operation below rated speed reduces the effectiveness of the fan. The motor may overheat.

This is usually not a problem for fan or pump applications, since the load is very small at light loads.

For constant torque applications, conveyors, hoists, cranes, forced cooling of the motor may be required.

The following shows typical torque derating for a fan cooled motor operated below rated frequency.

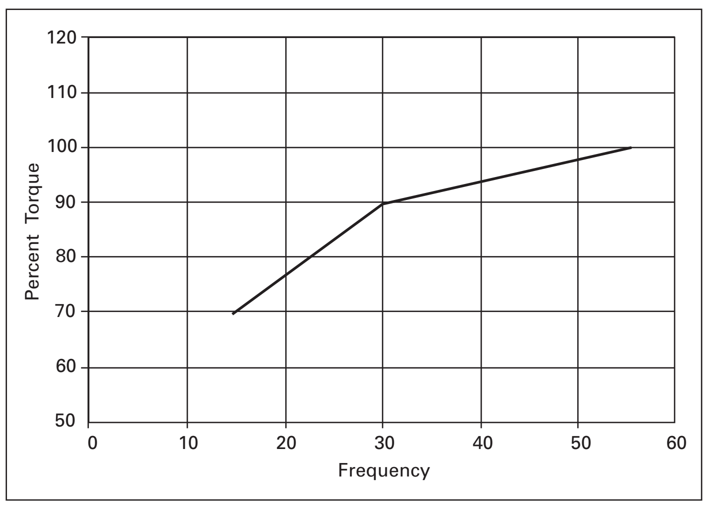

FIGURE 12. MOTOR TORQUE DE-RATING

Mechanical resonance may be present below the rated speed.

Continued operation at these speeds can effect the performance of the driven equipment, and lead to premature failures.

Most AC Drives allow certain speeds (frequencies) to be “skipped.” This avoids operating at the mechanical resonance speeds (also called critical speeds).

Operating Above Rated Motor Speed

Speed/Torque Considerations

Most AC Drives can have output frequencies of 120 Hz or greater.

However, the output voltage is limited to the magnitude of the line voltage. A drive supplied by 460 volts cannot output more than 460 volts.

Therefore, as frequency is increased above 60 Hz, the output voltage remains constant, and the volts per hertz ratio decreases.

This reduces the motor torque.

Below is a plot of AC Drive and Motor Torque versus Speed.

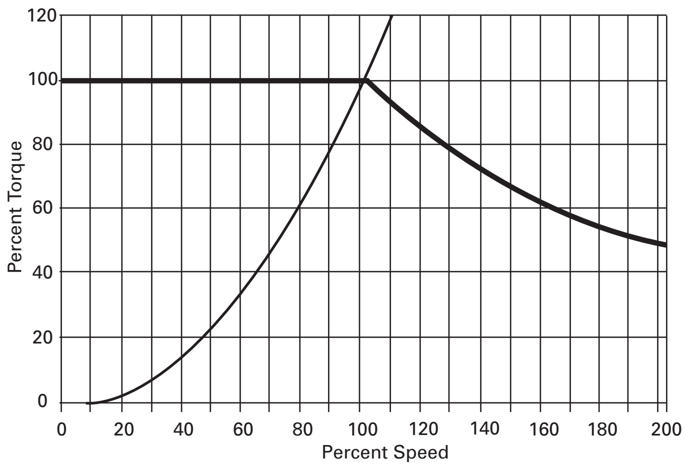

FIGURE 13. SPEED VS. AC DRIVE + MOTOR TORQUE

The thick line is the drive+motor torque curve.

The thin line is a typical speed torque curve for a centrifugal fan or pump. No overspeed is possible for this type of load, since the load torque exceeds the motor torque.

Operating above rated speed requires either:

- A load with low torque, such as a unloaded crane
- The motor to be oversized

Mechanical Considerations

Operating above the motor's rated speed should be carefully reviewed.

The NEMA MG-1 Standard gives typical overspeed capabilities of induction motors.

- Small motors can typically run at 200% speed
- Large motors can typically run at 125 – 150% speed

The mechanical vibration of a system will increase as speed increases. The rotating equipment mounting, alignment and balance is more critical as the speed increases.

Mechanical resonance may be present above rated speed. Some speeds (frequencies) may have to be skipped.

Multiple Motor Operation

We can connect any number of motors in parallel across a single AC drive. All motors will be operated at the same speed, since the frequency to all the motors will be the same. With NEMA B motors, motor speed will be matched within 3%, depending on load variations.

If it is necessary to have exact speed matching, synchronous AC motors must be used.

