Basics of Motors and Drives

Selecting the right motor and drive combination can save energy and improve performance.

The venerable electric motor that was the muscle of the industrial revolution is becoming the smart muscle of the computer-controlled plant and commercial facility of the future. The advent of powerful, reliable electronic drives is keeping motors in the forefront of this technological evolution.

Electric motors have a tremendous impact on overall energy use. Between 30 to 40 percent of all fossil fuels burned are used to generate electricity, and two-thirds of that electricity is converted by motors into mechanical energy.

The Fundamentals of Energy Management series this month will focus on topics that will allow facility managers and engineers at commercial and industrial facilities to understand the basics of motors and drives. This information will help them to select and implement strategies with the goal of reducing motor and drive costs as well as decreasing downtime.

AC Induction Motors

AC induction motors are ideal for most industrial and commercial applications because of their simple construction and low number of parts, which reduce maintenance cost. Induction motors are frequently used for both constant-speed and adjustable speed drive (ASD) applications.

The two basic parts of an induction motor are the stationary stator located in the motor frame and the rotor that is free to rotate with the motor shaft. Today's motor design and construction are highly refined. For example, stator and rotor laminations have been designed to achieve maximum magnetic density with minimum core losses and heating. The basic simplicity of this design ensures high efficiency and makes them easily adaptable to a variety of shapes and enclosures.

A three-phase induction motor can best be understood by examining the three-phase voltage source that powers the motor. Three-phase currents flowing in the motor leads establish a rotating magnetic field in the stator coils. This magnetic field continuously pulsates across the air gap and into the rotor. As magnetic flux cuts across the rotor bars, a voltage is induced in them, much as a voltage is induced in the secondary winding of a transformer.

Because the rotor bars are part of a closed circuit (including the end rings), a current begins to circulate in them. The rotor current in turn produces a magnetic field that interacts with the magnetic field of the stator. Since this field is rotating and magnetically interlocked with the rotor, the rotor is dragged around with the stator field.

When there is no mechanical load on the motor shaft (no-load condition), the rotor almost manages to keep up with the synchronous speed of the rotating magnetic field in the stator coils. Drag from bearing friction and air resistance prevents perfect synchronicity. As the load increases on the motor shaft, the actual speed of the rotor tends to fall further behind the speed of the rotating magnetic field in the stator. This difference in speed causes more magnetic lines to be cut, resulting in more torque being developed in the rotor and delivered to the shaft mechanical load. The rotor always turns at the exact speed necessary to produce the torque required to meet the load placed on the motor shaft at that moment in time. This is usually a dynamic situation, with the motor shaft speed constantly changing slightly to accommodate minor variations in load.

The rotor consists of copper or aluminum bars connected together at the ends with heavy rings. The construction is similar to that of a squirrel cage, a term often used to describe this type of ac induction motor.

The rotating magnetic field in the stator coils, in addition to inducing voltages in the rotor bars, also induces voltages in the stator and rotor cores. The voltages in these cores cause small currents, called eddy currents, to flow. The eddy currents serve no useful purpose and result in wasted power. To keep these currents to a minimum, the stator and rotor cores are made of thin steel discs called laminations. These laminations are coated with insulating varnish and then edge welded together to form a core. This type of core construction substantially reduces eddy current losses, but does not entirely eliminate them.

By varying the design of the basic squirrel-cage motor, almost any characteristic of speed, torque, and voltage can be controlled by the designer. To standardize motor features the National Electrical Manufacturers Association (NEMA) has established standards for a number of motor features.

The speed of an ac induction motor depends on the frequency of the supply voltage and the number of poles for which the motor is wound. The term poles refers to the manner in which the stator coils are connected to the three incoming power leads to create the desired rotating magnetic field. Motors are always wound with an even number of poles. The higher the input frequency, the faster the motor runs. The more poles a motor has, the slower it runs at a given input frequency. The synchronous speed of an ac induction motor is the speed at which the stator magnetic flux rotates around the stator core at the air gap. At 60 Hz the following synchronous speeds are obtained:

Number of poles	RPM
2	3,600
4	1,800
6	1,200
8	900
10	720
12	600

Providing the motor is properly constructed, the output speed can be doubled for a given number of poles by running an ASD supplying the motor at an output frequency of 120 Hz.

The actual speed of an induction motor rotor and shaft is always somewhat less than its synchronous speed. The difference between the synchronous and actual speed is called slip. If the rotor rotated as fast as the stator magnetic field, the rotor conductor bars would appear to be standing still with respect to the rotating field. There would be no voltage induced in the rotor bars and no current would be set up to produce torque.

