CHAPTER 6

PUMP DRIVERS

SECTION 6.1
PRIME MOVERS

6.1.1
ELECTRIC MOTORS AND MOTOR CONTROLS

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The two most common types of electric motors are *alternating current (ac) induction* and *direct current (dc) commutated shunt- or series-wound*. All electric motor configurations except one type (reluctance brushless) convert electrical energy to mechanical energy from the magnetic flux linkage of their two magnetic circuits. One of these circuits is in the stator and the other is in the bearing-mounted rotor. This flux linkage between the two magnetic circuits produces a moment of force at the rotor radius that results in a torque on the motor shaft causing shaft rotation. The speed of the rotation times the torque equals the output power at the motor shaft. This is, of course, the power used to drive a pump.

The basic difference between these two types of electric motors has to do with their electrical power source. The first type has been historically powered by 60 cycle (Hz) alternating voltages direct from the public utility power grid (50 Hz in most of Europe and some other parts of the world). For this type of motor, the speed is determined by the number of magnetic poles designed in the motor and the alternating sinusoidal frequency of the voltage from the power grid. Methods have been developed to alter the speed of an ac motor with a fixed number of poles and a fixed line frequency (it is also possible to wind such a motor with several poles for other speeds). However, the squirrel-cage induction motor remains without question the most common type of motor used to drive pumps. The reasons for this are worldwide availability, excellent reliability, excellent performance characteristics, and ease of replacement. As the pump industry continues to adopt variable speed motor/drives, the ac induction motor will likely continue to be by far the number one prime mover for most all types of pumps. This is also because of its adaptability to variable speed using ac inverters and vector drives.

The other motor type currently in use to drive pumps is the dc motor. Most of these applications are in the smaller sizes such as automotive and off road equipment. The overall use of dc motors for pump drives is predicted to decline.

The dc type of electrical machine also contains two magnet fields, one in each of the stator and rotor assemblies of the motor. Although the dc motor does not operate for its entire useful life without maintenance on the mechanical brushes and commutator, it is still selected for some pump applications when only a dc voltage power source is available. It has been also selected in a limited number of instances where adjustable speed is required. The dc motor, powered by the voltage from storage batteries or from a dc generator, can be speed-adjusted by varying the voltage with a power supply. Its speed relationship to the voltage is linear and very useful for some pump applications such as constant displacement types, which require speed adjustment to set flow. [See Subsection 6.2.2.]

The more recent availability of permanent magnet brushless dc motors should offer a more reliable prime mover for these applications, with superior performance and long life benefits.

There are other types of electric motors considered for driving pumps. The reasons for this include the dramatic recent advances in power electronics and microprocessors, advances in motor materials such as permanent magnets, and advances in the pumps themselves. Besides the active interest in adjustable speed pumps, another reason for the interest in some newer motor types for pump applications is because of recent U.S. government regulations enacted to improve energy conservation by implementing motor efficiency mandates along with a time schedule. For example, the *U.S. Energy Policy and Conservation Act* of September 10, 1992 (*EPACT*) stipulates that all covered electric motor products must meet the efficiency levels per NEMA MG1 1993. The requirement covers all electric motors from 1–200 horsepower (1–150 kW) manufactured after October 24, 1997 that operate from 230/460 VAC power at 60 Hz line frequency. The U.S. Department of Energy approved test method to meet the new efficiency levels is per IEEE-112B. This regulation was originally intended for ac induction motors.

For those pump applications that require the motor torque to increase as the square of speed, these new, more efficient motors will run at higher speeds because their slip is less. This could cause an appreciable increase in overload within the motor. Overload could also result in other mechanical parts of the system. There are other ramifications resulting from these new requirements that must be carefully analyzed when selecting an electric motor, starter, or inverter. The resulting analysis might very well cause the selection to be some other electric motor type, such as a permanent magnet brushless dc, permanent magnet ac, synchronous (sine wave driven version of the brushless dc), or even a switched reluctance brushless dc motor. Each of these types must be powered with an inverter and a controller. However, the result can most likely offer adjustable speed with a very high efficiency over a wide speed range. This use of an inverter is required for each of those other types of motors mentioned. With the availability of the new vector controlled ac inverters (Section 6.2.2), the high-efficiency ac induction motor can also be applied for variable speed. This will eliminate the need for a soft starter frequently required with line fed motors. The elimination of the starter helps somewhat to offset the additional cost of the inverter.

TYPES OF MOTORS

Alternating-Current Motors

SQUIRREL-CAGE INDUCTION MOTOR By far the most common motor used to drive pumps is the squirrel-cage induction motor (Figure 1). This motor consists of a conventional stator wound with a specific number of poles and phases, and a rotor that has either cast bars or brazed bars imbedded in it.

The squirrel-cage induction motor operates at a speed below synchronous speed by a specific slip or revolutions per minute. The synchronous speed is defined as

$$N = \frac{f \times 60 \times 2}{p}$$

where N = speed, rpm
f = line-power frequency, Hz
p = number of poles

FIGURE 1 Exploded view of a typical squirrel-cage induction motor (Courtesy of Leeson Electric Corp.)

The percent slip is defined as

$$\%\ \text{slip} = \frac{(N - s) \times 100}{N}$$

where s = slip, rpm

When the stator winding of a squirrel-cage induction motor is connected to a suitable source of power, a magnetic flux is generated in the air gap between the stator and rotor of the motor. This flux revolves around the perimeter of the air gap and induces a voltage in the rotor bars. Because the rotor bars are short-circuited to each other at their ends (end rings), a current circulates in the rotor bars. This current and the air-gap flux interact, causing the motor to produce a torque.

The squirrel-cage induction motor exhibits a characteristic speed-torque relationship that is determined by the resistance of the rotor bars. Thus, the desired speed-torque characteristics are obtained by selecting a metal of suitable resistance when designing the rotor bars. The slot shape and size for the bars in the rotor can be selected to achieve a certain rotor resistance.

Figure 2 suggests several typical speed-torque characteristics that have been standardized by NEMA (National Electrical Manufacturers Association), covering motor frames 143T through 449T. Motors larger than 449T may not have these same values, but generally have the same characteristic curves. Also, single-phase motors may not exhibit these characteristics and are defined specifically by NEMA with different values.

Most pumps are driven by NEMA B characteristic motors when operated from three-phase power sources.

WOUND ROTOR INDUCTION MOTOR The wound-rotor induction motor is in every respect similar to the squirrel-cage version except that the rotor is wound with insulated wire turns and this winding is terminated at a set of slip rings on the rotor shaft. Connections are made to the slip rings through brushes and in turn to an external resistor, which can be adjusted in ohmic value to cause the motor speed-torque characteristics to be changed. These types of motors have been used in some pump applications in the past, but due to

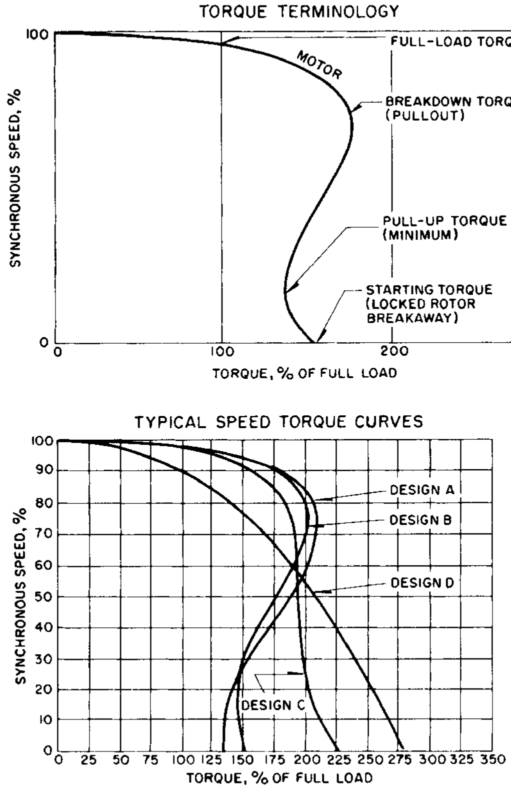


FIGURE 2 These curves are characteristic of NEMA frame size squirrel-cage induction motors through size 449T (typically through 300 hp–224 kW).

the availability of inverter-fed ac squirrel-cage induction motor drives, they are no longer very practical.

Figure 3 demonstrates the speed-torque characteristics of a wound-rotor induction motor for several resistor values. It will be noticed that increasing the external resistance of the control will cause the peak torque of the motor to be developed at lower speeds until the peak torque occurs at zero speed. Increasing the resistance beyond this value will cause the motor to have a limited torque as, for example, curves 4, 5, and 6. This motor can be used where torque control is required or where variable speed is necessary. In the variable-speed application, the rotor resistance is adjusted to produce a motor torque that matches the load torque at the specific speed desired. This system is not as useful and cost-effective as an inverter-fed ac induction motor due to the recent developments of power electronics and microprocessors.

SYNCHRONOUS MOTOR The synchronous motor is also similar to the squirrel-cage induction motor except that it operates at synchronous speed and its rotor is constructed with definite salient poles on which a field coil is wound and connected to a source of direct current for excitation. The most common synchronous motor is constructed with slip rings on the rotor shaft to connect the dc excitation to the field coils.

There are various means of providing the dc power to the slip rings:

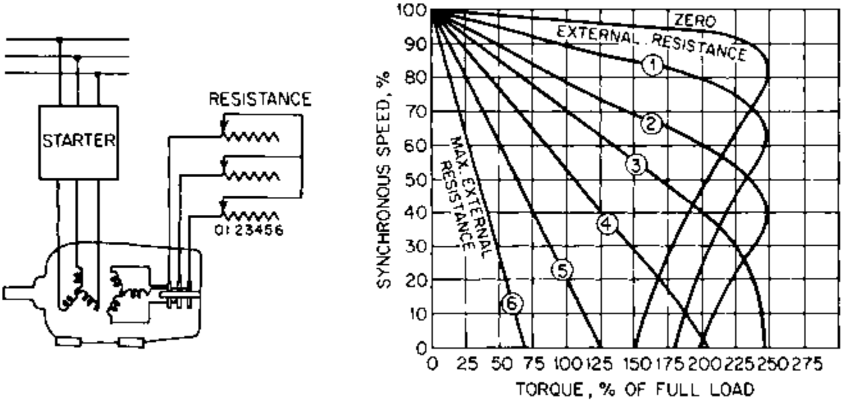


FIGURE 3 Typical speed-torque characteristics of a wound-rotor induction motor (Westinghouse Electric)

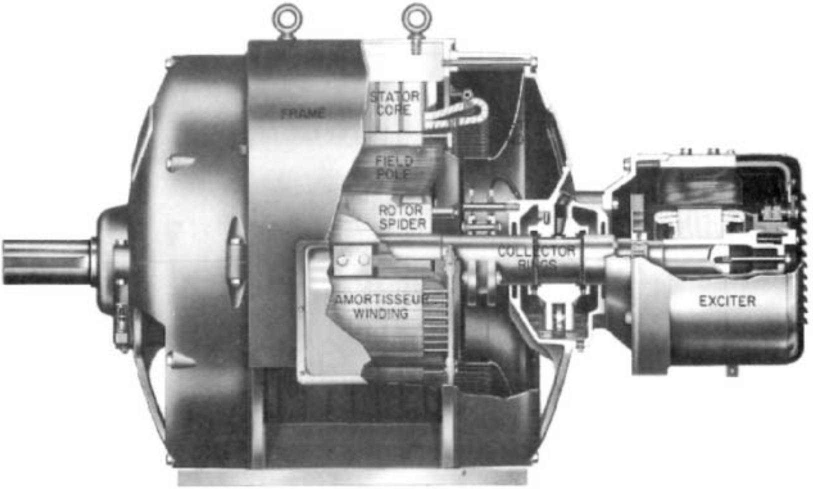


FIGURE 4 Synchronous motor with direct-connected exciter (Electric Machinery Manufacturing)

1. **Static excitation** The power to be connected to the slip ring brushes on the motor shaft is obtained from a transformer and rectifier package external to the motor.
2. **Direct-connected exciter** This arrangement has a dc generator directly connected to the synchronous motor shaft (Figure 4). The dc power from this generator is connected to the brushes of the synchronous motor slip rings.
3. **Motor-generated exciter** The dc power for exciting the synchronous motor is generated by means of a remote motor-generator set operating from normal ac power, and the dc voltage from this motor-generator set is connected to the brushes of slip rings of the synchronous motor.