If an adjustable speed ratio is desired between the motors, individual AC drives must be used.

The simplest multiple motor application is where all motors are started and stopped together and are permanently connected to the drive. In this case, it is simple to size the drive to provide an output current equal to the sum of the individual motors.

If motors are to be started and stopped separately, you must then determine the highest intermittent current that will be required for the worst case combination of motors running and motors starting. Stopping individual motors may cause difficulty in some situations.

If two or more motors are to be mechanically coupled together, load-sharing requirements must be considered.

Individual motor overload protection must be provided when using a multiple motor application.

AC Drive Application

Matching the AC Drive to the Motor

PWM and Vector AC Drives are designed for use with any standard squirrel cage motor. Sizing the drive is a simple matter of matching the drive output voltage, frequency and current ratings to the motor ratings.

Output Voltage and Frequency

Most modern AC Drives are designed for use with various voltages and frequencies. By adjusting the V/Hz properly, almost any 3-phase motor can be used.

Output Current

AC drive full load currents are matched to typical full load motor current ratings as listed in NEC® Table 430-150. Usually an AC drive can be matched to an AC motor by their hp ratings, however, actual motor current required under operating conditions is the determining factor. If the motor will be run at full load, the drive current rating must be at least as high as the motor current rating. If the drive is to be used with multiple motors, the sum of all the full load current ratings must be used, and adding up the hp ratings of the motors will usually not provide an accurate estimate of the drive needed.

Motor Protection

Motor overload protection must be provided as required by the applicable codes. Motor protection is not automatically provided as part of all AC drives. It may be provided as a standard feature on one model or it may be an optional feature on another.

The best means of motor protection is a direct winding over temperature protection such as an over temperature switch imbedded in the motor windings. Direct over temperature protection is preferred because overheating can occur at normal operating currents at low speeds.

Most AC drives are equipped with electronic overcurrent protection, such as I^2t protection, similar to a conventional overload. Conventional overloads also may be used. In some modern drives, the I^2t protection can be configured to protect the motor during low speed operation.

In multiple motor applications, individual motor overload protection must be provided even where electronic protection is provided by the drive. In some cases, short circuit protection may be required.

Motor Winding Damage

The voltage output of AC drives contains voltage steps. In modern PWM drives, the dV/dt of a motor causes can cause very large voltage spikes. Voltage spikes of 1500 volts or more are typical for a 460 volt motor.

This can cause the end windings of a Non-Inverter Duty or standard induction motor to fail.

This problem gets worse as the cable length from the drive to the motor gets longer. Corrective action is normally required for cables longer than 150 feet.

Load side reactors, installed at the drive output terminals, will reduce the voltage spikes at the motor terminals.

Most drive manufacturers have load side reactors available as an option.

AC Drive Performance

Operator Control and Interface Requirements

A means must be provided to start and stop the drive and provide a speed reference. This may be accomplished with a simple run/stop switch and a speed potentiometer, or by more elaborate means. Additional functions that may be required include reversing; lights or relays to indicate drive status; and meters to indicate operating speed, load, etc.

Speed Range

Speed range is usually determined by the characteristics of the motor, as the AC drive output frequency range is usually wider than the motor range.

Acceleration and Deceleration

Independently adjustable acceleration and deceleration rates are usually provided with a drive. Actual field conditions determine the optimum acceleration and deceleration rate of the drive.

Speed Regulation

As most AC drives do not use encoder feedback, speed regulation is determined by the slip of the motor. Typical slip for a NEMA B motor provides for 3% regulation. Slip compensation circuits can be used to improve this to about 1.0% regulation. In extreme cases, where very close speed regulation is essential, a motor encoder can be supplied to give 0.0l% speed regulation.

Current Limit

AC drives are equipped with current limit circuits. If current limit is not provided, the overcurrent trip circuits will shut you down in the event of an overload or attempting to accelerate too fast.

Regeneration Limit and Braking

During deceleration or in the event of an overhauling load, a motor will produce braking torque.

When a motor produces braking torque, it is operating as an induction generator. This means that the drive is being fed power from the motor. When power is being fed into the drive, it cannot pass current back out to the line. This means that this excess power is sent to the bus capacitors. If enough power is regenerated, the bus capacitors will charge to the trip level for the drive. When this occurs, bus voltage will rise. If the voltage rises above a preset level, the drive will trip.

When the drive is provided with some type of dynamic braking circuit, it will allow the motor to produce rated torque as braking torque.

A full regenerative drive will allow the drive to feed this excess power back onto the line.

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