Induction motors are made with slip ranging from less than 5% up to 20%. A motor with a slip of 5% or less is known as a normal-slip motor. A normal-slip motor is sometimes referred to as a 'constant speed' motor because the speed changes very little from no-load to full-load conditions. A common four-pole motor with a synchronous speed of 1,800 rpm may have a no-load speed of 1,795 rpm and a full-load speed of 1,750 rpm. The rate-of-change of slip is approximately linear from 10% to 110% load, when all other factors such as temperature and voltage are held constant. Motors with slip over 5% are used for hard to start applications.

The direction of rotation of a poly-phase ac induction motor depends on the connection of the stator leads to the power lines. Interchanging any two input leads reverses rotation.

Torque and Horsepower

Torque and horsepower are two very important characteristics that determine the size of the motor for a particular application. Torque is the turning effort. For example, suppose a grinding wheel with a crank arm one-foot long takes a force of one pound to turn the wheel at steady rate. The torque required is one pound times one foot or one foot-pound. If the crank is turned twice as fast, the torque remains the same. Regardless of how fast the crank is turned, the torque is unchanged as long as the crank is turned at a steady speed.

Horsepower takes into account how fast the crank is turned. Turning the crank more rapidly takes more horsepower than turning the crank slowly. Horsepower is the rate of doing work. By definition, one horsepower equals 33,000 foot-pounds per minute. In other words, to lift a 33,000-pound load one foot in one minute would require one horsepower.

The discussion so far has only involved torque at a steady speed. More effort is required to start a load than to keep it going.

An ac induction motor is built to supply the extra torque needed to overcome the inertia of starting a load. The speed-torque curve for a representative motor is shown in Figure 4 and illustrates in this example that the starting torque is 210% of rated-load torque.

Motor Losses and Loss Reduction Techniques

The only way to improve motor efficiency is to reduce motor losses. Since motor losses produce heat, reducing losses not only saves energy directly but can also reduce cooling load on a facility's air conditioning system.

Motor energy losses can be segregated into five major areas. Each area is influenced by the motor manufacturer's design and construction decisions. One design consideration, for example, is the size of the air gap between the rotor and the stator. Large air gaps tend to maximize efficiency at the expense of a lower power factor. Small air gaps slightly compromise efficiency while significantly improving power factor.

Motor losses may be grouped as fixed or variable losses. Fixed losses occur whenever the motor is energized and remain constant for any given voltage and speed. Variable losses increase with an increase in motor load. Core loss and friction windage losses are fixed. Variable losses include stator- and rotor-resistance losses and stray load losses.

Motor Economics

The principal factors in energy-saving calculations are motor efficiency, run hours (at a certain load), and the cost of electricity. When a motor runs at nearly full load for many hours at a facility with high electrical costs, the higher resulting savings will indicate the use of a 'premium efficiency' unit. In some cases, the savings may be great enough to warrant taking a perfectly serviceable older motor off-line and upgrading to a new, premium-efficiency model. For applications with less than continuous use or at lower than full loading, upgrading a working motor will usually not make sense.

Some other application considerations: The full-load speed of high-efficiency motors is usually somewhat higher than standard efficiency models. When applied to centrifugal loads such as pumps and fans, the higher speed can translate to an increased horsepower requirement, and this can offset the anticipated energy savings. The higher output speed may also increase overall output by allowing a piece of machinery to finish its job faster. Results will vary with the application. There are energy efficient motor designs that can exhibit some unusual characteristics such as lower power factor and higher locked rotor amperage; these must be considered when choosing a motor.

Adjustable Speed Drive Systems

Commercial and industrial firms today use adjustable-speed drive (ASD) systems for a variety of applications.

Most common of these include standard pumps, fans, and blowers. Newer applications include hoists and cranes, conveyors, machine tools, film lines, extruders, and textile-fiber spinning machines.

Many applications have unique demands and characteristics.

Drive vendors have responded to this demand by producing a variety of drives. The combination of the many types of drives available and the abundance of applications has made the selection of the optimum drive for a given application a challenge.

New generation ASDs have evolved with advancements in solid-state electronics. ASDs can now be applied to ac motors regardless of motor horsepower or location within a facility and can be used to drive almost all types of motorized equipment, from a small fan to the largest extruder or machine tool. Commercial and industrial facilities can expect to dramatically reduce both energy consumption and operating and maintenance costs while offering improved operating conditions by using new generation electronic ASDs. The latest generation of ASDs allows ac induction motors to be just as controllable and efficient as their dc counterparts were.

