CHAPTER 40

MOTORS, MOTOR CONTROLS, AND VARIABLE-SPEED DRIVES

MOTORS

MANY TYPES of alternating-current (ac) motors are available, and while the direct-current (dc) motor is also used, it is only to a limited degree. NEMA *Standard* MG 1 provides technical information on all types of ac and dc motors.

ALTERNATING CURRENT POWER SUPPLY

Important characteristics of an ac power supply include (1) voltage, (2) number of phases, (3) frequency, (4) voltage regulation, and (5) continuity of power.

The **nominal voltage** (or **service voltage**) is the value assigned to the circuit or system to designate its voltage class. It is the voltage at the connection between the supplier and the user. **Utilization voltage** is the voltage at the line terminals of the equipment.

Single-phase and three-phase motor and control voltage ratings shown in Table 1 are adapted to the nominal voltages indicated. Motors with these ratings are considered suitable for ordinary use on their corresponding systems; for example, a 230 V motor should generally be used on a nominal 240 V system. A 230 V motor should not be installed on a nominal 208 V system because the utilization voltage is below the tolerance on the voltage rating for which the motor is designed. Such operation generally results in overheating and a serious reduction in torque.

Motors are usually guaranteed to operate satisfactorily and to deliver their full power at the rated frequency and at a voltage 10% above or below rating, or at the rated voltage and plus or minus 5% frequency variation. Table 2 shows the effect of voltage and frequency variation on induction motor characteristics.

The phase voltages of three-phase motors should be balanced. If not, a small voltage imbalance can product a greater current imbalance and a much greater temperature rise, which can result in nuisance overload trips or motor failures. Motors should not be operated where the voltage imbalance is greater than 1% without checking with the manufacturer. Voltage imbalance is defined in NEMA *Standard* MG 1, Paragraph 14.34, as

$$\%\ \text{Voltage imbalance} = 100 \times \frac{\begin{array}{c}\text{Maximum voltage deviation}\\ \text{from average voltage}\end{array}}{\text{Average voltage}}$$

In addition to voltage imbalance, current imbalance can be present in a system where Y-Y transformers without tertiary windings are used, even if the voltage is in balance. As stated previously, this current imbalance is not desirable. If this current imbalance exceeds either 10% or the maximum imbalance recommended by the manufacturer, corrective action should be taken (see NFPA *Standard* 70).

Table 1 Motor and Motor Control Equipment Voltages

System Nominal Voltage	Equipment Nameplate Voltage Ratings			
	Integral Horsepower		Fractional Horsepower	
	Three-Phase	Single-Phase	Three-Phase	Single-Phase
120	—	115	—	115
208	200	—	200	—
240	230	230	230	230
277	—	265	—	265
480	460	—	460	—
600[a]	575	—	575	—
2,400	2,300	—	—	—
4,160	4,000	—	—	—
4,800	4,600	—	—	—
6,900	6,600	—	—	—
13,800	13,200	—	—	—

[a] Certain control and protective equipment have a maximum voltage limit of 600 V. Consult the manufacturer, power supplier, or both to ensure proper application.

$$\%\ \text{Current imbalance} = 100 \times \frac{\begin{array}{c}\text{Maximum current deviation}\\ \text{from average current}\end{array}}{\text{Average current}}$$

Another cause of current imbalance is normal winding impedance imbalance, which adds or subtracts from the current imbalance caused by voltage imbalance.

CODES AND STANDARDS

The *National Electrical Code* (NEC) (NFPA *Standard* 70) and the *Canadian Electrical Code*, Part I (CSA *Standard* C22.1) are important in the United States and Canada. The *National Electrical Code* contains minimum recommendations considered necessary to ensure safety of electrical installations and equipment. It is referred to in Subpart S (Electrical) of the Occupational Safety and Health Acts (OSHA) of 1970 and, therefore, is part of the OSHA requirements. In addition, practically all communities in the United States have adopted the NEC as a minimum electrical code.

Underwriters Laboratories (UL) promulgates standards for various types of equipment. UL standards for electrical equipment cover construction and performance for the safety of such equipment and interpret requirements to ensure compliance with the intent of the NEC. A complete list of available standards may be obtained from UL, which also publishes lists of equipment that comply with their standards. These listed products bear the UL label and are recognized by local authorities.

The preparation of this chapter is assigned to TC 8.11, Electric Motors and Motor Control.

Table 2 Effect of Voltage and Frequency Variation on Induction Motor Characteristics

Voltage and Frequency Variation		Starting and Maximum Running Torque	Synchronous Speed	% Slip	Full-Load Speed	Efficiency		
						Full Load	0.75 Load	0.5 Load
Voltage variation	120% Voltage	Increase 44%	No change	Decrease 30%	Increase 1.5%	Small increase	Decrease 0.5 to 2%	Decrease 7 to 20%
	110% Voltage	Increase 21%	No change	Decrease 17%	Increase 1%	Increase 0.5 to 1%	Practically no change	Decrease 1 to 2%
	Function of voltage	Voltage^2	Constant	1/Voltage^2	Synchronous speed slip	—	—	—
	90% Voltage	Decrease 19%	No change	Increase 23%	Decrease 1.5%	Decrease 2%	Practically no change	Increase 1 to 2%
Frequency variation	105% Voltage	Decrease 10%	Increase 5%	Practically no change	Increase 5%	Slight increase	Slight increase	Slight increase
	Function of frequency	1/Frequency^2	Frequency	—	Synchronous speed slip	—	—	—
	95% Frequency	Increase 11%	Decrease 5%	Practically no change	Decrease 5%	Slight decrease	Slight decrease	Slight decrease

Voltage and Frequency Variation		Power Factor			Full-Load Current	Starting Current	Temperature Rise, Full Load	Maximum Overload Capacity	Magnetic Noises, No Load in Particular
		Full Load	0.75 Load	0.5 Load					
Voltage variation	120% Voltage	Decrease 5 to 15%	Decrease 10 to 30%	Decrease 15 to 40%	Decrease 11%	Increase 25%	Decrease 9 to 11°F	Increase 44%	Noticeable increase
	110% Voltage	Decrease 3%	Decrease 4%	Decrease 5 to 6%	Decrease 7%	Increase 10 to 12%	Decrease 5 to 7°F	Increase 21%	Increase slightly
	Function of voltage	—	—	—	—	Voltage	—	Voltage^2	—
	90% Voltage	Increase 3%	Increase 2 to 3%	Increase 4 to 5%	Increase 11%	Decrease 10 to 12%	Increase 11 to 13°F	Decrease 19%	Decrease slightly
Frequency variation	105% Frequency	Slight increase	Slight increase	Slight increase	Decrease slightly	Decrease 5 to 6%	Decrease slightly	Decrease slightly	Decrease slightly
	Function of frequency	—	—	—	—	$\frac{1}{\text{Frequency}}$	—	—	—
	95% Frequency	Slight decrease	Slight decrease	Slight decrease	Increase slightly	Increase 5 to 6%	Increase slightly	Increase slightly	Increase slightly

Note: These variations are general and differ for specific ratings.

The *Canadian Electrical Code*, Part I, is a standard of the Canadian Standards Association (CSA). It is a voluntary code with minimum requirements for electrical installations in buildings of every kind. The *Canadian Electrical Code*, Part II, contains specifications for the construction and performance of electrical equipment, in compliance with Part I. UL and CSA standards for electrical equipment are similar, so equipment designed to meet the requirements of one code may also meet the requirements of the other. However, agreement between the codes is not complete, so individual standards must be checked when designing equipment for use in both countries. The CSA examines and tests material and equipment for compliance with the *Canadian Electrical Code.*

MOTOR EFFICIENCY

The many factors affecting motor efficiency include (1) sizing of the motor to the load, (2) type of motor specified, (3) motor design speed, and (4) type of bearing specified. Oversizing a motor may reduce efficiency. As shown in the performance characteristic curves for single-phase motors in Figures 1, 2, and 3, the efficiency falls off rapidly at loads lighter than the rated full load. Polyphase motors usually reach peak efficiency at loads slightly lighter than full load (Figure 4). Motor performance curves are available from the motor manufacturer and can help in applying the optimum motor for an application. Larger output motors are more efficient at rated load than smaller motors. Also, higher speed induction motors are more efficient.

The type of motor specified is significant because, for example, a permanent split-capacitor motor is more efficient than a shaded-pole fan motor. A capacitor-start/capacitor-run motor is more efficient than either a capacitor-start or a split-phase motor. In polyphase motors, the lower the locked rotor torque specified, the higher the efficiency obtained in the design.

The motor industry offers high-efficiency motors that include more material than a standard-efficiency motor of the same type. NEMA *Standards* MG 10 and MG 11 have more information on motor efficiency.

GENERAL-PURPOSE INDUCTION MOTORS

The electrical industry classifies motors as **small kilowatt** (**fractional horsepower**) or **integral kilowatt** (**integral horsepower**). In this context, kilowatt refers to power output of the motor. Small kilowatt motors have ratings of less than 1 hp at 1700 to 1800 rpm for four-pole and 3500 to 3600 rpm for two-pole machines. Single-phase motors are available through 5 hp and are most common through 0.75 hp because motors larger than 0.75 hp are usually polyphase.