Another form of synchronous motor is known as the *brushless synchronous motor* (Figure 5). As the name implies, this motor has its rotating field excited without the use of slip rings for connecting the external direct current to the motor field. The construction of this

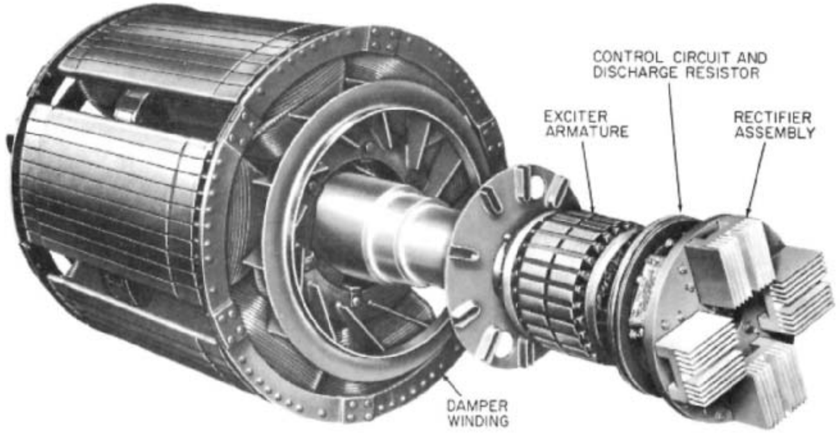


FIGURE 5 Brushless synchronous motor with ac generator mounted on the shaft with rectifier and control devices (Electric Machinery Manufacturing)

motor incorporates a shaft-connected ac generator. The field of the ac generator is physically stationary and connected to a source of dc voltage. The rotor of this ac generator is connected through a solid-state controlled rectifier mounted on the synchronous motor rotor and in turn connected to the synchronous motor field. This arrangement facilitates a connection between external excitation power and the rotating field of the synchronous motor through the air gap of the shaft-connected ac generator. The brushless synchronous motor has many advantages over the conventional slip-ring synchronous motor. Among these are the elimination of brushes and slip rings, which are high-maintenance items; the elimination of sparking devices, which are not permissible in certain atmospheres; and the use of static devices for field control, which are more reliable than conventional electromagnetic controls.

Synchronous motors are used for pump applications requiring larger horsepower ratings at lower speed conditions, as illustrated in Figure 6. Also, they are used on applications where a high power factor or a power-factor-correction capability is desired. Of less importance is the characteristic of the synchronous motor that it will always operate at synchronous speed (does not have a slip) regardless of load. Synchronous motors are started on their damper windings (the same as squirrel-cage induction motors), and when they have accelerated to within 5% of synchronous speed, the field is applied and the motor accelerates to synchronous speed (Figure 7). Typical characteristic curves are shown in Figure 8.

Direct-Current Motors Dc motors are only occasionally used to drive pumps. Most of the current applications for dc pump drives are in some form of automobile or off-the-road equipment due to the dc power from storage batteries. There are some other situations that might call for dc motor pump drives such as shipboard duty, railway applications, aircraft, mining installations, and some other emergency battery operations.

There are three types of dc motors available (Figure 9): shunt, series, and compound-connected.

Larger horsepower ratings of shunt-wound dc motors are frequently qualified as "stabilized shuntwound" motors and incorporate a series field similar to that of a compound wound motor. This is necessary to adjust the regulation of the shunt motor so as not to exhibit a rising speed-torque characteristic. It is important to be aware of the speed at which a dc motor will operate on pump applications because of pump performance guarantees.

The windings in the stators of the wound types are connected to the armature windings through brushes and a commutator three different ways to achieve different performance

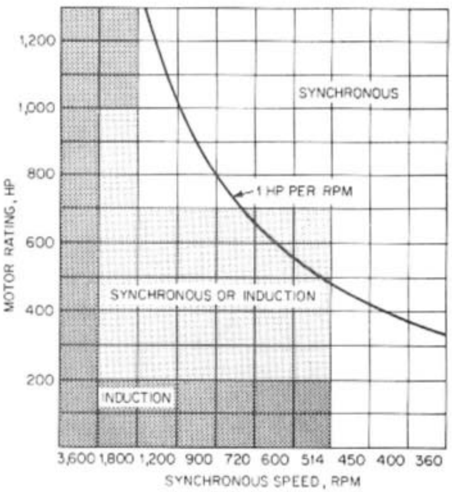


FIGURE 6 Below 514 rpm, or powers greater than approximately 1 hp/rpm (0.746 kW/rpm), synchronous motors are a better selection than squirrel-cage induction motors because higher cost can generally be offset by higher power factor and efficiency (from *Power* special report, "Motors," June 1969).

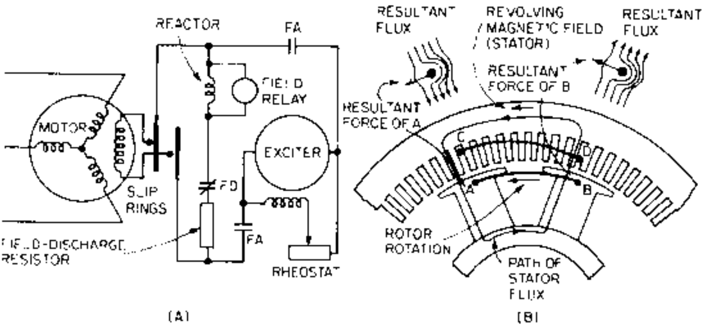


FIGURE 7 Method of starting synchronous motor. (A) Typical field control (brush type) energizes the dc field to pull the rotor into synchronism as it comes up to speed. Field relay senses change in induced frequency as motor speeds up. (B) Damper winding is similar to a squirrel-cage rotor winding. It produces most of the starting torque, and the synchronous motor starts with essentially induction-motor characteristics (from *Power* special report, "Motors," June 1969).

characteristics (see Figure 3 for details). With the use of pulse width modulation (PWM) or silicon-controlled rectifiers (SCR), variable dc power supplies the armature voltage, which can be controlled along with a separate control for the field current (see Subsection 6.2.2). Using this control scheme, the dc motor can be used to control speed over a very wide range in a smooth manner. For example, constant voltage can be produced from zero rpm up to base design speed of the motor by armature control and constant power above base speed using flux weakening of the armature field. When operating from a constant voltage, dc motors are available to provide up to a 4 to 1 speed range with an adjustable dc field power supply. With this separate control scheme for both field and armature, a 100 to 1 speed range is easily achievable. Figure 9 summarizes the various field connection

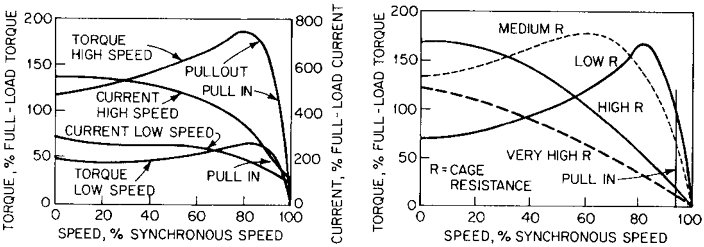


FIGURE 8 Characteristics of synchronous motors depend on rotor design. Torque and current relations are influenced by synchronous speed. High-resistance cage produces high starting torque but low pull-in torque (from *Power* special report, "Motors," June 1969).

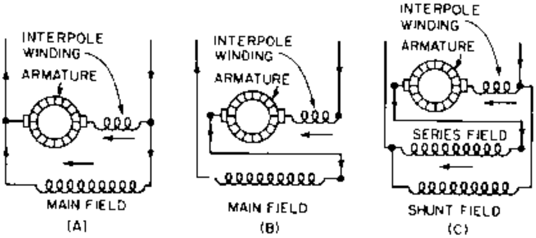


FIGURE 9A through C Types of dc motors. (A) Shunt motor has field winding of many turns of fine wire connected in parallel with the armature circuit. The interpole winding aids commutation. (B) Series motor has field in series with the armature. Field has a few turns of heavy wire carrying full-motor current flowing in the armature. (C) Compound motor has both a shunt and a series field to combine characteristics of both shunt- and series-type motors in the same machine (from *Power* special report, "Motors," June 1969).

schemes for dual wound dc machines with mechanical commutation systems. Figure 10 illustrates typical characteristics of the dc motors discussed. Figure 11 shows the equivalent circuit of a permanent magnet type dc motor.

Permanent Magnet (PM) Brushless Motors The permanent magnet brushless dc motor has been in existence for about three decades and is finally being widely used for many applications. Its being brushless has frequently been mentioned as justification for its cost, higher than most other motor types. However, the PM brushless motor has two other features that are arguably more important than the fact that it contains no mechanical brushes and commutator for commutation of the phase windings to the power source. First, it produces the highest continuous output power per unit volume of any motor yet invented. The other important virtue of a PM brushless motor is that it produces its output power with the least input power. For a given size and output performance envelope, it has the most efficient motor of any electric motor yet invented. With the emphasis on reducing power consumption, this type of motor will be used in many pump applications. In addition, and perhaps most importantly for the application of pumps, the PM brushless motor posseses one other very important feature or use of the permanent magnets contained within the rotor assembly. Although the magnets are there to supply a magnetic field from the rotor to pass through the air gap of the motor into the stator, these same magnets can serve as a magnetic coupling. If a sleeve-shaped liquid barrier made of a suitable material to be impervious to the liquid is fitted between the rotor and stator, the PM brushless can be used as the best hermetically sealed wet motor known. There are, of course, many possible configurations of this PM brushless hermetic motor concept. These PM brushless hermetic motors can be configured as axial gap, radial gap inside

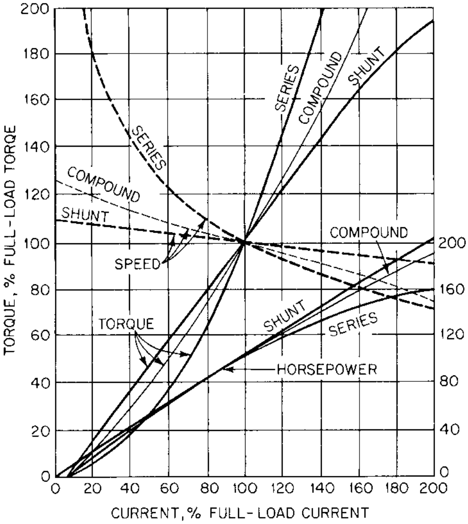
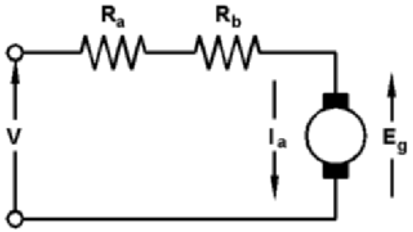


FIGURE 10 Speed, torque, and power characteristics of dc motors (from *Power* special report, "Motors," June 1969)



V = Terminal voltage, volts
R_a= Armature resistance, ohms
R_b= Resistance of the brushes, ohms
I_a = Amature current, amperes
E_g= Back-EMF, volts

FIGURE 11 The equivalent circuit of a dc motor with a permanent magnet stator

rotor, or radial gap outside rotor motors (Figure 12). The choice depends upon the best way to design the pump integration.