Historically a variety of terms have been used to describe a system that permits a mechanical load to be driven at user-selected speeds. These terms include, but are not limited to:

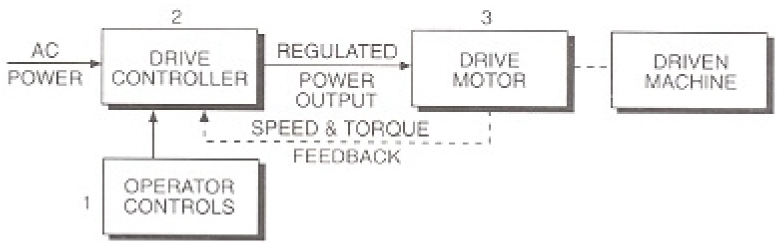
Variable-Speed Drive
Variable-Frequency Drive
Adjustable-Frequency Drive
Adjustable-Speed Drive

The term variable implies a change that may or may not be under the control of the user. Adjustable is the preferred term since this refers to a change directly under control of the user. The term frequency can only be applied to drives with an ac output, while the term speed is preferred since this includes both ac and dc drives. Thus, the term most commonly accepted is Adjustable-Speed Drive (ASD).

Basic ASD Components

Most ASD units consist of three basic parts. A rectifier that converts the fixed frequency ac input voltage to dc. An inverter that switches the rectified dc voltage to an adjustable frequency ac output voltage. (The inverter may also control output current flow, if desired.) The dc link connects the rectifier to the inverter. A set of controls directs the rectifier and inverter to produce the desired ac frequency and voltage to meet the needs of the ASD system at any moment in time.

The advantages of ASDs do not stop with saving energy and improving control. ASD technology can now be applied to manufacturing equipment previously considered too expensive or uneconomical. Such applications are often unique to a particular industry and its equipment, or even to a particular facility. Cost benefits, such as those obtained from improved quality, may be desirable for each application.



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For more details see the files at "Fieldbus Class Room"

Tutorial Motor Basics Lecture	**2.1MB**
Adjustable Speed Drives Tutorial	**300kB**
Electric Motor Controls Tutorial	**653kB**

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THREE-PHASE ALTERNATING CURRENT MOTORS

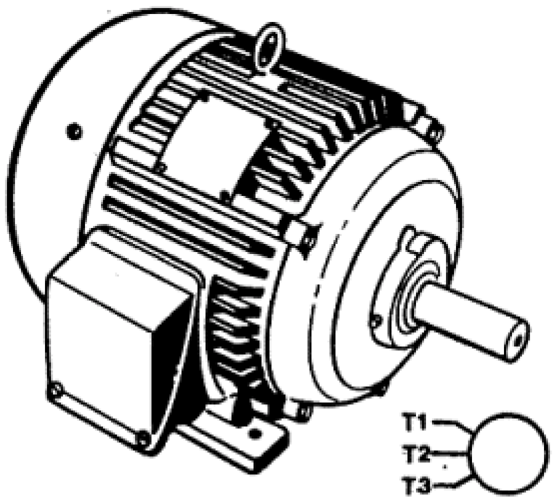
THREE-PHASE ALTERNATING CURRENT MOTORS - Free Online Tutorial Part 1

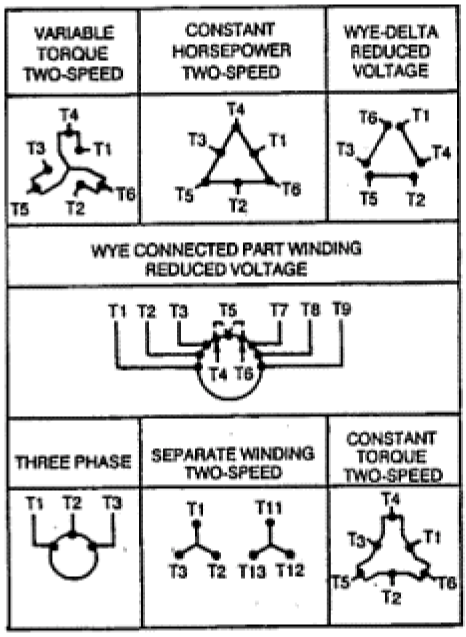
Most of the power-generating systems produce AC. For this reason, a majority of the motors used operate on AC. There are other advantages to using AC. In general, AC motors are less expensive and easier to maintain than DC machines.

An AC motor is particularly well suited for constant speed operations. This is because its speed is determined by the frequency of the power source and the number of poles constructed in the motor.

Alternating current motors are built in different sizes, shapes, and ratings for many different applications.