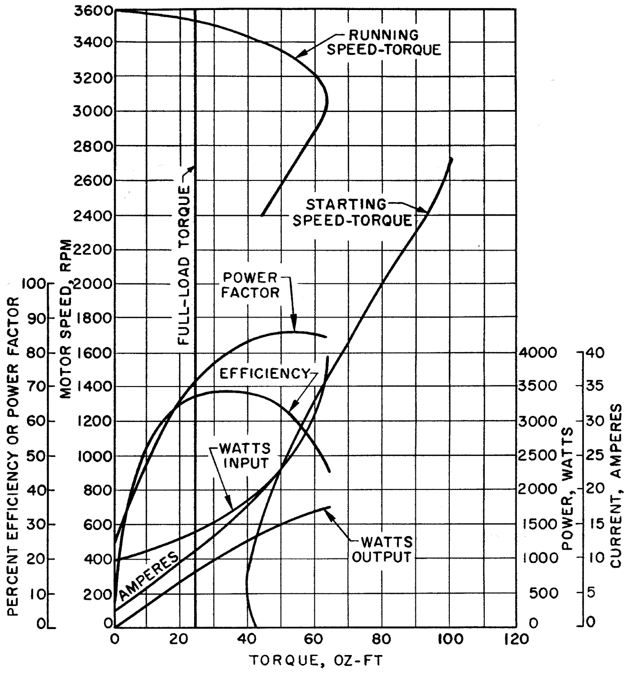


Fig. 1 Typical Performance Characteristics of Capacitor-Start/Induction-Run Two-Pole General-Purpose Motor, 1 hp

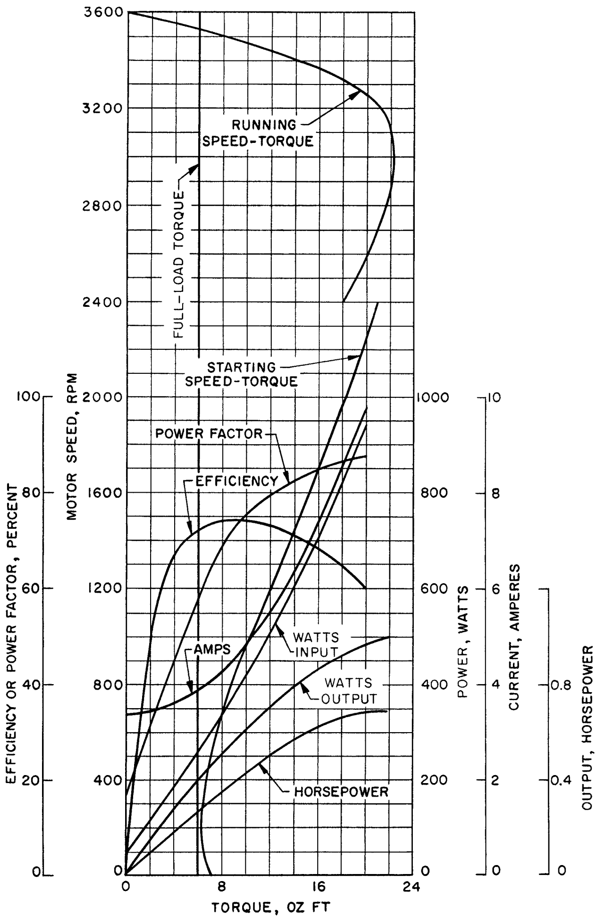


Fig. 2 Typical Performance Characteristics of Resistance-Start Split-Phase Two-Pole Hermetic Motor, 0.25 hp

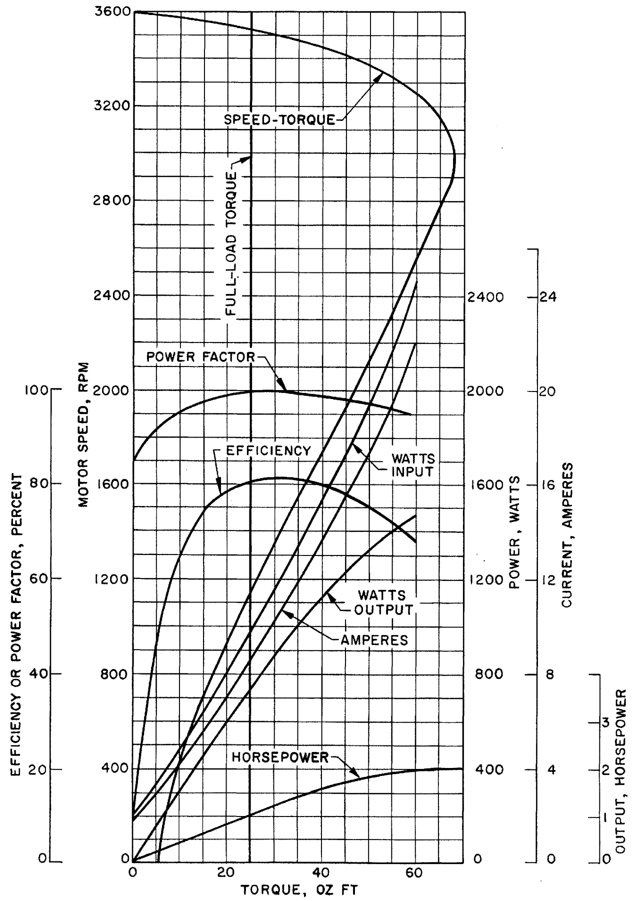


Fig. 3 Typical Performance Characteristics of Permanent Split-Capacitor Two-Pole Motor, 1 hp

Table 3 lists motors by types indicating the normal kilowatt range and the type of power supply used. All motors listed are suitable for either direct or belt drive, except shaded-pole motors (limited by low starting torque).

Application

When applying an electric motor, the following characteristics are important: (1) mechanical arrangement, including position of the motor and shaft, type of bearing, portability desired, drive connection, mounting, and space limitations; (2) speed range desired; (3) power requirement; (4) torque; (5) inertia; (6) frequency of starting; and (7) ventilation requirements. Motor characteristics that are frequently applied are generally presented in curves (see Figures 1 through 4).

Torque. The torque required to operate the driven machine at all times between initial breakaway and final shutdown is important in determining the type of motor. The torque available at zero speed or standstill (**starting torque**) may be less than 100% or as high as 400% of full-load torque, depending on motor design. The **starting current**, or **locked-rotor current**, is usually 400 to 600% of the current at rated full load.

Full-load torque is the torque developed to produce the rated power at the rated speed. **Full-load speed** also depends on the design of the motor. For induction motors, a speed of 1725 rpm is typical for four-pole motors, and a speed of 3450 rpm is typical for two-pole motors at 60 Hz.

Motors have a **maximum or breakdown torque**, which cannot be exceeded. The relation between breakdown torque and full-load torque varies widely, depending on motor design.

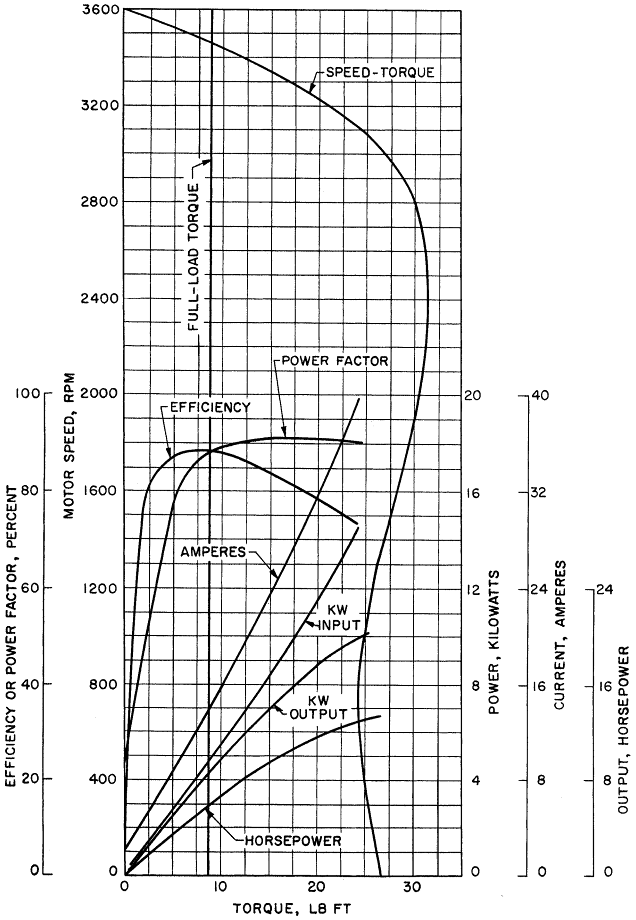


Fig. 4 Typical Performance Characteristics of Polyphase Two-Pole Motor, 5 hp

Power. The power delivered by a motor is a product of its torque and speed. Because a given motor delivers increasing power up to maximum torque, a basis for power rating is needed. The National Electrical Manufacturers Association (NEMA) bases **power rating** on breakdown torque limits for single-phase motors, 10 hp and less. All others are rated at their power capacity within voltage and temperature limits as listed by NEMA.

Full-load rating is based on the maximum winding temperature. If the nameplate marking includes the maximum ambient temperature for which the motor is designed and the insulation designation, the maximum temperature rise of the winding may be determined from the appropriate section of NEMA *Standard* MG 1.