All PM brushless motors must be powered with an electronic inverter and controller, which can be used for controlling pump performance in controlled loop systems of all types. The electronic drive can be a simple square wave, a six-step trapezoid type, or a sinusoidal drive. Also, some sort of electronic remote or motor mounted shaft position system that is no different than that used for an ac induction vector drive is required.

Three permanent magnet choices can be used for these motors. The lowest priced magnet material is known as ferrite or ceramic with a magnetic flux output of about one-third

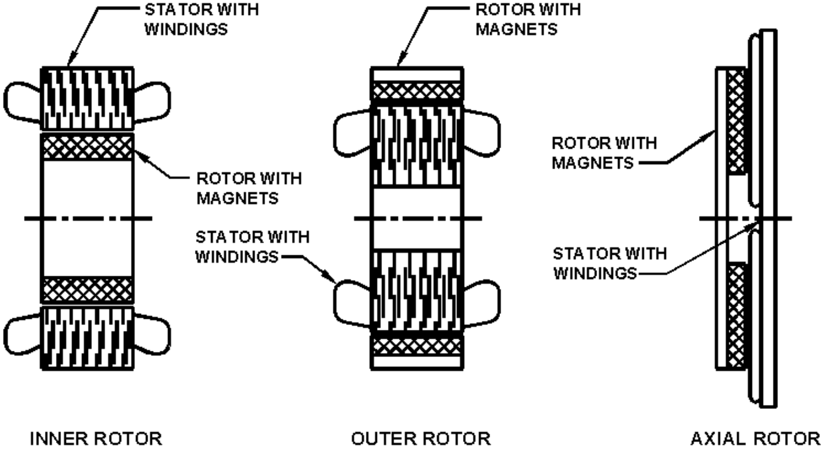


FIGURE 12 Inner, outer, and axial rotor PM brushless motor choices for pump drives

to one-half of the other two magnet choices. By careful design, this magnet material can be used for 50 hp (37 kW) and up in PM brushless machines to keep costs competitive with other machine types. For brushless motors less than 50 hp (37 kW), the two high energy or rare earth magnet grades are frequently useful. The more expensive of the two, Samarium Cobalt, is used for high temperature and other hostile environment pump motor applications. The newer rare earth magnets, known as Neodymium Iron Boron, are much lower in cost, with the highest useful magnetic flux at moderate operating temperatures. Either the magnets can be assembled onto the surface of the rotor or they can be imbedded within the laminated rotor structure. In either design, the rotor can be made to be quite robust and yield a very long useful operating life. In fact, the only failure modes for PM brushless motors have to do with bearings or winding insulation. Figure 13 shows examples of large PM brushless motors.

The speed can be controlled to greater than 100 to 1 if required with constant power over the highest speed range of any other motor type. The efficiency remains very high over the entire speed range. There are many design possibilities including axial gap and outside rotor configurations. For example, because of the high magnetic strength of the permanent magnets, the rotor of a PM brushless motor can also serve as the impeller of a pump that is integrated with the motor in a hermetically sealed package with no shaft seals. Utilizing the axial-gap rotor configuration of Figure 12, the concept is illustrated in Figure 14. Commercially significant impeller torque levels can be generated by the PM brushless motor in this configuration[1]. This eliminates the need for a separate magnetic coupling or larger-size canned induction motor (see the discussion at the end of this section and in Section 2.2.7).

The PM brushless motor can be driven with either square wave currents over a 120 degrees electrical commutation angle or with sinusoidal currents over 180 degrees electrical commutation angle. The latter scheme generally yields lower torque fluctuations, which is sometimes important for pump applications. Either drive requires shaft angle feedback data to tell the phases when to be powered. This feedback data is also a requirement for vector driven ac induction motors. The sensor used for this feedback can be as simple as *Hall* switches mounted in the motor that send out a pulse to the controller each time a rotor magnetic pole changes polarity as the motor rotates. An optical encoder or a *resolver* can also be used for this purpose. Several sensorless or remote sensors have been developed that capture the rotor angle location from the stator phase windings so a shaft-mounted sensor is not required.

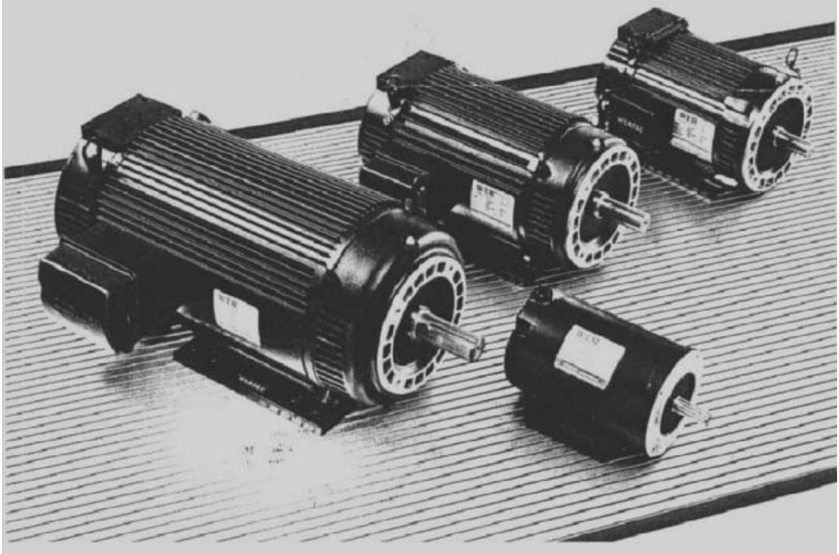


FIGURE 13 Large horsepower (kW) high-performance permanent magnet inside rotor brushless motors (courtesy of Pacific Scientific)

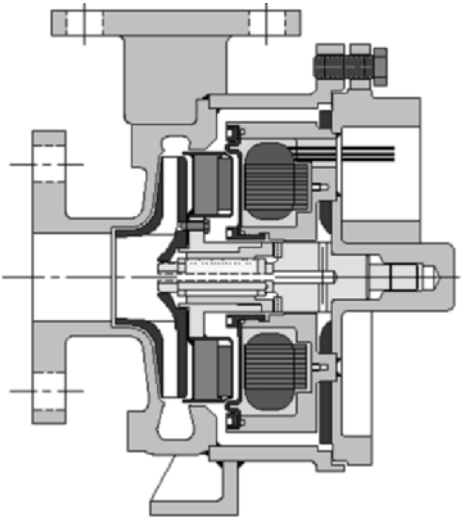


FIGURE 14 Permanent magnet brushless motor integrated into a seamless pump. Permanent magnets are mounted on the impeller, which serves as the rotor of the motor. (Courtesy of Flowserve Corporation)[1]

Switched Reluctance Brushless Motor The SR brushless dc motor is one of the oldest motors known, but it has not been used much until recently. Its main feature is that it is a true brushless motor with most of the virtues of its PM cousin, but it does not require permanent magnets. This feature is a great benefit for the PM brushless motor when it is used in a hermetic pump application. However, the PM brushless motor is limited in the availability of practical sizes because of the cost of permanent magnets. As the

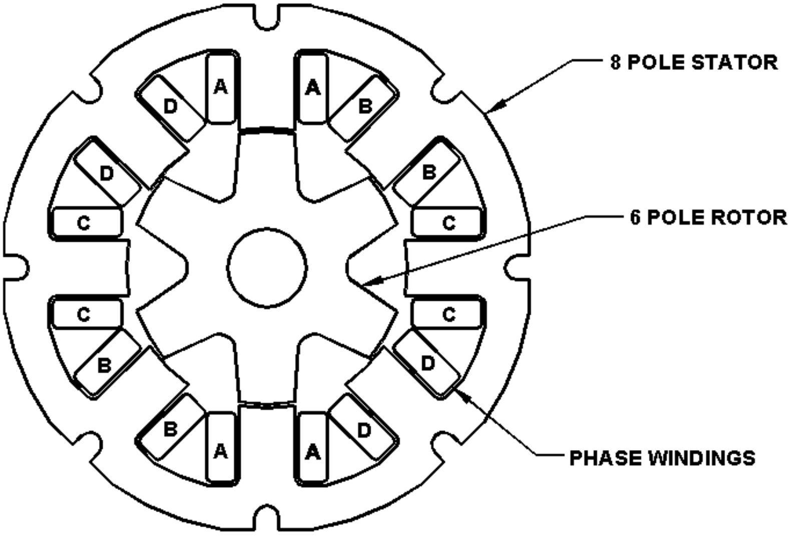


FIGURE 15 Switched reluctance brushless dc motor, (6) rotor poles, (2) stator poles per phase

PM motor gets larger in power and frame size, the cost of the magnets becomes prohibitive. The ac induction motor is still a very good choice for most high-power applications, even when adjustable speed is needed. However, as centrifugal high-speed pumps gain popularity, the ac induction motor has difficulty surviving the forces on the rotor. Proponents of switched reluctance motors point out its inherent robustness. The rotor of the SR motor is so simple and rugged it can survive very at high speeds as well as in a variety of other unusual environmental conditions. Figure 15 shows the typical cross section of a switched reluctance motor, illustrating how simple this motor is with phase coils placed around the stator poles. The rotor consists of a set of magnetic steel gear-shaped laminations taken from the bore of the stator laminations. They are stacked and retained on the motor shaft. No magnets or windings of any kind are required to produce torque. The SR motor is said to be a doubly salient pole machine. The torque is produced by the magnetic attraction of the closest rotor poles to those stator poles which are magnetized by the phase coils. There is an abundance of technical information regarding the performance details of this technology. The important point is that the SR motor is an excellent choice for high-speed high-powered centrifugal pumps.

There is a considerable difference in the inverter topology for the SR motor as compared to either the PM brushless or the ac induction motor. The SR machine must be driven as a unipolar machine rather than a bipolar motor like the other two. This means the standard ac inverter cannot be used for the SR motor. The phases are each connected to the dc power in parallel rather in the standard bridge fashion with all of the phases connected together at a center tap. Figure 16 shows the normal power circuit for the (4) phase SR motor shown in Figure 15. The same circuit is applicable for both two phase or three phase. It is essentially an independent half bridge circuit for each phase. Certain two phase designs are very cost effective for high speed pump drives that are required to rotate in only one direction without the need for reversing.

MOTOR ENCLOSURES

Electric motors are manufactured with a variety of mechanical enclosure features to provide protection to the working parts for specific environmental conditions. Although these

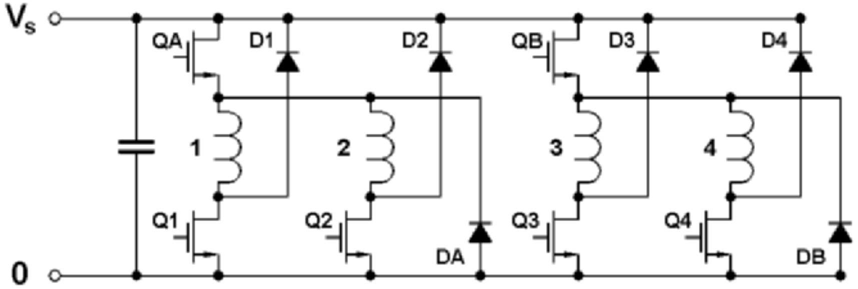


FIGURE 16 Power control circuit for (4) phase SR motor, (6) transistors, (6) diodes, (3) current sensors, (1) capacitor, and (6) motor lead connections

special enclosures are classified, they are not, for reasons of economy, available for all size motors. The electric motor industry has incorporated a number of specific enclosure classifications on standard designs of small- and medium-size motors.