Service Factor. This factor is the maximum overload that can be applied to general-purpose motors and certain definite-purpose motors without exceeding the temperature limitation of the insulation. When the voltage and frequency are maintained at the values specified on the nameplate and the ambient temperature does not exceed 104°F, the motor may be loaded to the power obtained by multiplying the rated power by the service factor shown on the nameplate.

The power rating is normally established on the basis of a test-run in still air. However, most direct-drive, air-moving applications are checked with air flowing over the motor. If the motor nameplate marking does not specify a service factor, refer to the appropriate section of NEMA *Standard* MG 1. Characteristics of alternating current motors are given in Table 4.

Table 3 Motor Types

Type	Range, hp	Type of Power Supply
Fractional Sizes		
Split phase	0.05 to 0.5	Single phase
Capacitor-start	0.05 to 1.5	Single phase
Repulsion-start	0.13 to 1.5	Single phase
Permanent split-capacitor	0.05 to 1.5	Single phase
Shaded-pole	0.01 to 0.25	Single phase
Squirrel cage induction	0.17 to 1.5	Polyphase
Direct current	0.5 to 1.5	DC
Integral Sizes		
Capacitor-start/capacitor-run	1 to 5	Single phase
Capacitor-start	1 to 5	Single phase
Squirrel cage induction (normal torque)	1 and up	Polyphase
Slip-ring	1 and up	Polyphase
Direct current	1 and up	DC
Permanent split-capacitor	1 to 5	Single phase

HERMETIC MOTORS

A hermetic motor is a partial motor usually consisting of a stator and a rotor without shaft, end shields, or bearings. It is for installation in hermetically-sealed refrigeration compressor units. With the motor and compressor sealed in a common chamber, the winding insulation system must be impervious to the action of the refrigerant and lubricating oil. Hermetic motors are used in both welded and accessible hermetic (semihermetic) compressors.

Application

Domestic Refrigeration. Hermetic motors up to 0.33 hp are used. They are split-phase, permanent split-capacitor, or capacitor-start motors for medium or low starting torque compressors and capacitor-start and special split-phase motors for high starting torque compressors.

Room Air Conditioners. Motors from 0.33 to 3 hp are in use. They are permanent split-capacitor or capacitor-start/capacitor-run types. These designs have high power factor and efficiency and meet the need for low current draw, particularly on 115 V circuits.

Central Air Conditioning (Including Heat Pumps). Both single-phase (6 hp and below) and polyphase (1.5 hp and above) motors are used. The single-phase motors are permanent split-capacitor or capacitor-start/capacitor-run types.

Small Commercial Refrigeration. Practically all these units are below 5 hp, with single-phase being the most common. Capacitor-start/induction-run motors are normally used up to 0.75 hp because of starting torque requirements. Capacitor-start/capacitor-run motors are used for larger sizes because they provide high starting torque and high full-load efficiency and power factor.

Large Commercial Refrigeration. Most motors are three-phase and larger than 5 hp.

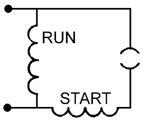
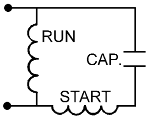
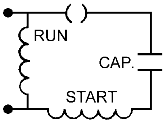
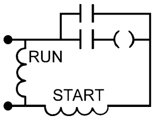
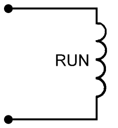
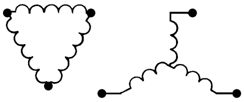
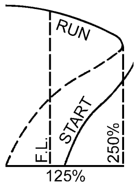
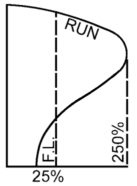
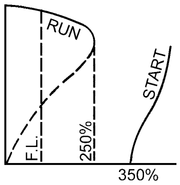
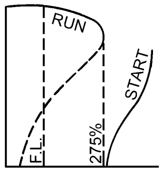
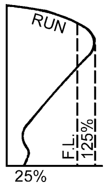
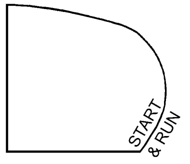
Power ratings of motors for hermetic compressors do not necessarily have a direct relationship to the thermodynamic output of a compressor. Designs are tailored to match the compressor characteristics and specific applications. Chapter 35 briefly discussed hermetic motor applications for various compressors.

INTEGRAL THERMAL PROTECTION

The *National Electrical Code* and UL standards cover motor protection requirements. Separate, external protection devices include the following:

Thermal Protectors. These protective devices are an integral part of a motor or hermetic motor refrigerant compressor. They

Table 4 Characteristics of AC Motors (Nonhermetic)

	Split-Phase	Permanent Split-Capacitor	Capacitor-Start/ Induction-Run	Capacitor-Start/ Capacitor-Run	Shaded-Pole	Polyphase, 60-Hz
Connection Diagram						
Speed Torque Curves						
Starting Method	Centrifugal switch	None	Centrifugal switch	Centrifugal switch	None	Motor controller
Ratings, hp	0.05 to 0.5	0.05 to 5	0.05 to 5	0.05 to 5	0.01 to 0.25	0.5 and up
Full-Load Speeds at 60-Hz (Two-Pole, Four-Pole)	3450 to 1725	3450 to 1725	3450 to 1725	3500 to 1750	3100 to 1550	3500 to 1750
Torque[a]						
Locked Rotor	125 to 150%	25%	250 to 350%	250%	25%	150 to 350%
Breakdown	250 to 300%	250 to 300%	250 to 300%	250%	125%	250 to 350%
Speed Classification	Constant	Constant	Constant	Constant	Constant or adjustable	Constant
Full-Load Power Factor	60%	95%	65%	95%	60%	80%
Efficiency	Medium	High	Medium	High	Low	High-Medium

[a] Expressed as percent of rated horsepower torque.

protect the motor against overheating caused by overload, failure to start, or excessive operating current. Thermal protectors are required to protect polyphase motors from overheating because of an open phase in the primary circuit of the supply transformer. Thermal protection is accomplished by either a line break device or a thermal sensing control circuit.

The protector of a hermetic motor-compressor has some unique capabilities compared to nonhermetic motor protectors. The refrigerant cools the motor and compressor, so the thermal protector may be required to prevent overheating from loss of refrigerant charge, low suction pressure and high superheat at the compressor, obstructed suction line, or malfunction of the condensing means.

Article 440 of the NEC limits the maximum continuous current on a motor-compressor to 156% of rated load current if an integral thermal protector is used. NEC Article 430 limits the maximum continuous current on a nonhermetic motor to different percentages of full-load current as a function of size. If separate overload relays or fuses are used for protection, Article 430 limits maximum continuous current to 140% and 125%, respectively, of rated load.

UL *Standard* 984 specifies that the compressor enclosure must not exceed 300°F under any conditions. The motor winding temperature limit is set by the compressor manufacturer based on individual compressor design requirements. UL *Standard* 547 sets the limit for the motor winding temperature for open motors as a function of the class of the motor insulation used.

Line-Break Thermal Protectors. Integral with a motor or motor-compressor, line-break thermal protectors that sense both current and temperature are connected electrically in series with the motor; their contacts interrupt the total motor line-current. These protectors are used in small, single-phase and polyphase motors up through 15 hp.

Protectors installed inside a motor-compressor are hermetically sealed because exposed arcing in the presence of refrigerant cannot be tolerated. They provide better protection than the external type for loss of charge, obstructed suction line, or low voltage on the stalled rotor. This is due to low current associated with these fault conditions, hence the need to sense the motor temperature increase by thermal contact. Protection inside the compressor housing must withstand pressure requirements established by UL.

Protectors mounted externally on motor-compressor shells, sensing only shell temperature and line current, are typically used on smaller compressors, such as those in household refrigerators and small room air conditioners. One benefit occurs during high head pressure starting conditions, which can occur if voltage is lost momentarily or if the user inadvertently turns off the compressor with the temperature control and then turns it back on immediately. Usually, these units do not start under these conditions. When this happens, the protector takes the unit off the line and resets automatically when the compressor cools and pressures have equalized to a level that allows the compressor to start.

Protectors installed in nonhermetic motors may be attached to the windings or may be mounted off the windings but in the motor housing. Those protectors placed on the winding are generally installed prior to varnish dip and bake, and their construction must prevent varnish from entering the contact chamber.

Since the protector carries full motor line current, its size is based on adequate contact capability to interrupt the stalled current of the motor on continuous cycling for periods specified in UL *Standards* 984 and 547.

The compressor or motor manufacturer applies and selects appropriate motor protection in cooperation with the protector manufacturer. Any change in protector rating, by other than the specifying manufacturer after the proper application has been made, may result in either overprotection and frequent nuisance tripouts or underprotection and burnout of the motor windings. Connections to protector terminals, including lead wire sizes, should not be changed, and no additional connections should be made to the terminals. Any change in connection changes the terminal conditions and affects protector performance.

Control circuit thermal protectors approved for use with a motor or motor-compressor, either sensing both current and temperature or sensing temperature only, are used with integral horsepower single-phase and three-phase motors.

The current and temperature protector uses a bimetallic temperature sensor installed in the motor winding in conjunction with thermal overload relays. The sensors are connected in series with the control circuit of a magnetic contactor that interrupts the motor current. Thermostat sensors of this type, which depend on their size and mass, are capable of tracking motor winding temperature for running overloads. When a rotor is locked (when the rate of change in winding temperature is rapid), the temperature lag is usually too great for such sensors to provide protection when they are used alone. However, when the bimetallic sensor is used with separate thermal overload or magnetic time-delay relays that sense motor current, the combination provides protection; on a locked rotor condition, the thermal or magnetic relays protect for the initial heating cycle, and the combined functioning of relay and thermostat protects for subsequent cycles.

The resistance change of a thermistor may be used to provide a switching signal to the electronic circuit, whose output is in series with the control circuit of a magnetic contactor used to interrupt the motor current. The output of the electronic protection circuitry (module) may be an electromechanical relay or a power triac. The sensors may be installed directly on the stator winding end turns or buried inside the windings. Their small size and good thermal transfer allow them to track the temperature of the winding for locked rotor, as well as running overload.

Three types of sensors are available. One type uses a ceramic material with a positive temperature coefficient of resistance; the material exhibits a large, abrupt change in resistance at a particular design temperature. This change occurs at the **anomaly point**, which is inherent in the sensor. The anomaly point remains constant once the sensor is manufactured; sensors are produced with anomaly points at different temperatures to meet different requirements. However, a single module calibration can be supplied for all anomaly temperatures of a given sensor type.

Another type of sensor uses a metal wire, which has a linear increase in resistance with temperature. The sensor assumes a specified value of resistance corresponding to each desired value of response or operating temperature. It is used with an electronic protection module calibrated to a specific resistance. Modules supplied with different calibrations are used to achieve various values of operating temperatures.

A third type is a negative temperature coefficient of resistance sensor, which is integrated with electronic circuitry similar to that used with the metal wire sensor.

More than one sensor may be connected to a single electronic module in parallel or series, depending on design. However, the sensors and modules must be of the same design and intended for use with the particular number of sensors installed and the wiring method used. Electronic protection modules must be paired only with sensors specified by the manufacturer, unless specific equivalency is established and identified by the motor or compressor manufacturer.

MOTOR CONTROL

In general, motor control equipment may (1) disconnect the motor and controller from the power supply, (2) start and stop the motor, (3) protect against short circuits, (4) protect from overheating, (5) protect the operator, (6) control motor speed, and (7) protect motor branch circuit conductors and control apparatus.

Separate Motor Protection

Most air-conditioning and refrigeration motors or motor-compressors, whether open or hermetic, are equipped with integral motor protection by the equipment manufacturer. If this is not the case, separate motor-protection devices, sensing current only, must be used. These consist of thermal or magnetic relays, similar to those used in industrial control, that provide running overload and stalled-rotor protection. Because hermetic motor windings heat rapidly due to the loss of the cooling effect of refrigerant gas flow when the rotor is stalled, **quick-trip devices** must be used.

Thermostats or **thermal devices** are sometimes used to supplement current-sensing devices. Such supplements are necessary (1) when automatic restarting is required after trip or (2) to protect from abnormal running conditions that do not increase motor current. These devices are covered in the section on Integral Thermal Protection.

Protection of Control Apparatus and Branch Circuit Conductors

In addition to protection of the motor itself, Articles 430 and 440 of the *National Electrical Code* require the control apparatus and branch circuit conductors to be protected from overcurrent resulting from motor overload or failure to start. This protection can be given by some thermal protective systems that do not permit a continuous current in excess of required limits. In other cases, a current-sensing device, such as an overload relay, a fuse, or a circuit breaker, is used.

Circuit Breakers. These devices are used for disconnecting as well as circuit protection and are available in ratings for use with small household refrigerators as well as in large commercial installations. Manual switches for disconnecting and fuses for short-circuit protection are also used. For single-phase motors up to 3 hp, 230 V, an attachment plug is an acceptable disconnecting device.

Controllers. The motor control used is determined by the size and type of motor, the power supply, and the degree of automation. Control may be manual, semiautomatic, or fully automatic.

Central air conditioners are generally located some distance from the controlled space environment control, such as room thermostats and other control devices. Therefore, **magnetic controllers** must be used in these installations. Also, all dc and all large ac installations must be equipped with in-rush **current-limiting controllers**, which are discussed later. **Synchronous motors** are sometimes used to improve the power factor. **Multi-speed motors** provide flexibility for many applications.

Manual Control. For an ac or dc motor, manual control is usually located near the motor. If so, an operator must be present to start and stop or change the speed of the motor by adjusting the control mechanism.

Manual control is the simplest and least expensive control method for small ac motors, both single-phase and polyphase, but it is seldom used with hermetic motors. The manual controller usually consists of a set of main line contacts, which are provided with thermal overload relays for motor protection.

Manual speed controllers can be used for large air conditioners using **slip-ring motors**; they may also provide reduced-current starting. Different speed points are used to vary the amount of cooling provided by the compressor.

Across-the-Line Magnetic Controllers. These controllers are widely used for central air conditioning. They may be applied to motors of all sizes, provided power supply and motor are suitable to this type of control. Across-the-line magnetic starters may be used with automatic control devices for starting and stopping. Where push buttons are used, they may be wired for either low-voltage release or low-voltage protection.

Full-Voltage Starting. For motors, full-voltage starting is preferable because of its lower initial cost and simplicity of control. Except for dc machines, most motors are mechanically and electrically designed for full-voltage starting. The starting in-rush current, however, is limited in many cases by power company requirements made because of voltage fluctuations, which may be caused by heavy current surges. Therefore, the starting current must often be reduced below that obtained by across-the-line starting in order to meet the limitations of power supply. One of the simplest ways to make this reduction is to place resistors in the primary circuit. As the motor accelerates, the resistance is cut out by the use of timing or current relays.

Another method of reducing the starting current for an ac motor uses an **autotransformer** motor controller. Starting voltage is reduced, and, when the motor accelerates, it is disconnected from the transformer and connected across-the-line by timing or current relays. Primary resistor starters are generally smaller and less expensive than autotransformer starters for moderate size motors. However, primary resistor starters require more line current for a given starting torque than do autotransformer starters.

Star-Delta (Wye Delta) Motor Controllers. These controllers limit current efficiently, but they require motors designed for this type of starting. They are particularly suited for centrifugal, rotary screw, and reciprocating compressor drives starting without load.

Part-Winding Motor Controllers (or Incremental Start Controllers). These controllers limit line disturbances by connecting only part of the motor winding to the line and connecting the second motor winding to the line after a time interval of 1 to 3 s. If the motor is not heavily loaded, it accelerates when the first part of the winding is connected to the line; if it is too heavily loaded, the motor may not start until the second winding is connected to the line. In either case, the voltage dip will be less than the dip that would result if a standard squirrel cage motor with an across-the-line starter were used. Part-winding motors may be controlled either manually or magnetically. The magnetic controller consists of two contactors and a timing device for the second contactor.

Multispeed Motor Controllers. Multispeed motors provide flexibility in many types of drives in which variation in capacity is needed. Two types of multispeed motors are used: (1) motors with one reconnectable winding and (2) motors with two separate windings. Motors with separate windings need a contactor for each winding, and only one contactor can be closed at any time. Motors with a reconnectable winding are similar to motors with two windings, but the contactors and motor circuits are different.

Slip-Ring Motor Controllers. Slip-ring ac motors provide variable speed. The wound rotor of these motors functions in the same manner as in the squirrel cage motor, except that the rotor windings are connected through slip rings and brushes to external circuits with resistance to vary the motor speed. Increasing the resistance in the rotor circuit reduces motor speed, and decreasing the resistance increases motor speed. When the resistance is shorted out, the motor operates with maximum speed, efficiency, and power factor. On some large installations, manual drum controllers are used as speed-setting devices. Complete automatic control can be provided with special control devices for selecting motor speeds.

Controllers for Direct-Current Motors. These motors have favorable speed-torque characteristics, and their speed is easily controlled. Controllers for dc motors are more expensive than those for ac motors, except for very small motors. Large dc motors are started with resistance in the armature circuit, which is reduced step by step until the motor reaches its base speed. Higher speeds are provided by weakening the motor field.

Single-Phase Motor-Starting Methods

Motor-starting switches and relays for single-phase motors must provide a means for disconnecting the starting winding of split-phase or capacitor-start/induction-run motors or the start capacitor of capacitor-start/capacitor-run motors. Open machines usually have a centrifugal switch mounted on the motor shaft, which disconnects the starting winding at about 70% of full-load speed.

The starting methods by use of relays are as follows:

Thermally Operated Relay. When the motor is started, a contact that is normally closed applies power to the starting winding. A thermal element that controls these contacts is in series with the motor and carries line current. Current flowing through this element heats it until, after a definite time, it is warmed sufficiently to open the contacts and remove power from the starting winding. The running current then heats the element enough to keep the contacts open. The setting of the time for the starting contacts to open is determined by tests on the components (i.e., the relay, the motor, and the compressor) and is based on a prediction of the time delay required to bring the motor up to speed.