The following list describes the motor enclosure specifications available for polyphase ac induction motors used with pumps. This availability depends on demand. Furthermore, the PM brushless and SR brushless motors might not be available in some of the enclosures listed. In general, totally enclosed motors are required for most integral horsepower (kilowatt) pump applications regardless of the motor type. In some instances, such as high-speed centrifugal pumps with integral motors, the motor is furnished to the pump manufacturer as a rotor and stator parts kit. The motor is then included in the pump enclosure.

OPEN This enclosure permits passage of external cooling air over and around the windings and rotor of a motor and normally includes no special restrictions to ventilation other than those that are inherent in the mechanical parts of the motor. Most designs include openings at each end of the motor frame either in the bearing end frame or openings around each end of the frame.

OPEN DRIPPROOF This is an open machine with ventilating openings designed to permit satisfactory operation when liquids or solids fall on the machine at any angle up to 15° from the vertical. Openings are normally in the bottom portions of the frame assembly. This construction includes mechanical baffling to prevent materials from entering the machine within these limits.

SPLASHPROOF This is an open machine with ventilating openings designed to permit satisfactory operation when liquids or solids fall *directly* on the machine or come toward the machine in a straight line at any angle up to 100° from the vertical.

GUARDED ENCLOSURE This provision limits the size of the ventilating opening to prevent accidental contact with the operating parts of the motor other than the shaft.

SEMIGUARDED This is an open construction where some of the ventilating openings are guarded and the remaining openings are left open.

OPEN, EXTERNALLY VENTILATED This motor is ventilated by a separate motor-driven blower mounted on the motor enclosure (piggyback construction).

OPEN, PIPE-VENTILATED This motor is equipped to accommodate an air-inlet duct or pipe for accepting cooling air from a location remote from the motor. Air is circulated in the motor either by its own internal blower parts or by an external blower, in which case the motor is said to be *forced-ventilated.*

WEATHER-PROTECTED TYPE I This is an open-construction motor with ventilating openings to minimize the entrance of rain, snow, and airborne particles to the motor's electrical parts, and with the openings arranged to prevent the passage of a $\frac{3}{4}$-in (19-mm) round rod.

WEATHER-PROTECTED TYPE II This construction has the same features as the type I machine, but in addition the intake and discharge ventilating passages are designed so high-velocity air and airborne particles blown into the machine by storms can be discharged without entering the internal ventilating passages of the motor leading to the electrical parts. The ventilating passages leading to the electrical parts of the motor are provided with baffles or other features to allow at least three abrupt changes of at least 90° for the ventilating air. The intake air path and openings are proportioned to maintain a maximum of 600 ft/mm (3 m/s) velocity of the entering air.

TOTALLY ENCLOSED This motor is designed without air openings, so there is no free exchange of air between the inside and outside of the motor frame; the construction is not liquid- or airtight. Normally the rotor has die-cast air circulating fins at each end to circulate the trapped inside air and improve convection cooling to the frame.

TOTALLY ENCLOSED, FAN-COOLED This totally enclosed motor is equipped with an external fan operating on the motor shaft to circulate external air over the outside of the motor. Most motors have cast fins the length of the frame to increase surface area and take advantage of the fan cooling.

EXPLOSIONPROOF This totally enclosed motor is designed to withstand an internal explosion of gas or vapor and constructed to prevent ignition by the internal explosion of gases or vapors outside the motor.

TOTALLY ENCLOSED, PIPE-VENTILATED This motor enclosure is similar to the open, pipe-ventilated motor except that it is equipped to accept outlet ducts or pipes in addition to inlet ducts or pipes.

TOTALLY ENCLOSED, WATER-COOLED This is a totally enclosed motor cooled by water passages or conductors internal to the motor frame.

TOTALLY ENCLOSED, WATER-TO-AIR HEAT EXCHANGE This is a totally enclosed motor equipped with a water-to-air heat exchanger in a closed, recirculating air loop through the motor. Air is circulated through the heat exchanger and motor by integral fans or fans separate from the rotor shaft and powered by a separate motor.

TOTALLY ENCLOSED, AIR-TO-AIR HEAT EXCHANGE This motor is similar to the water-to-air heat exchanger motor, except external air is used to remove the heat from the heat exchanger instead of water.

SUBMERSIBLE This totally enclosed motor is equipped with sealing features to permit operation while submerged in a specified medium at a specified depth.

Environmental Factors The environmental conditions of the pump application dictate the type of motor enclosures to be used. A brief set of rules for selecting motor enclosures follows.

DRIPPROOF For installation in nonhazardous, reasonably clean surroundings free of any abrasive or conducting dust and chemical fumes. Moderate amounts of moisture or dust and falling particles or liquids can be tolerated.

MILL AND CHEMICAL MOTOR (TO NEMA FRAME 449T) For installation in nonhazardous, high-humidity, or chemical applications free of clogging materials, metal dust, or chips, or where hosing down or severe splashing is encountered.

TOTALLY ENCLOSED, NONVENTILATED OR FAN-COOLED For installation in nonhazardous atmospheres containing abrasive or conducting dusts, high concentrations of chemical or oil vapors, where hosing down or severe splashing is encountered.

TOTALLY ENCLOSED, EXPLOSIONPROOF For installation in hazardous atmospheres containing:

Class I, Group D	Acetone, acrylonitrile, alcohol, ammonia, benzine, benzol, butane, dichloride, ethylene, gasoline, hexane, lacquer-solvent vapors, naphtha, natural gas, propane, propylene, styrene, vinyl acetate, vinyl chloride, or xylenes
Class II Group G	Flour, starch, or grain dust
Class II, Group E	Metal dust including magnesium and aluminum or their commercial alloys.
Class II, Group F	Carbon black, coal, or coke dust

NOTE: Under Class 1 only, there are two divisions that allow some latitude on motor selection. Generally, Class 1, Division 1 locations are those in which the atmosphere is or may be hazardous under normal operating conditions, including locations which can become hazardous during normal maintenance. An explosionproof motor is mandatory for Division 1 locations. Class 1, Division 2 refers to locations where the atmosphere may become hazardous only under abnormal or unusual conditions (breaking of a pipe, for example). In general, a motor in a standard enclosure can be installed in Division 2 locations if the motor has no normally sparking parts. Thus, open or standard totally enclosed squirrel-cage motors are acceptable, but motors with open slip rings or commutators (wound rotor, synchronous or dc) are not allowed unless the commutators or slip rings are in an explosionproof enclosure.

BEARINGS AND LUBRICATION

Very large horsepower (kilowatt) motors are generally supplied with oil-lubricated sleeve bearings with oil supplied from a reservoir. In some cases, pressurized oil lubrication systems are installed by the pump manufacturer along with hydrodynamic thrust bearings. All NEMA frame induction motors are available with ball bearings. These standard ball bearings are normally permanently grease lubricated. The bearings used in a motor must be sealed to keep the lubricant inside the bearings and keep contaminates from getting into the bearings. Double-sealed bearings are common for many pump applications.

Ball bearings are subject to early failure when used in electric motors driven by PWM inverters. This very common problem must be addressed. It is caused by the high carrier frequency used in the inverter to generate the sinusoidal currents for each phase. This results in generation of high common-mode voltages inside the phase windings of the stator. Because there is an excellent electrostatic coupling between the stator/frame and the rotor from the windings, a voltage is induced in the shaft. The ball bearings represent the least-resistant path for a short circuit to the stator. However, the balls seldom actually contact the races because of the film of grease or oil in between. When the voltage builds up in the shaft until it is greater than the insulating capability of the film of lubricant, the voltages arc across the lubrication gap and a flashover current goes through the bearing. In a relatively short amount of time, the bearing races will become grooved, causing the bearings to become noisy. Metal particulate will then egress from the bearing surfaces as the process continues, causing catastrophic bearing failures after a few months.

Therefore, all electric motors that are driven by PWM drives must have a shaft grounding system to provide a low resistance path between the shaft and the motor frame. There are other solutions to this potential problem, which can be discussed with the motor supplier.

Sleeve Bearings Motors that use oil-impregnated porous sleeve bearings are lubricated with an oil-soaked wick. These bearings are available in motors up to approximately 1 hp (0.75 kW). Sleeve-bearing motors larger than 1 hp (0.75 kW) are ring-lubricated. Lubricating oil is drawn up from the bearing sump to the bearing by a ring that rolls over the top of the motor shaft as the shaft rotates. Larger motors, having bearing heat losses that cannot be dissipated directly, may require the use of a pressurized lubrication system wherein oil is pumped into the bearings and allowed to recirculate through a heat exchanger. The oil delivered to each bearing is metered to provide only the required amount. A lubrication system composed of heat exchanger, sump, and pump is normally common to a number of bearings, rather than having a single lubricating pump for each bearing. Other types of bearings must be used in place of, or in addition to, sleeve bearings when thrust loads are present. Smaller sleeve bearings are in the form of a cylindrical shell and are usually made of bronze or steel-backed babbitt metal. Larger sleeve bearings are usually split on a horizontal centerline, allowing easy assembly and disassembly for inspection and replacement. The bearing housing is also split on the horizontal centerline and held together with bolts between the top and bottom halves.

Rolling Element Bearings All new electric motors manufactured to NEMA standards use grease-lubricated ball bearings with high radial and thrust load capacities. They are axially pre-loaded to eliminate any radial or axial play for quiet operation and long life. Most motor end frames include an outer race locking plate on the shaft end bearing to prevent race rotation due to output shaft loads. These bearing mounting features are required for high performance, long life, and high efficiency operation. Most motor manufacturers provide their larger frame sizes with grease fittings for relubrication during the lifetime of the motor. The smaller frames use bearings that are grease-packed and sealed for life at the factory and cannot be relubricated.

NEMA motors subject to very high loads and operating temperature in the larger frames may require oil lubrication to the rolling element bearings. This can be by either oil circulation within the bearing frame or from a pressurized lubrication system similar to that used with sleeve bearings. In addition, for motors required to carry very high thrust loads, quite often in only one direction, taper or spherical roller thrust bearings may be used.

Hydrodynamic Thrust Bearings Certain types of pump applications, such as very large vertical pumps, exhibit very high thrust loads that cannot be accommodated by rolling element bearings. Hydrodynamic bearings, usually with tilting, self-leveling thrust pads, are used for very high thrust loads. These bearings are sometimes referred to as “Kingsbury-type” in recognition of the original manufacturer of this bearing type. This type of bearing is oil-lubricated from a self-contained oil sump or an external pressurized pumping system, depending on size and rating.

MOTOR INSULATION

Insulation systems must be used in a motor to electrically insulate the windings from the mechanical parts of the motor as well as to insulate the phase winding conductors from one another. Extra insulation is also required between any adjacent phase windings for 230 or higher voltage motors. In general, the higher the operating voltage, the better the insulation system must be.