An alternate form of a thermally operated relay is a positive temperature coefficient of resistance (PTC) starting device. This device has a ceramic element with low resistance at room temperature that increases about 1000 times when it is heated to a predetermined temperature. It is placed in series with the start winding of split-phase motors and allows current flow when power is applied. After a definite period, the self-heating of the PTC resistive element causes it to reach its high-resistance state, which reduces current flow in the start winding. The small residual current maintains the PTC element in the high-resistance state while the motor is running. A PTC starting device may also be connected in parallel with a run capacitor, and the combination may be connected in series with the starting winding. It allows the motor to start like a split-phase motor and then, when the PTC element reaches the high-resistance state, operate as a capacitor-run motor. When power is removed, the PTC element must be allowed to cool to its low resistance state before restarting the motor.

Current-Operated Relay. In this type of connection, a relay coil carries the line current going to the motor. When the motor is started, the in-rush current to the running winding passes through the relay coil, causes the normally open contacts to close, and applies power to the starting winding. As the motor comes up to speed, the current decreases until, at a definite calibrated value of current corresponding to a preselected speed, the magnetic force of the coil diminishes to a point that allows the contacts to open to remove power from the starting winding. This relay takes advantage of the **main winding current** versus **speed** characteristics of the motor. The current-speed curve varies with line voltage, so that the starting relay must be selected for the voltage range likely to be encountered in service. Ratings established by the manufacturer should not be changed because this may result in undesirable starting characteristics. They are selected to disconnect the starting winding or start capacitor at approximately 70 to 90% of synchronous speed for four-pole motors.

Voltage-Operated Relay. Capacitor-start and capacitor-start/capacitor-run hermetically sealed motors above 0.5 hp are usually started with a normally closed contact voltage relay. In this method of starting, the relay coil is connected in parallel with the starting winding. When power is applied to the line, the relay does not operate because it is calibrated to operate at a higher voltage. As the motor comes up to speed, the voltage across the starting winding and relay coil increases in proportion to the motor speed. At a definite voltage corresponding to a preselected speed, the relay opens, thereby opening the starting winding circuit or disconnecting the starting capacitor. The relay keeps these contacts open because sufficient voltage is induced in the starting winding when the motor is running to hold the relay in the open position.

AIR VOLUME CONTROL

A review of the fan laws (Chapter 18) shows that volume delivered by a fan is directly proportional to its speed, pressure is proportional to the square of the speed, and power is proportional to the cube of the speed. According to these laws, a fan operating at 50% volume requires only 12.5% of the power required at 100% volume.

While the fan in a typical VAV system is sized to handle peak volume, the system operates at reduced volume most of the time. For example, Figure 5 shows the volume levels of a typical VAV system operating below 70% volume over 87% of the time. Thus, adjustable speed operation of the fan for this duty cycle could provide a significant energy saving.

Historically, centrifugal fans have been driven by fixed-speed ac motors, and volume has been varied by outlet dampers, variable inlet guide vanes, or eddy current couplings.

Outlet dampers are mounted in the airstream on the outlet side of the fan. Closing the damper reduces the volume, but at the expense of increased pressure. Points B and C on the fan performance curve in Figure 6 show the modified system curves for two closed damper positions. The natural operating point corresponds to a wide open damper position shown as point A. The input power profile is also shown for the referenced points.

Variable inlet vanes are mounted on the fan inlet to control air volume. Altering the pitch of the vane imparts a spin to the air entering the fan wheel, which results in a family of fan performance curves as shown in Figure 7. With reference to the required power at reduced flows, the inlet vane is more efficient than an outlet damper.

An **eddy current coupling** connects an ac motor driven fixed-speed input shaft to a variable-speed output shaft through a magnetic flux coupling. Reducing the level of flux density in the coupling increases slip between the couplings input and output shafts and reduces speed. **Slip** is wasted energy in the form of heat that must be dissipated by fan cooling or by water cooling for large motors.

Figure 8 shows that reducing fan speed also generates a family of performance curves, but the required input power still remains relatively high because the speed of the induction motor remains relatively constant.

VARIABLE-SPEED DRIVES

An alternative to these VAV speed control methods is the variable-speed drive. [In this section, the term variable-speed drive (VSD) is considered synonymous with variable frequency drive (VFD), pulse width modulated drive (PWM drive), adjustable speed drive (ASD), and adjustable frequency drive (AFD).] An alternating-current adjustable-speed drive consists of a pulse width modulation (PWM) controller with inverter gate bipolar transistors (IGBTs) and an induction motor. These very fast switching power transistors generate a variable-voltage, variable-frequency waveform that changes the speed of the prime mover. As shown in Figure 9, as speed is reduced, input power is reduced substantially because the power required varies as the cube of the speed (plus losses).

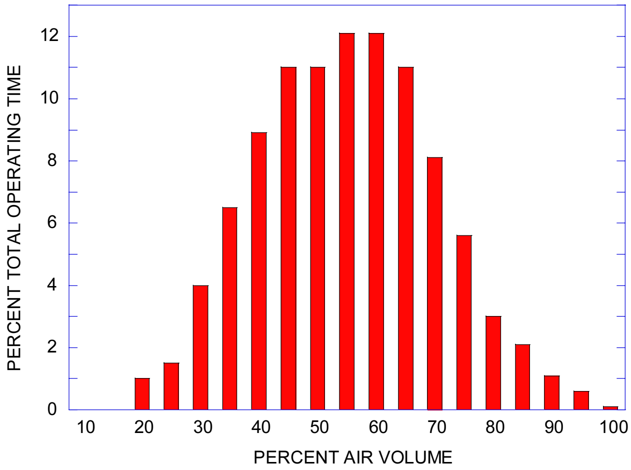


Fig. 5 Typical Fan Duty Cycle for VAV System

Table 5 Comparison of VAV Energy Consumption with Various Volume Control Techniques

	Outlet Damper	Inlet Guide Vane	Eddy Current Coupling	AC PWM Drive
Input Power, hp	91	62	62	28
Annual kWh	340,000	230,000	230,000	105,000

Typical 100 hp application at average of 60% design airflow rate for 5000 h operation.

A comparison of Figures 6, 7, 8, and 9 shows that significant energy savings can be achieved by using an ac adjustable-speed drive to achieve variable air volume control. In addition, very high efficiencies can be achieved by using the solid-state controller, which is over 96% efficient, with a state-of-the-art, energy-efficient ac motor with an efficiency of 93 to 95%. Table 5 shows typical annual energy use for the four VAV control techniques.

Power Transistor Characteristics

The key technology used to generate the output waveform is the IGBT. This transistor changes the characteristics of waveforms applied to a motor due to the speed at which the transistor cycles on and off. Pulse width modulation has been used for many years for variable-speed drives; however, as switching speeds increased from 1 or 2 kHz to 8, 15, or as high as 20 kHz to allow higher carrier frequencies, concerns arose over phenomena previously seen only in wave transmission devices like antennae and broadcast signal equipment. The faster switching time began to change the application variables such as drive to motor lead length. These factors must be considered when applying newer IGBT-based variable-speed drives.

Switching Times and d*v*/d*t*. Figure 10 shows the switching of a bipolar junction transistor (BJT) versus an IGBT as an example of how the increased switching speeds affect the turn-on and turn-off times as a ratio of the overall cycle. Note that the BJT switches at 2 kHz and the IGBT switches at 8 kHz, or 4 times faster.

The high rate of change in voltage over a relatively short time is know as the dv/dt of the voltage pulse. The amount of dv/dt is usually 10 to 90%. As the number of pulses increases so must the dv/dt. Note that this voltage waveform is a function of the drive design and is not user-settable. The maximum design carrier frequency sets the limits on how fast a transistor must cycle on and off.

Motor and Conductor Impedance

If the waveform shown at the output of the drive were identical at the motor terminals, a high dv/dt would not be a concern. But impedance or electrical resistance in ac circuits has an impact on the voltage pulse as it travels from the drive to the motor. When the cable impedance closely matches the motor impedance, the voltage pulse is evenly distributed. However, when the motor impedance is much larger than the cable impedance, the pulse reflects at the motor terminals, causing standing waves. Figure 11 shows the surge impedance of both the motor and the cable for different size drives and motors. Note that a relatively small motor (less than 2 hp) has a very high impedance with respect to the typical cable. Larger motors (greater than 100 hp) closely match cable impedance values.

Potential for Damaging Reflected Waves. Reflected waves damage motors because transmitted and reflected pulses can add together, causing a very high voltage. Because these voltage pulses are transmitted through the conductor over specific distances, cable length is a key variable when examining the potential for damaging voltages. Figure 12 shows the relationship between cable distance,

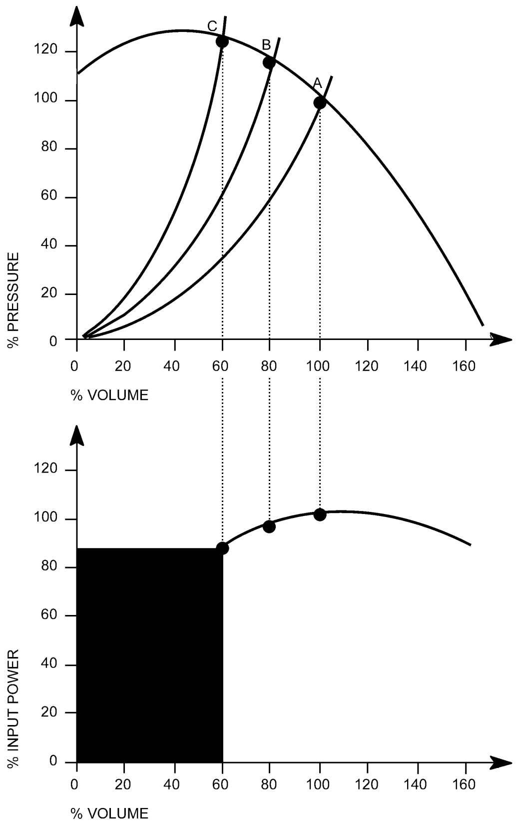


Fig. 6 Outlet Damper Control

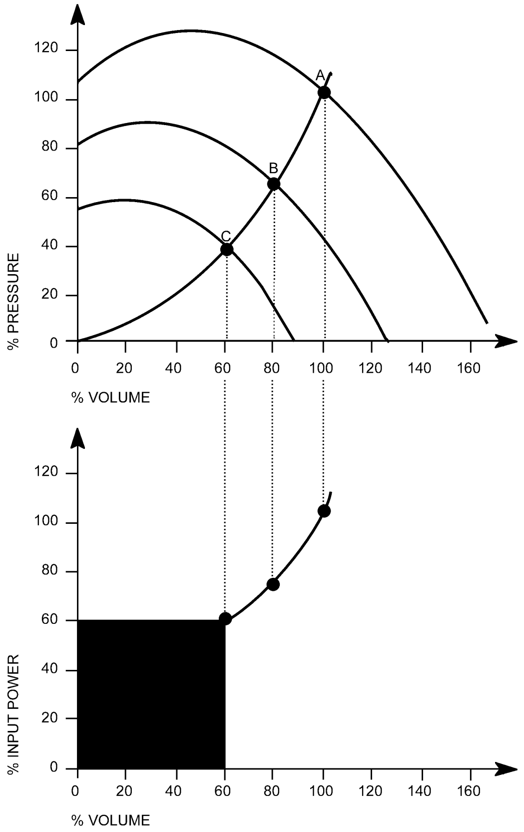


Fig. 8 Eddy Current Coupling Control

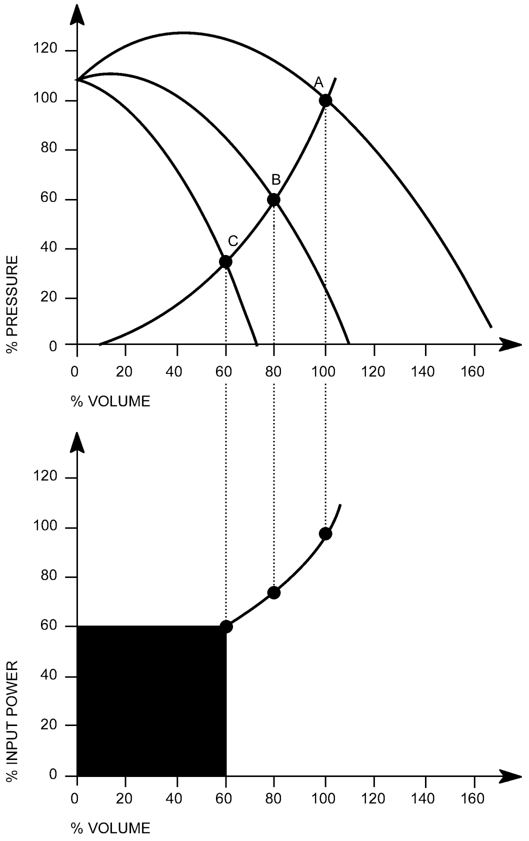


Fig. 7 Variable Inlet Vane Control

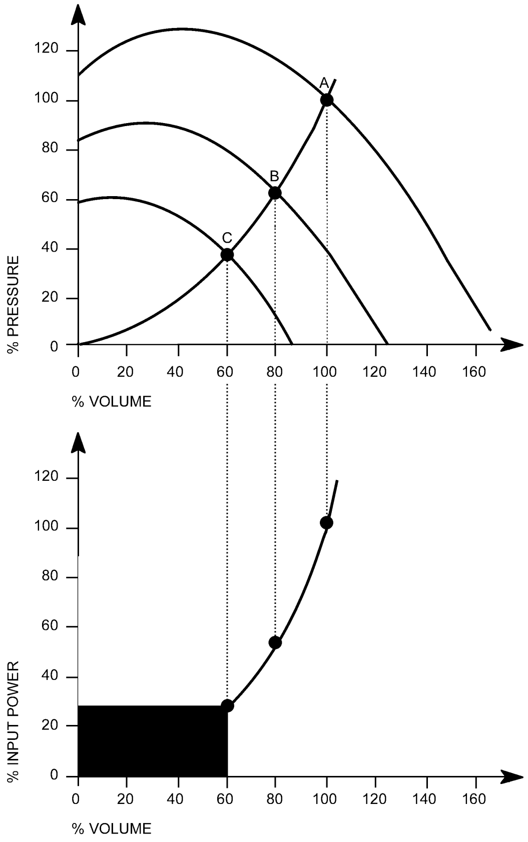


Fig. 9 AC Drive Control

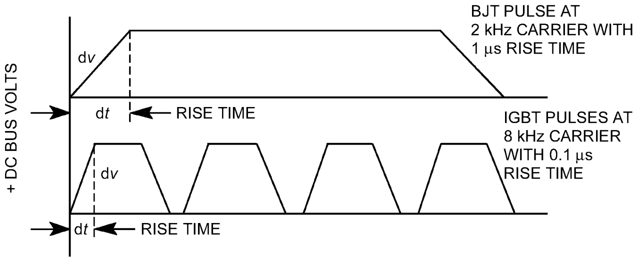


Fig. 10 Bipolar Versus IGBT PWM Switching

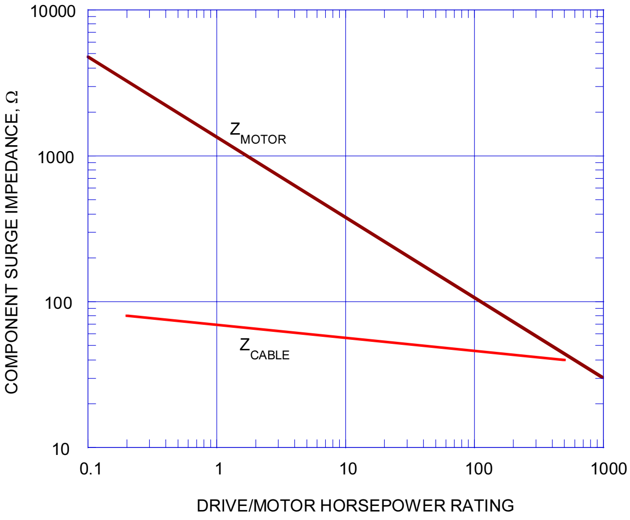


Fig. 11 Motor and Drive Relative Impedance

switching times, and voltage levels of pulses at motor terminals. Damaging reflected waves are more likely to occur in smaller motors because of the mismatch in surge impedance value. Special design techniques are required if multiple small motors are run from a single drive because the potential for reflected waves is high.

Figure 13 shows oscilloscope measurements taken at each end of the drive-to-motor conductor to describe the reflected wave phenomena. The two traces demonstrate the effect of transmitted and reflected pulses adding together to form damaging voltages. The induction motor must be designed to withstand these voltage levels.

Motor Ratings and NEMA Standards

An induction motor is constructed to withstand voltage levels higher than the nameplate suggests. The specific maximum **voltage withstand value** should be obtained from the manufacturer, but typical values for 208 V and 460 V motors range from 1000 to 1800 V. Higher voltage motors, such as 575 V motors, may be rated up to 2000 V peak. NEMA *Standard* MG 1, Revision 1, Part 31.40.4.2 states the established PWM drive motor limits, which are shown graphically in Figure 14. This standard establishes a peak of 1600 V and a minimum rise time of 0.1 µs for motors rated less than 600 V. When specifying motors for operation on variable-speed PWM drives, the voltage withstand level based on the d*v*/d*t* of the drive and the known cable distance should be specified.

Motor Insulation Breakdown. If reflected waves generate voltage levels higher than the allowable peak, insulation begins to break down. This phenomenon is known as **partial discharge** (PD) or **corona**. When two phases or two turns in the motor pass next to each other, high voltage peaks can cause a spark plug effect and damage the insulation. The voltage at which this effect begins is referred to as the **corona inception voltage** (CIV) rating of the motor (Figure 15). NEMA *Standard* MG 1 specifies this level at 1600 V.