All NEMA-designed electric motors are manufactured with cord laced end turns to assure that they are positioned so they cannot touch any mechanical parts. In addition, the phase windings are nearly always impregnated with a varnish by either dipping or trickling into the heated end turns. The purpose of this is to secure the conductors to prevent them from vibrating between one another, which would wear through the wire insulation and cause turn-to-turn shorts. This stator varnish also provides some additional insulation protection to the system. For example, this coating makes the windings resistant to ambient conditions such as moisture. Consequently, a motor insulation system is very complex, utilizing several different materials, parts, and processes to effectively insulate the windings. The parts considered in an insulation system include slot cells, phase barriers, conductor insulation, slot wedges, end turn supports, tie material, and winding impregnation material.

Since the introduction of PWM inverters for use with all types of variable speed drives, such as ac induction, PM brushless and switched reluctance brushless, a new insulation system failure mode has emerged. This is a most significant problem in installations where the inverter is located 50 ft (15 m) or more away from the motor. The long motor lead cables used in these applications cause very high voltage spikes not present at the inverter end of the lead cables. These voltage spikes across the first turns of each phase winding result in the degradation of the wire insulation due to the corona insulation failure. Special magnet wire insulation and motor manufacturing methods are available to overcome this problem. Therefore, if an inverter is to be used to drive a pump motor with long connection cables, an "inverter duty" motor should be specified.

There are four basic classes of insulating materials currently recognized by the motor industry. Each differs according to its physical properties and can withstand a certain maximum operating temperature (frequently termed total *temperature* or *hot-spot temperature)* and provide a practical and useful insulation life. The insulation classes and their maximum operating temperatures are

Class A	90°C
Class B	130°C
Class F	155°C
Class H	180°C

Those factors that contribute to the maximum operating temperature of a motor insulation system are the ambient temperature, the temperature rise in the motor winding caused by motor losses, and any overload allowance designed into the motor (service factor).

The current standard for motors within the range of NEMA ratings (frames 140T to 449T) requires nameplate marking for the maximum allowance ambient temperature, the power rating, the associated line current needed to develop this power, the class of insulation used, and the service factor provided. Motors larger and smaller than NEMA frame sizes have nameplate marking for maximum allowable ambient temperature, temperature rise in degrees Celsius either by thermometer or resistance measurement, power rating, line current needed to develop this rating, and any service factor provided.

In addition to ambient temperature, there are several additional environmental conditions that must be considered when applying an electric motor. In applications where chemical fume or moisture levels are abnormal and can cause decomposition of an insulation system, standard insulation will be inadequate. These applications require a motor with a premium insulation system that will incorporate highly resistant components and may include special impregnation techniques. Chemical fumes and moisture can also be destructive to the mechanical parts of a motor, and special protective treatment should be provided to these parts. NEMA frame-size motors have a special motor for chemical industry applications that has standard features to resist these environmental factors. For example, these motors usually contain shafts made from stainless steel.

Applications with excessive vibration can destroy a winding and damage the mechanical parts of a motor. In such cases, it is advisable to provide (1) extra treatment for the winding to ensure that it is rigid and will not vibrate and chafe the insulating materials and (2) a mechanical construction that will have the strength to withstand the above.

If abrasive dust is present, the motor insulation should be protected with a resilient surface coating to withstand the impact of the abrasive particles.

Because all insulation systems employ components that can in some degree support fungus growth in tropical locations, motors applied in such areas should incorporate fungus-proofing treatment on the insulation.

Obviously, applications exhibiting a combination of any or all of the environmental conditions discussed should have special protection for each condition. Applications in unusual environmental conditions may require special protection and should be discussed with the motor manufacturer or distributor.

COUPLING METHODS FOR PUMP APPLICATIONS

Direct Coupling Pumps are frequently directly coupled to motors, and where the pump is not close-coupled, it is usually coupled by means of a flexible coupling. The use of a flexible coupling permits minor misalignment (angular and parallel) between motor and pump shafts. The use of some older style flexible or solid couplings could cause severe radial and axial loads on the motor bearings. Since the development of the flexible disk couplings, the earlier coupling designs have largely disappeared, as have the severe loads resulting from misalignment. The flexible disk coupling is capable of transmitting very high torque for its size, with minimum radial and axial forces on the shafts resulting from misalignment. [See Subsection 6.3.1.]

Close-Coupling Close-coupled pumps have become very popular for certain applications. In this arrangement, no coupling is provided between the pump and motor shafts and the pump housing is flange-mounted between close-tolerance fits on both the motor and the pump flanges. The pump impeller is mounted directly on the motor shaft. Care must be taken in this arrangement to ensure that the motor shaft runout or axial movement plus machine tolerances do not cause interference between the pump housing and its rotor. This is usually not a problem if properly fitted ball bearings are used in the motor. The motor shaft material must be compatible with the fluid being pumped, and if the pump impeller is held in place by a nut, the threat must respect the rotation of the motor. High-pressure close-coupled pumps of a nonbalanced design can cause excessive shaft thrust, which may be incorporated in the motor bearing capacity. It is always good practice with close-coupled pumps to provide some form of flinger on the motor shaft to prevent liquids that leak past the pump seal from entering the motor bearing.

Flanged Motors Flanged motors allow an easy means of aligning pump housings with motors. This construction is usually in the form of a vertical mounting in which the motor is set on top of the pump and the pump supports the motor weight. The pump and motor shafts are normally coupled, and those comments made under the subject of direct-coupling methods are applicable. Also, as in the case of coupled pumps, this construction permits thrust forces that must be considered when selecting a motor if the pump does not have a thrust bearing.

A further extension of flange motors includes the vertical hollow-shaft motor. With this design, a variable length of shafting connects the pump and motor. The pump shaft passes through the center of the motor bore, and the motor torque is imparted to the pump shaft by a suitable coupling at the top of the motor. The weight of the shaft and the pump impeller and the force of the hydraulic thrust are assumed by the motor bearings.

The coupling on the motor can be made a *self-release coupling* (Figure 17) to prevent the motor from delivering torque to the shaft in the event the motor is started in the wrong direction and to prevent reversed motor rotation from unscrewing the threaded joints between lengths of pump shafting.

Another modification to a coupling is a nonreverse *ratchet* (Figure 18), which prevents the remaining head of liquid in a pump from rotating the pump in the reverse direction when the pump is stopped. This prevents possible overspeeding of the pump and motor when the pump is connected to a large reservoir and most of the total pump head is static. This also prevents a pump with a long discharge column pipe from running in reverse with no liquid in the upper portion of the pipe to lubricate the line shaft bearings. Starting a pump capable of back spinning is also prevented.

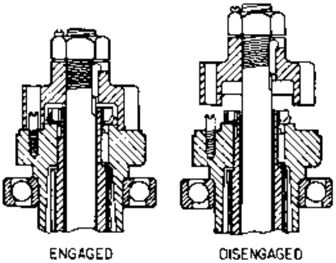


FIGURE 17 Self-release coupling connecting pump head shaft to hollow shaft of vertical motor disengages as a result of pump shaft couplings unscrewing (U.S. Electrical Motors).

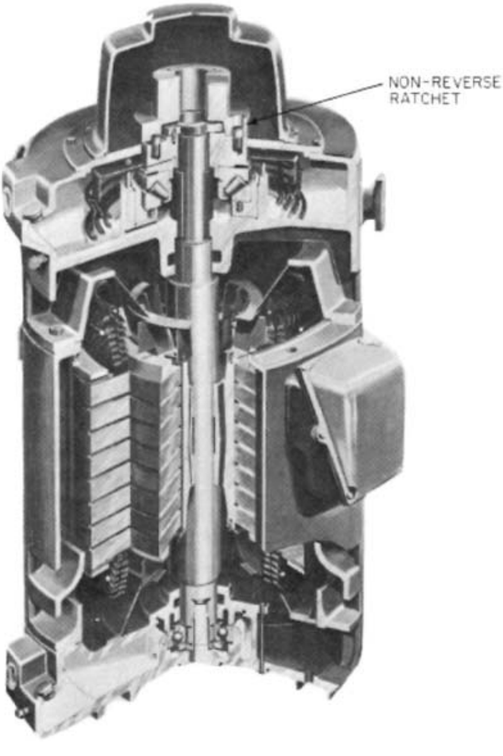


FIGURE 18 Section of vertical hollow shaft motor showing nonreverse ratchet. Spring-loaded pins ride on ratchet plate in one direction only (General Electric).

PERFORMANCE

Ac induction motors are designed to produce their rated power at a certain speed at a specific line voltage, line frequency, and ambient temperature. These motors will also operate at a specific efficiency and power factor when all of these conditions are met. The normal operating conditions of a motor are stipulated on its nameplate with values for power, speed, ambient temperature, and frequency. If the operating conditions are different from the nameplate ratings, the motor performance will be altered. Many of the newer PM and SR brushless motors are designed to produce their rated output power over a wide speed range. A high efficiency ac induction motor can also perform similarly if a Flux Vector Inverter is used for control.

Voltage Ac motors are designed to operate satisfactorily at their nameplate voltage rating with a ±10% variation from nameplate voltage when operating at rated nameplate frequency. This dictates that the motor will develop rated power and speed to a pump and will operate at a safe insulation temperature over the range of voltage. The motor torque will vary directly with the square of the applied voltage divided by the nameplate voltage. This affects the peak torque of the motor and will cause the motor speed-torque curve as shown in Figure 2 to be altered. Within the ±10% voltage band, a motor can be expected to accelerate and operate a pump safely and continuously. A motor should never be expected to operate continuously beyond the ±10% band. If the voltage varies more than ±10%, the pump and motor may not operate satisfactorily.

For example, assume a pump is operated by a NEMA design B motor (refer to Figure 2) that will produce 200% pull-out torque at rated voltage. If the line voltage were to fall to 70% of the rated name-plate voltage, the motor would produce only 49% of its peak torque value. The pull-out torque of the motor would then become $0.49 \times 200 = 98\%$ of rated torque. It then becomes very doubtful whether the motor will be able to sustain the pump load, and the motor can be expected to lose speed, stall, or become overloaded. Certainly, it will also heat up, which will shorten the expected life of the bearing lubrication and winding insulation system.

In a similar sense, a motor may be unable to accelerate a pump if low line voltage exists. In the example previously discussed, this same motor develops 150% of rated torque when started at zero speed and rated voltage. If the line voltage is again 70% of nameplate voltage, the motor will develop $0.49 \times 150 = 73\%$ of rated torque. This may be a problem with certain types of pumps, such as a constant displacement pump. It is conceivable that this would not be a problem in starting a centrifugal pump because of its square-law speed-torque characteristics. If the motor voltage never increased beyond 70%, the centrifugal pump would not reach normal operating speed. An exception to this rule is the commutating ac motor, for which a ±6% voltage variation is allowable.

Varying motor voltage from nameplate rated voltage will also affect the motor operating speed, power factor, and efficiency established for rated voltage and load. Most polyphase ac induction motors will operate at several rpm faster than nameplate speed at 10% over voltage and several rpm below nameplate speed at 10% under voltage. The speed of a synchronous motor is determined by the line frequency of the alternating voltage not the voltage level. Therefore, voltage variation has no effect on the speed of a synchronous motor. However, voltage variation does effect maximum torque output of a synchronous motor.

Dc motors can also be operated over a ±10% voltage range from nameplate rated voltage. However, it should be recognized that different types of dc motors will have different speed and torque characteristics over the voltage range. This should be taken into account when meeting pump performance requirements.

One of the most common applications for dc motors has been for metering pumps because of their ease of setting the speed to precisely meter the fluid being pumped. Although a voltage variation would change the pump speed, it is customary to include a speed control loop with the dc supply to maintain constant speed in spite of line voltage variations.