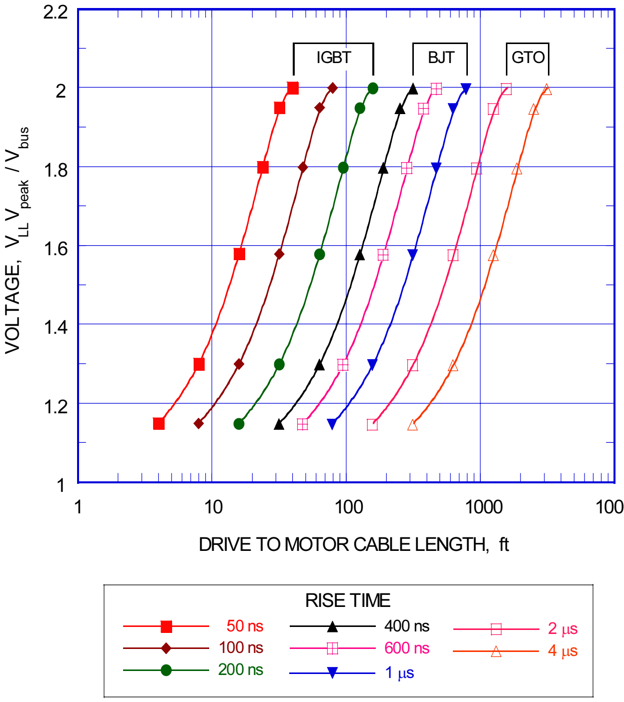


Fig. 12 Switching Times, Cable Distance, and Pulse Peak Voltage

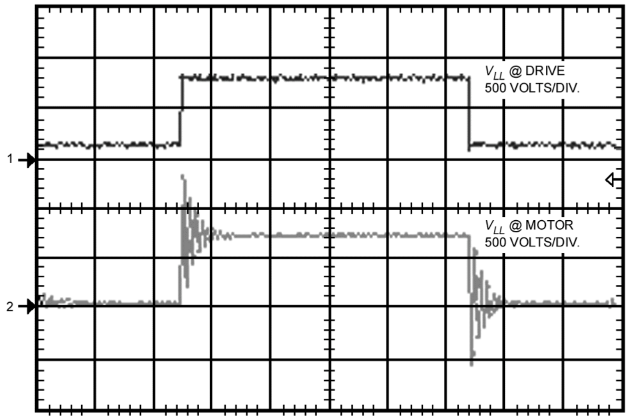


Fig. 13 Reflected Wave Voltage Levels at Drive and Motor Insulation

Eventually air gaps inside the varnish material ionize due to the high voltage gradients, causing phase-to-phase or turn-to-turn short circuits. This causes microscopic insulation breakdown, which is usually detected by the drive current sensors and results in overcurrent trips. Under this short-circuit condition, a motor may operate properly when run across the line or in bypass mode but consistently trip when run from drive power. Factory testing may be required to confirm this PMV failure mode.

Motor Noise and Drive Carrier Frequencies

The first implementation of PWM drive technology caused extreme motor noise at objectionable frequencies. IGBT technology

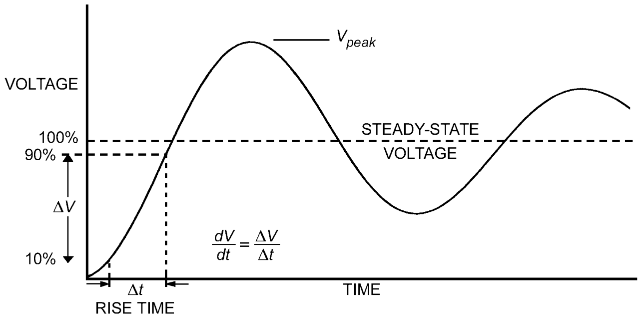


Fig. 14 Motor Voltage Peak and d*v*/d*t* Limits
(NEMA *Standard* MG 1, Part 30, Figure 30-5)

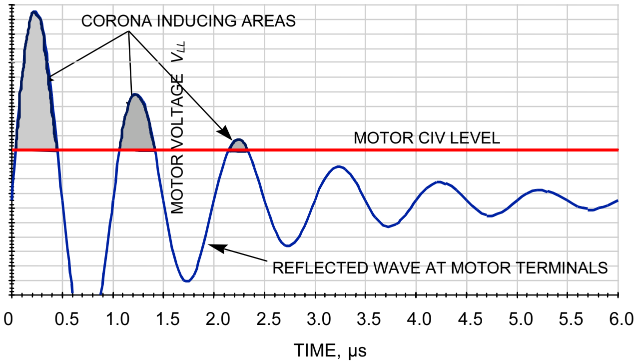


Fig. 15 Damaging Reflected Waves above Motor CIV Levels

allows drive designers to increase the carrier frequency to levels that minimize objectionable noise in the human hearing spectrum. Drive designs can switch up to 20 kHz, if required; however, some engineering compromises must be made to optimize the design. During the transition between turning off and on, the transistor generates heat that must be dissipated. This heat loss rises proportionally with the carrier frequency. While higher carrier frequencies do eliminate objectionable audible noise, they also require larger heat sinks and, consequently, yield lower efficiency.

Audible noise measured in the dBA-weighted scale does not increase proportionally with drive carrier frequency. Additionally, concern with noise may not be over the measured total mean pressure level but a particular frequency band that is objectionable to humans.

Figure 16 shows audible noise test results measured on a 100 hp energy-efficient motor. Note that the dominant octave band is at the drive carrier frequency setting. Sine wave power is used as a reference point on the left side of the table. When running at 2 kHz, the total sound pressure is almost 6 dBA over the sine wave power recordings. This represents 4 times the sound pressure from the motor because the scale is logarithmic and an increase of 3 dBA doubles the mean pressure level. By comparison, running the drive at 4 kHz increases the mean pressure by only 3 dBA, or half the mean pressure of the 2 kHz setting. (For reference, a 10 dB rise in sound pressure is perceived by the human ear as being twice as loud.)

High Carrier Frequencies and Subharmonics. At high (above 5 kHz) carrier frequencies, harmonics can create vibration forces that match the natural mechanical resonant frequency of the stator and cause sound pressure to exceed 85 dB. The likelihood of subharmonics increases as carrier frequency approaches 20 kHz. If subharmonic vibrations appear, the carrier frequency setting should be decreased to lower the sound pressure generated from the motor.

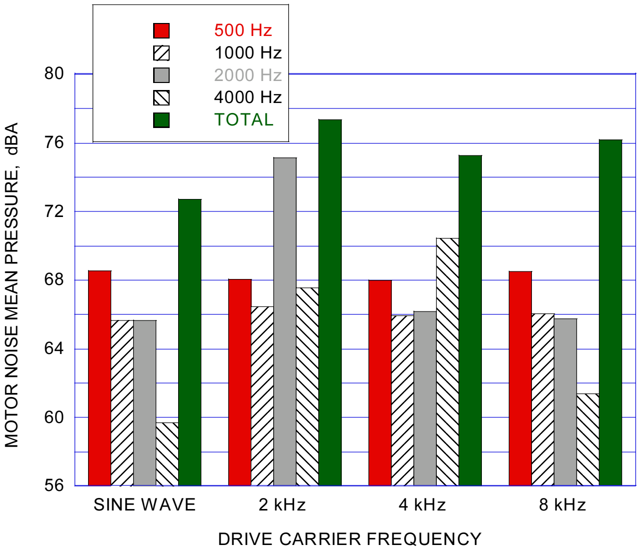


Fig. 16 Motor Audible Noise

Carrier Frequencies and Drive Ratings

As carrier frequency increases, drive output ampere ratings decrease largely due to the heat that must be dissipated from the IGBT switching. If the rated carrier frequency of a drive is 2 kHz, setting the carrier frequency up to 8 kHz decreases the ampere output. Generally, for every 1 kHz increase in carrier frequency, the drive output current must be derated by 2%. As an example, a 10 hp, 460 V drive rated at 2 kHz may have an output of 14 A. If this drive is run at 10 kHz, or an increase of 8 kHz, it must be derated to 11.76 A, or a 16% decrease in current. If the motor nameplate full load were 14 A, this drive would not generate enough output current to obtain the full 10 hp. In effect, the drive and motor would only generate 8.4 hp continuously. This may not be enough power to drive a fan or pump at the performance specified for the application. For this reason, the specifying engineer should always state the desired running carrier frequency of the drive to ensure proper operation.

POWER DISTRIBUTION SYSTEM EFFECTS

Some concern has been expressed that adjustable frequency drives may cause harmonic disturbances to the basic powerline waveform. Line harmonics are particularly critical to ac drive users for the following reasons:

- Current harmonics cause additional heating in transformers, conductors, and switchgear.
- Voltage harmonics upset the smooth, predictable voltage waveform in a normal sine wave. A line wave severely distorted by voltage harmonics may damage components connected to the line or cause erratic operation of some equipment.
- High-frequency components of voltage distortion can interfere with signals transmitted on the ac line for some control systems.

However, PWM ac drives with built-in bus reactors cause little, if any, disturbance to the input power. A **linear load**, such as a three-phase induction motor operated across the line, may cause a phase displacement between the voltage and current waveforms (phase lag or lead), but the shapes of these waveforms are nearly identical sine waves.

In contrast, a **nonlinear load** draws current only from the peaks of the ac sine wave, flattening the top of the voltage waveform. Many nonlinear loads connected to a power system can inject harmonics. Single-phase equipment (e.g., TVs, VCRs, computers, and electronic lighting) and three-phase equipment (e.g., AFDs, uninterruptible power supplies (UPSs), electric arc furnaces, electric heaters, and welders) convert ac voltage to dc voltage and contain circuitry that draws current in a nonlinear fashion. Figure 17 shows how the current drawn by a PWM full wave rectification AFD distorts the voltage waveform measured at the input terminals.