Frequency Ac induction motors will operate satisfactorily at rated load and voltage with a frequency variation up to ±5% from rated nameplate frequency. However, the speed of the motor will vary almost directly with the line frequency. The speed of a synchronous motor will vary directly with applied frequency. The combined variation of voltage and frequency must not be more than ±10% from rated nameplate voltage and frequency, provided the frequency variation does not exceed ±5% from rated nameplate frequency. The reason is that frequency variation from the nameplate frequency will cause motors to operate at a power factor and efficiency other than those established for rated frequency. Any electric motor such as PM or SR brushless and even ac induction, which is powered from an inverter, is unaffected by frequency variations.

Speed and Speed Range Synchronous and induction motors were originally expected to be operated at one specific speed when powered from line voltage and frequency. However, with the availability of inverters, this is no longer the case. In fact, the use of inverters for driving induction motors is expanding at a fast pace as the merits and benefits of adjustable speed are being realized. The use of speed controlled PM and SR brushless motors along with their inverters and controllers allow the pump application to take advantage of the usefulness of adjustable speed. Using the inverter with any of these types of motors eliminates any difficulties from speed variations from the past. This is because most inverters have a speed control loop that will automatically maintain the set speed.

Acceleration A motor must be capable of accelerating as well as driving a pump at rated speed and power. The acceleration can be analyzed by examining a typical pump-motor combination involving a centrifugal pump driven by a six-pole squirrel-cage induction motor rated 10 hp (7.46 kW) with NEMA design B torque characteristics. The curve in Figure 19 demonstrates this combination when the pump is loaded and the motor is operating at nameplate frequency and voltage. It will be noted that the torque produced by the motor at any speed must be greater than the torque required by the pump when up to speed. The excess torque at any speed is available to accelerate the motor, coupling, and pump rotating parts.

NEMA has provided a handbook for motion control that outlines the fundamental equations for the required torque calculations to accelerate any inertial loads to a predetermined speed. For the use of ac induction motors that are line-fed with constant voltage and frequency, the formulas are used to calculate the time to the motor slip from synchronous speed for a given total rotating inertia. For the use of inverter-fed ac induction, PM or SR brushless motors, the formulas are used to determine the torque required to accelerate the total rotating inertial load to the desired speed in the desired time.

The fundamental equations for motion, which include torque, inertia, time and acceleration relationships, are given below. They can be used for motor selection analysis for pumps. For example, if the torque available from an induction motor is known, the equation can be solved for the acceleration time of the system inertia (from NEMA "Programmable Motion Control Handbook").

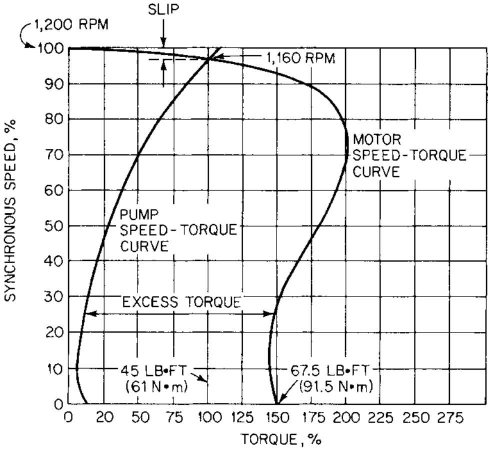


FIGURE 19 Typical speed-torque characteristic curves for a centrifugal pump and a squirrel-cage induction, NEMA design B motor. Excess torque accelerates pump.

$T_{TOTAL} = T_A + T_C$: Total torque = Acceleration torque + constant torque

$T_A = J_{\text{TOTAL}} \times \alpha$: Acceleration torque = Inertia × Angular acceleration

$\alpha = \dfrac{\omega_{\max}}{t_a} \times 2\pi$: Angular acceleration = Max RPM/acceleration time

T_C = Torque from all other constant forces, friction, windage, preload, and so on.

NOTE: Use consistent units depending on whether U.S. Customary or SI.
The time to accelerate the pump is equal to

in USCS units $$t = \frac{WK^2 \times \Delta\text{rpm}}{308T}$$

in SI units $$t = \frac{MK^2 \times \Delta\text{rpm}}{9.55T}$$

where t = time, s
WK^2 = total weight (force) moment of inertia, lb · ft^2
Δrpm = change in speed
T = torque, lb · ft ($N \cdot m$)
MK^2 = total mass moment of inertia, kg · m

Because the difference in torque is not uniform over the speed range, the curve (Figure 19) can be analyzed by assuming discrete changes in speed and an average torque over this change in speed. A time period can be calculated for each discrete speed change, and all time values can be totaled to obtain the complete acceleration time.

Increasing the inertia of the pump, the operating speed of the pump and motor, or the torque required by the pump at any speed will result in a longer acceleration time, which may not be possible for the motor. Each motor can operate at a reduced speed and at a torque in excess of rated torque for a given time. Beyond this time, the windings and/or rotor can be damaged. The use of an inverter-driven ac induction SR or PM brushless motor eliminates all of these problems associated with the use of line-fed ac induction motors. This is due to the torque control capability of the inverter/motor drive system using current control. The limit on the ability of the adjustable speed drive to control acceleration is a function of the current capability of the inverter (as long as the thermal limit of the motor has not been exceeded).

When an application is analyzed and found to present an acceleration-time problem, consideration should be given to

1. Unloading the pump during acceleration
2. Reducing the inertia of the rotating parts
3. Selecting a larger motor
4. Considering an adjustable speed motor and drive

When very large pumps are started, the line voltage will sometimes drop because of the high starting current, which causes the motor torque to be reduced by the square of the voltage ratio. Naturally, the acceleration time is greater because of the reduced torque produced by the motor. This will not hamper the ability of the motor to accelerate the pump as long as the motor develops more torque than is required to drive the pump at any speed over the accelerating range. The use of SR or PM brushless induction motors eliminates this problem because these motors do not draw high inrush currents. In fact, the starting current is controlled very precisely.

A similar analysis can be made for synchronous motors after the accelerating speed-torque curve for the motor is known. It should be recognized that a synchronous motor operates as a squirrel-cage induction motor up to the moment of synchronization. At that time, the synchronous motor must have an additional capability of synchronizing torque, frequently called *pull-in torque,* to accelerate the motor from subsynchronous to synchronous speed. If the motor cannot develop enough torque at its synchronous speed, it will pull out or stall. When this type of motor is used for a pump, it is advisable to unload the pump during acceleration operation to reduce the torque required from the motor for acceleration.

When using a synchronous motor, attention should always be given to the breakaway torque that is required to start the pump from zero speed. This is particularly important with constant displacement pumps, where the pump will operate at a constant torque over the entire accelerating speed range. Again, a better selection might be an inverter-driven ac induction motor, SR or a PM brushless motor.

Service Factor Motors are available with service factor ratings that range from 1.0 to as high as 1.5. A service factor implies that a motor has a built-in thermal capacity to operate at the nameplate power times the service factor stamped on the nameplate. It should be noted, however, that when the motor is operated at the service factor power, the motor will operate at what is termed a *safe temperature.* This means that the motor will operate at a total temperature that is greater than the temperature for a motor designed for the same power with a 1.0 service factor. Consequently, it is not advisable to apply a motor with a service factor larger than 1.0 where the continuous power requirements will be greater than the normal power.

A service factor rating on a motor is to provide an increased power capacity beyond nominal nameplate capacity for occasional overload conditions. Also, the speed-torque characteristics are related to the nominal power rating and not the service factor power. When adjustable speed motor/drive systems are selected, the old service factor ratings are not useful. The supplier of the drive system will assist in selecting a thermally rated system that will satisfy the pumping operation. All inverters are equipped with thermal safety protection for both the motor and the drive so the system cannot be overloaded to minimize overheating. This is a very useful feature for many pump applications.

Efficiency Motors are designed to operate with an efficiency expressed in percent at rated voltage, frequency, and power. Efficiency is defined as

$$\text{Efficiency } \% = \frac{\text{shaft output power} \times 100}{\text{electrical input power}}$$

The efficiency of a given motor design will vary slightly from unit to unit because of manufacturing tolerances and variations in materials. For this reason, guaranteed efficiencies are usually lower than actual efficiencies. When motors are operated at reduced powers, the tendency is for the efficiency to decrease because the losses tend to be fixed.

Several other factors have an effect on motor efficiency. Increasing the applied voltage and operating a motor at its rated power will increase efficiency very slightly, whereas decreasing applied voltage will decrease the efficiency noticeably. Also, increasing the frequency will cause a very slight increase in efficiency, and decreasing the applied frequency will cause a slight decrease in efficiency.

Inverter-fed ac induction and PM or SR brushless motors are not subject to changes in their efficiencies due to changes in line voltage or frequency because the ac line voltage is rectified into a dc voltage before the regeneration of the power to the motor. The dc voltage is always reasonably constant and unaffected by changes in the line power. This of course assumes that there is sufficient voltage and power headroom in the design.

Dynamometers are used to determine efficiency for small motor ratings—up to approximately 500 hp (373 kW)—and standard methods and formulas are used for calculating efficiency for large motors. For the latter, efficiency values can vary, depending upon which "standard" procedure is used. Several suppliers market torque and power analyzers for induction motors that base their output on these formulas using current data measured from the motor. These methods are accurate enough to be acceptable. They have been reasonably verified by applying the method to smaller motors that have been tested on a dynamometer. NEMA has established one method, but some suppliers use different methods, depending upon their national standards or established practices.

Higher efficiencies have been designed into most new motors by selecting materials and proportions that reduce losses, but such design choices usually make the motor more costly. This also includes filling the stator slots with more copper of a larger wire gage to reduce ohmic losses. These new motors designed for higher efficiencies offer improvements from 2% to as high as 7% depending upon the size and manufacturer.

Motor operating efficiency in a typical application often may not be that described by the manufacturer. Quoted efficiencies are always at rated power output, rated frequency, and rated voltage. However, it is almost universal in application that a motor is oversized for its applied load and frequently operates at other-than-normal voltage. Both of these variables can greatly reduce the efficiency of a motor. However, when a motor is inverter-driven, the efficiency of the system can be much better controlled.

Power Factor The power factor of a motor is expressed as

$$PF = 100 \cos \theta$$

where θ is the angle between voltage and current at motor terminals (leading or lagging).

The power factor at which a motor operates is dependent on the design of the motor and is established at rated voltage, frequency, and power output.

For induction motors, the power factor can never be 100% leading. A number of factors will influence the power factor of an induction motor:

Condition	Effect on power factor
Increase applied voltage	Decrease
Decrease applied voltage	Increase
Increase load	Increase
Decrease load	Decrease
Increase applied frequency	Slight increase
Decrease applied frequency	Slight increase

In synchronous motors, it is usual to use two varieties of motors, the 100 (unity) and 80% leading motors. The power factor of a synchronous motor operated at rated voltage and frequency is fixed by its field excitation and its power output. At a given power output, the power factor can be adjusted over a range by adjusting the field excitation. Increasing the field excitation will cause the motor to operate at a more leading power factor, and, conversely, reducing the field excitation will make the power factor lag.

Varying the power output of a synchronous motor with a constant field excitation will vary the operating power factor. A decrease in power output will cause a more leading power factor; conversely, increasing the power output will induce operation at a lagging power factor. Consequently, to operate the motor at rated power factor with a varying output power, it is necessary to adjust the field excitation. However, this is not normally done because a synchronous motor is frequently used for improving the power factor and the more leading power factor is used to accommodate power factor improvement. When a synchronous motor is overloaded and operates at a more lagging power factor, it is not usual to increase the excitation beyond its rated excitation because of the extra heating this will develop in the motor. In this case, the more lagging power factor is simply accepted.

The power factor is not of much concern for SR and PM brushless motors driven by inverters because of the control capabilities for these systems. The PM machine exhibits the best power factor of any known motor under nearly all operating speeds and power levels except if excessive field weakening or phase advance is used.

TYPES OF CONTROLS

In order to use an electric motor to drive a pump, a means of starting and stopping the motor is required. The devices used for this purpose can be called controls. Only small—perhaps up to two or three hp (kW)—motors can be controlled with a simple on-off switch (starting from full rated line voltage). This is because when a motor is first started it produces no back EMF and will draw very high starting currents. If the load inertia is very high, the motor can overheat during the long acceleration time. In addition, the high starting current peaks can cause heavy dips in the line voltage. Therefore, for larger motors, these line voltage dips must be minimized by the use of starters. There are four basic ways to start ac induction motors:

1. Direct online starting
2. Low voltage starting
3. Rotor resistance starting
4. Low frequency starting

Other devices used to control motors such as s*oft starters, adjustable frequency controls,* and *vector drives* are discussed along with the inverters and controls for other motor types such as dc motors, SR and PM brushless in Subsection 6.2.2.

Alternating-Current Motor Starters

MANUAL STARTERS Manual motor starters are designed to provide positive overload protection and start and stop control of single-phase and polyphase motors up to about 3 HP (2.5 kW). A single manual toggle switch or a push button switch is used for "on," "off," and "tripped" states. These types of starters use full line voltage applied to the motor.

MAGNETIC STARTERS Magnetic motor starters cost more and are more reliable than manual starters. They are designed to control a motor by incorporating a magnetically operated contactor to apply power to the motor terminals rather than allowing full current to pass through the contacts.

An overload relay is incorporated to protect the motor from overloading. Magnetic starters are available for reversing and nonreversing service and are also made as noncombination or combination types. The non-combination starter combines only the motor contactor and overload relay. The combination starter combines these parts along with either a circuit breaker or a fused switch to provide shortcircuit protection.

REDUCED-VOLTAGE STARTERS Reduced-voltage starters are available in several types and are basically magnetic starters with additional features to provide reduced voltage, which in turn provides for reduced motor-starting current or torque. These starters include the types discussed in the following paragraphs.

Primary-Resistor Starters Primary-resistor starters, sometimes known as *cushion-type* starters, will reduce the motor torque and starting inrush current to produce a smooth, cushioned acceleration with closed transition. Although not as efficient as other methods of reduced-voltage starting, primary-resistor starters are ideally suited to applications where reduction of starting torque is of prime consideration. A typical diagram for this type of starter is shown in Figure 20.

Autotransformer Starters Autotransformer starters are widely used reduced-voltage starters because of their efficiency and flexibility. All power taken from the line, except

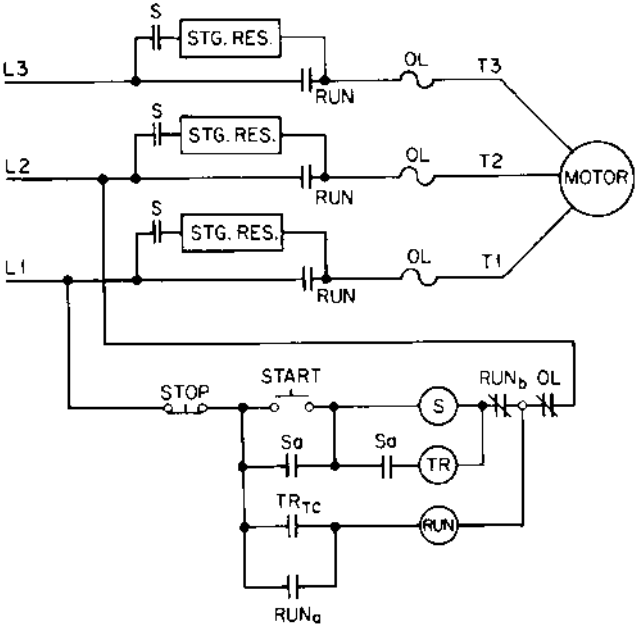


FIGURE 20 Typical primary-resistor, reduced-voltage starter wiring diagram (Westinghouse Electric)

transformer losses, is transmitted to the motor to accelerate the load. Taps on the transformer allow adjustment of the starting torque and inrush to meet the requirements of most applications. The following characteristics are produced by the three voltage taps:

Tap, %	Starting torque, % locked torque	Line inrush, % locked current
50	25	28
65	42	45
80	64	67

A typical diagram for this type of starter is shown in Figure 21.

Part-winding starting provides convenient, economical, one-step acceleration at reduced current where the power company specifies a maximum or limits the increments of current drawn from the line. These starters can be used with standard dual-voltage motors on the lower voltage and with special part-winding motors designed for any voltage. When used with standard dual-voltage motors, it should be established that the torque produced by the first half-winding will accelerate the load sufficiently so as not to produce a second undesirable inrush when the second half-winding is connected to the line. Most motors will produce a starting torque equal to between one-half and two-thirds of NEMA standard values with half the winding energized and draw about two-thirds of normal line-current inrush. A typical diagram is shown in Figure 22.

Star-delta starters have been applied extensively to starting motors driving high-inertia loads with resulting long acceleration times. They are not, however, limited to this application. When 6 or 12 lead delta-connected motors are started star-connected, approximately 58% of full-line voltage is applied to each winding and the motor develops 33% of full-voltage starting torque and draws 33% of normal locked rotor current from the line.

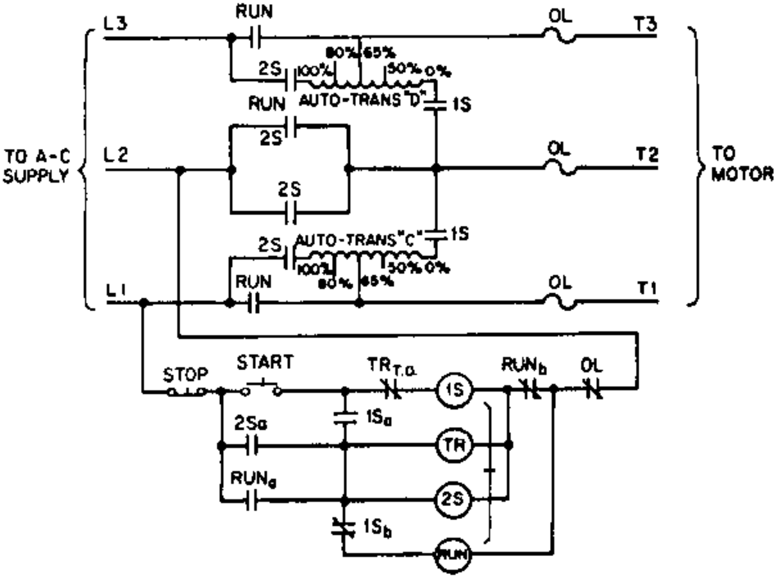


FIGURE 21 Typical autotransformer, reduced voltage starter wiring diagram (Westinghouse Electric)

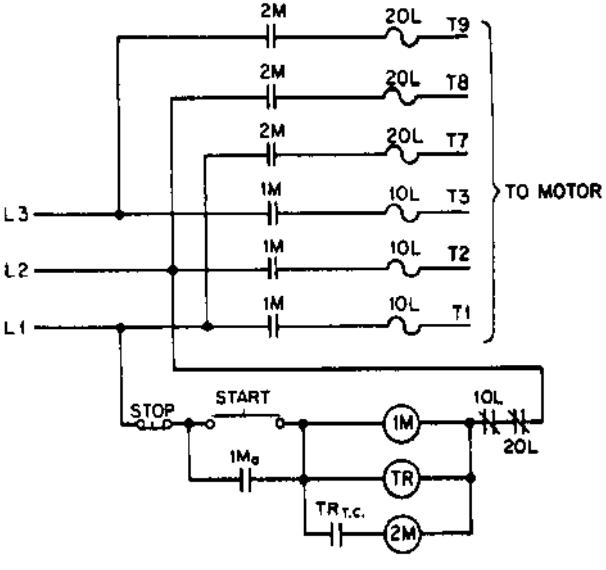


FIGURE 22 Typical part-winding starter wiring diagram (Westinghouse Electric)

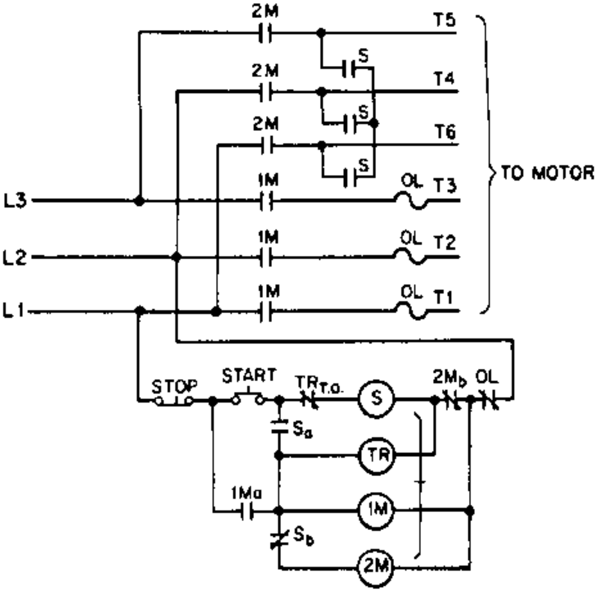


FIGURE 23 Typical star-delta, reduced-voltage starter wiring diagram (Westinghouse Electric)

When the motor has accelerated, it is reconnected for normal delta operation. A typical diagram is shown in Figure 23.

Wound Rotor Motor Starters These magnetic motor starters are used for starting, accelerating, and controlling the speed of wound-rotor motors. The primary control includes overload protection and low-voltage protection or low-voltage release, depending on the type of pilot device. Disconnect switches, circuit breakers, and reversing can be added to the primary circuit when required. Reversing starters are not designed for plugging.

The secondary circuit contains the NEMA recommended number of accelerating or running contactors and resistors to allow approximately 150% of motor full-load torque on first point of acceleration. Additional accelerating points can be added for high-inertia loads or exceptionally smooth starts. Adjustable timing relays permit field adjustment. Standard starting duty NEMA 135 resistors allow 10 s starting out of every 80 s. A typical diagram is shown in Figure 24.

Synchronous-Motor Starter Synchronous, magnetic, full-voltage starters provide reliable automatic starting of synchronous motors. They can be used whenever full-voltage starting is permissible. Automatic synchronization is provided by field relay, which assures application of the field at the proper motor speed and at a favorable angular position of stator and rotor poles. As a result, line disturbance resulting from synchronization is reduced and effective motor pull-in torque is increased. A typical diagram is shown in Figure 25.

Brushless synchronous-motor starters require special consideration inasmuch as all brushless synchronous motors are not constructed in the same way. The usual starter incorporates a low-power adjustable dc excitation source to energize and control the output of an integral shaft-connected exciter.

In addition, a pull-out relay and a timing relay are incorporated to initiate synchronization and stop the motor in event of pull-out.

Direct-Current Motor Starters Direct-current motor starters are designed to apply normal voltage to the motor field and, by means of a resistor, reduce voltage to the armature.