A single-phase load is not necessarily too small to be of concern. With ac-to-dc converters, the demand current occurs around the peak of the voltage sine wave. A thousand 100 W fluorescent lights consume 100 kW of power. If the lights are nonlinear loads, the peaks add directly and cause the voltage waveform to dip. This distortion in the single-phase voltage waveform contributes to the harmonic distortion of the three-phase power source. On single-phase harmonic distortion, these loads produce even-numbered harmonics such as 2nd, 4th, 6th, etc. Thus, if a balanced system is experiencing even-numbered harmonics, they must originate from a single-phase load and not from the drives.

AFDs and Harmonics

Figure 18 shows the basic elements of any solid-state drive. The converter section (for conversion of ac line power to dc) and the inverter section (for conversion of dc to variable frequency ac) both contain nonlinear devices that cause harmonics on both the input and output lines. Input line harmonics are caused solely by the converter section and are usually referred to as **line-side harmonics**. Output line harmonics are caused solely by the inverter section and are known as **load-side** or **motor harmonics**.

These effects are isolated from each other by a dc bus capacitor and in some designs by a dc choke so that load-side harmonics only affect equipment driven by the AFD and line-side harmonics affect the power system as a whole.

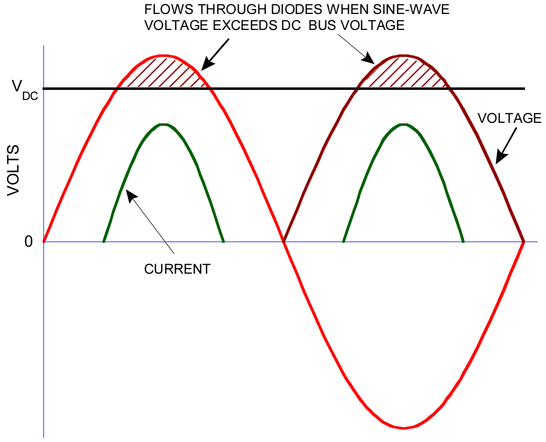


Fig. 17 Voltage Waveform Distortion by Pulse Width Modulated AFD

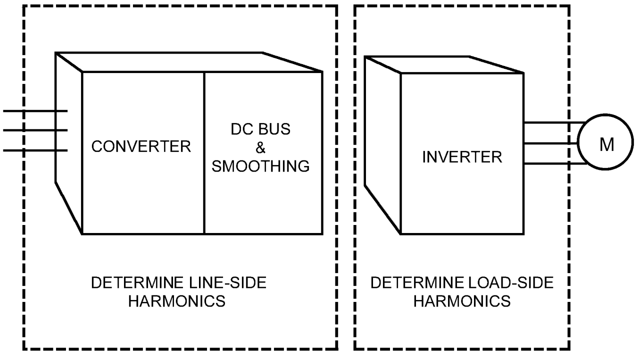


Fig. 18 Basic Elements of Solid-State Drive

Effects of Load-Side Harmonics. Load-side harmonics generated by the inverter section of an AFD are of concern only for the motor. The load-side harmonics can slightly decrease motor life due to the **additional heating** created. However, the use of high-efficiency motors or motors designed specifically for AFDs compensates for any damaging effects. Additionally, hermetic refrigerant-cooled motors, as used in some variable-speed chiller designs, experience insignificant, if any, increases in motor heat. Selection and matching of both the motor and drive should account for these effects and ensure that motor performance and equipment life are not compromised when applying variable speed. Retrofit applications should be engineered to make sure that the motor and drive are capable of providing enough power to the connected load.

As discussed previously in the section on Motor and Conductor Impedance, a second phenomenon associated with inverters on the load side is the effect of high voltage spikes on motor life. The fast-switching capability of the inverter combined with long power lines between the drive and motor can produce reflected waves that have high peak voltages. If these voltages are large enough, they will produce potentially destructive stresses in the motor insulation.

Effects of Line-Side Harmonics. Generally, PWM ac drives that contain internal bus reactors or three-phase ac input line reactors do not create electrical interference with other electrical equipment. But any harmonic current flowing through the source impedance causes a voltage drop that results in harmonic distortion of the supply voltage waveform. A distorted supply voltage waveform can have undesirable effects on some equipment connected to the power line:

- Communications equipment, computers, and diagnostic equipment are “sensitive” equipment having a low tolerance to harmonics. Typical effects include receipt of false commands and data corruption.
- Transformers may experience trouble due to possible additional heating in the core and windings. Many transformer manufacturers rate special transformers by K-factor, which indicates the transformer’s ability to withstand degradation due to harmonics. Special cores to reduce eddy currents, specially designed windings that reduce heating, and an oversized neutral bus are some of the special design features found in some K-factor transformers. Other manufacturers simply derate their standard transformers to compensate for harmonic effects.
- Standby generators operate at frequencies that change with load. When an AFD is switched onto generator power, the frequency fluctuation could affect the AFD converter. Standby generators also have voltage regulators that are susceptible to harmonics. In addition, generators have a very high impedance in comparison to the normal power. The harmonic currents flowing in this higher impedance can give rise to harmonic voltages three to four times the normal levels. Compounding this problem is the fact that standby generators are usually installed where sensitive equipment is prevalent (e.g., in hospitals and computer centers). However, because generator power is typically used only during emergencies for short periods, higher harmonic distortion levels may be tolerable.

Any AFD application with standby generators requires careful design, and the following information should be gathered:

- Power output (kW, MW or kVA) of the generator
- Subtransient reactance
- How the generator is being applied in reference to the AFD; what is the worst-case running condition of the drives (number of drives running at one time and the load on these drives)

Additional problems can be caused by resonance that can occur when **power factor correction capacitors** (PFCCs) are installed.

Resonance can severely distort the voltage waveform. PFCCs may fail prematurely, or capacitor fuses may blow. Additionally, because AFDs have an inherent high power factor (typically 0.96 or greater), PFCCs should never be required or used with a drive because they can cause the drive to fail if installed on the load side of the AFD. If an older motor is retrofitted with capacitors, PFCCs should be removed since they are no longer required.

Only the fundamental current transmits power to the load. Harmonic currents increase the equipment input kVA without contributing to input power. Operating with a high harmonic content is much like operating at a low input power factor. High harmonic content means that higher total current is required to deliver a given amount of power due to equipment heat losses. This means that all components of the power distribution system must be oversized to handle the additional current. If the utility meters are capable of measuring the harmonic content and/or power factor, they may assess a distortion (demand) charge or power factor penalty.

Effect of Harmonics on a System. In most applications, no harmonic problems will occur with PWM AFDs that use a series reactor in the dc bus or in the input ac line. With other converter loads (e.g., arc furnaces, dc drives, current source drives) and other high reactive current loads, harmonic problems may exist. The following problems, typically more common on single-phase systems, may indicate a harmonic condition, but they may also indicate line voltage unbalance or overloaded conditions:

- Nuisance input fuse blowing or circuit breaker tripping
- Power factor capacitor overheating, or fuse failure
- Overheating of supply transformers

Problems that are *not* harmonic problems include

- Overcurrent tripping of AFDs
- Interference with AM radio reception
- Wire failure in conduits

CODES AND STANDARDS

CSA. 1998. *Canadian electrical code, Part I. Standard* C22.1-98, p. 8. Canadian Standards Association, Etobicoke, Ont.

NEMA. 1977. Energy management guide for selection and use of single-phase motors. *Standard* MG 11-1977. National Electrical Manufacturers Association, Rosslyn, VA.

NEMA. 1994. Energy management guide for selection and use of polyphase motors. *Standard* MG 10-1994.

NEMA. 1995. Electrical power systems and equipment—Voltage ratings (60 Hz). ANSI/NEMA *Standard* C84.1-1995.

NEMA. 1998. Motors and generators. *Standard* MG 1-1998.

NFPA. 1998. *National electrical code*. ANSI/FFPA *Standard* 70-1998. National Fire Protection Association, Quincy, MA.

BIBLIOGRAPHY

Evon, S., D. Kempke, L. Saunders, and G. Skibinski. 1996. IGBT drive technology demands new motor and cable considerations. IEEE Petroleum & Chemical Industry Conf. IEEE, New York.

Kerkman, R., D. Leggate, and G. Skibinski. 1997. Cable characteristics and their influence on motor over-voltages. IEEE Applied Electronic Conference (APEC). IEEE, New York.

Kerkman, R., D. Leggate, and G. Skibinski. 1996. Interaction of drive modulation & cable parameters on ac motor transients. IEEE Industry Application Society Conf. IEEE, New York.

Malfait A., R. Reekmans, and R. Belmans. 1994. Audible noise and losses in variable speed induction motor drives with IGBT inverters-influence of the squirrel cage design and the switching frequency. IEEE 1194. Proceedings Industry Application. IEEE, New York.

Saunders, L., G. Skibinski, R. Kerkman, D. Schlegel, and D. Anderson. 1996. Modern drive application issues and solutions. IEEE PCIC Conf. Tutorial on Reflected Wave, Motor Failure, CM Electrical Noise, Motor Bearing Current. IEEE, New York.

Sung, J. and S. Bell, S. 1996. Will your motor insulation survive a new adjustable frequency drive? IEEE Petroleum & Chemical Industry Conf. IEEE, New York.

Takahashi, T., G. Wagoner, H. Tsai, and T. Lowery. 1995. Motor lead length issues for IGBT PWM drives. IEEE Pulp and Paper Conf. IEEE, New York.