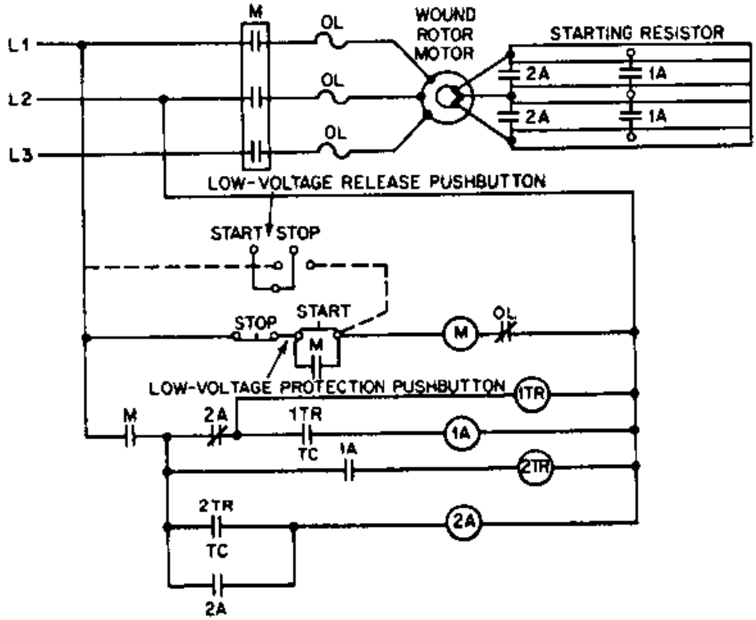


FIGURE 24 Typical wound-rotor motor starter wiring diagram (Westinghouse Electric)

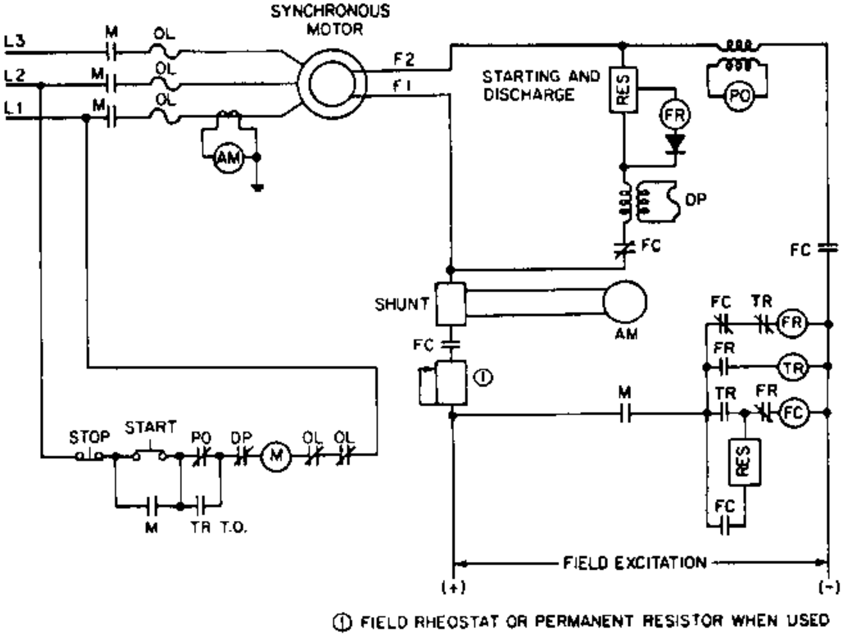


FIGURE 25 Typical synchronous-motor starter wiring diagram (Westinghouse Electric)

Timing relays and contractors progressively short out the resistor until full voltage is on the armature.

If the motor is equipped with a field rheostat for field-range speed adjustment, the starter will apply the preset field voltage as adjusted by the field rheostat after full voltage is applied to the armature.

These starters incorporate a field failure relay to deenergize in the event of field failure and overload relays to protect the motor against overspeed.

The use of dc drives or SCR voltage controllers includes the facilities for all required types of starting conditions for using dc motors for pump applications. Some of these issues are covered in Subsection 6.2.2.

SEALLESS PUMP MOTORS

Various centrifugal pump designs are available that require no shaft sealing; that is, no packing or mechanical seal. These pumps are completely leakproof, and some are submersible. Such pumps are used when leakage cannot be tolerated or when pumping conditions such as pressure and/or temperature make conventional sealing difficult, if not impossible.

The shaft seal is eliminated by joining the pump and motor housings together to create a single leakproof unit. The impeller and motor rotor are mounted on a single shaft. Most designs permit the pumped liquid to circulate through the motor rotor and motor bearings. However, there are designs where either circulation is also through the stator or the stator is sealed and filled with dialectric oil. See Subsection 2.2.7.2.

Another popular method used for smaller pumps is to separate the pump shaft completely from the motor shaft. A permanent magnet coupling is provided to transmit the motor torque to the pump shaft through a nonmagnetic shell or section of the pump housing. The pump and motor can be integrated in these designs. See Subsection 6.3.2 and 2.2.7.1.

Figure 26 classifies various motor designs and references other places in the handbook where the special features and applications of these units are described in more detail.

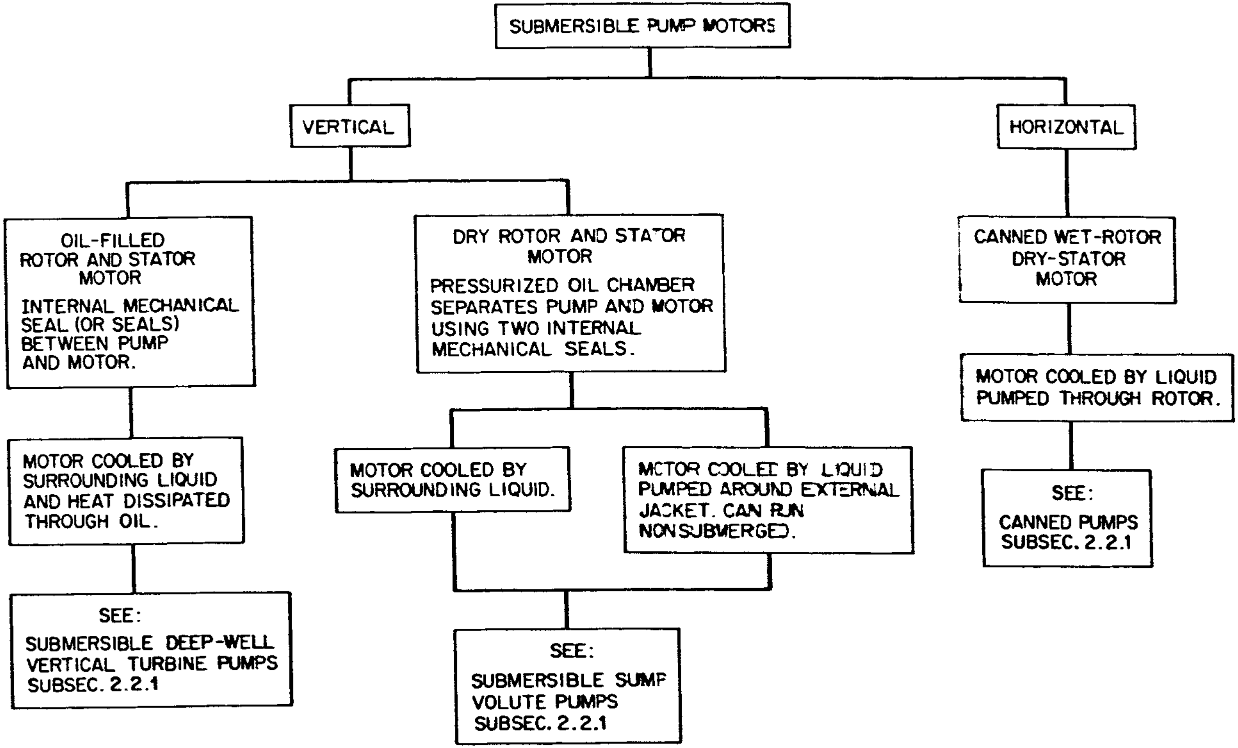


FIGURE 26A Pump motors for sealless centrifugal pumps: Submersible pumps

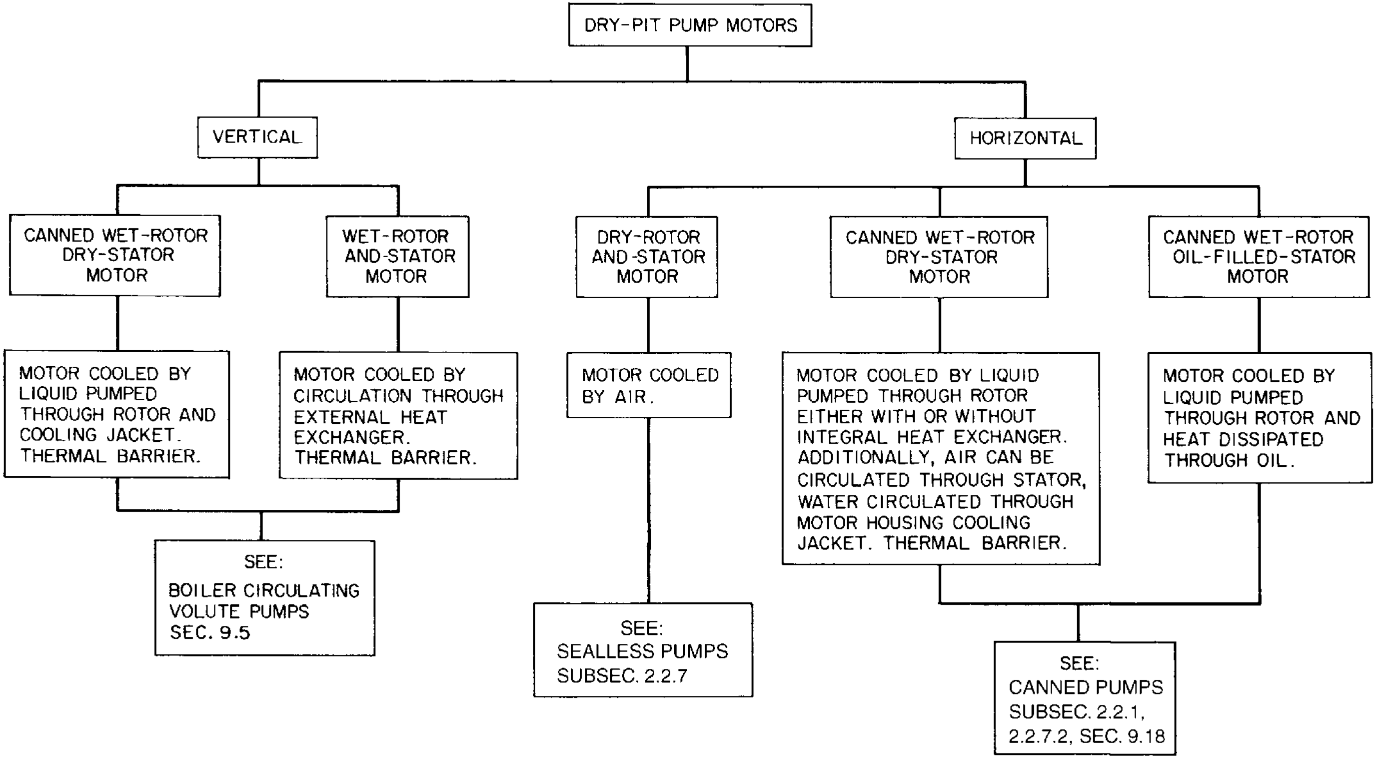


FIGURE 26B Pump motors for sealless centrifugal pumps: Dry pit pumps

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1. Sloteman, D. P., and Piercy, M. "Developing Sealless Integral Motor Pumps Using Axial Field, Permanent Magnet Disk Motors." *Proceedings of the 17th International Pump Users Symposium,* Texas A&M University, College Station, TX, March 2000, pp. 53–67.