It is impossible to address all forms of AC motors in this text. This article will address only the squirrel cage induction motor.





INDUCTION MOTOR PRINCIPLE

The principle of the revolving magnetic field is the key to the operation of the AC motor. Induction motors rely on revolving magnetic fields in their stators (stationary windings) to cause their rotors to turn. Stators themselves do not turn. Stators are permanently attached to the inside of the motor housing in the same manner that the stationary windings in the generator are connected to the main frame. The revolving magnetic fields created in the stator windings provide the necessary torque to move the rotor.

The idea is simple. A magnetic field in a stator can be made to appear to rotate electrically, around the inside periphery of the motor housing. This is done by overlapping several different stator windings. A magnetic field is developed in each different stator winding at a different time. Just before the magnetic field of one winding decays, the winding overlapping it develops the same magnetic polarity. As this second magnetic field decays in the second winding, another overlapping winding develops a magnetic field of the same polarity, and the sequence repeats itself. Successive stator windings develop magnetic fields in an orderly procession and appear to progressively move around the inside of the motor housing.

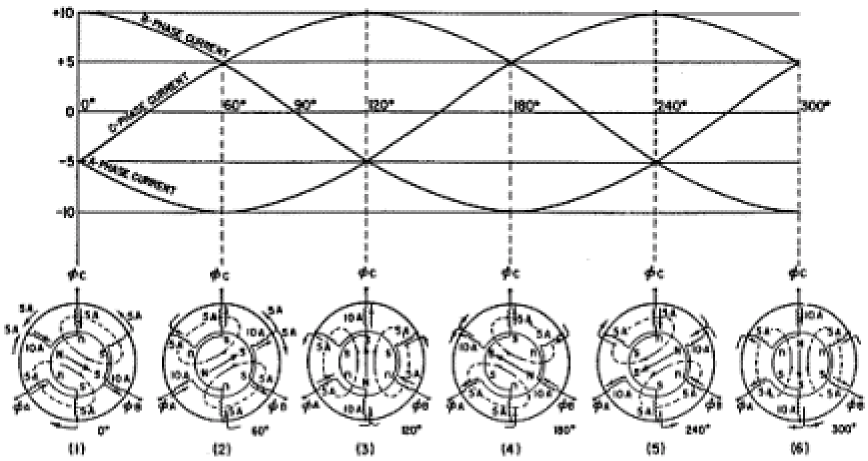
These individual magnetic fields are the property of current flow in the motor stator. This current flow comes from the three individual phase currents of the three-phase generator output. The figure shows the three single-phase voltages/currents that develop in the generator main armature completing individual circuits. Circuit A-B in the generator armature has a like A-B winding in the motor's stator.

Each of the three circuit combinations (A-B, B-C, and C-A) are developed independently in the generator over a short period of time. The generator circuits are then completed through the motor's stator windings in a similar manner. As long as the current and magnetic field develops and decays in an orderly, progressive manner around the periphery of the motor frame, a revolving magnetic field exists.

A revolving magnetic field in the stator is only part of the operation. Another magnetic field needs to be created in the rotor so that the torque and rotation can develop using the principles of magnetic attraction and repulsion. The magnetic field developed in the rotor is a product of induction. As soon as the stator and the rotor windings develop their magnetic affiliation, torque will develop, and the rotor will turn.

REVOLVING FIELD OPERATION

The rotating field is set up by out-of-phase currents in the stator windings. The figure below shows the manner in which a rotating field is produced by stationary coils or windings when they are supplied by a three-phase current source. For the purpose of explanation, rotation of the field is developed in the figure by "stopping" it at six selected positions, or instants. These instants are marked off at 60-degree intervals on the sine waves representing currents in the three phases A, B, and C.



At instant 1, the current in phase B is maximum positive. (Assume plus 10 amperes in this example.) Current is considered to be positive when it is flowing out from a motor terminal. At the same time (instant 1), current flows into A and C terminals at half value (minus 5 amperes each in this case). These currents combine at the neutral (common connection) to supply plus 10 amperes out through the B phase.

The resulting field at instant 1 is established downward and to the right as shown by the arrow NS. The major part of this field is produced by the B phase (full strength at this time) and is aided by the adjacent phases A and C (half strength). The weaker parts of the field are indicated by the letters n ands. The field is a two-pole field extending across the space that would normally contain the rotor.

At instant 2, the current in phase B is reduced to half value (plus 5 amperes in this example). The current in phase C has reversed its flow from minus 5 amperes to plus 5 amperes, and the current in phase A has increased from minus 5 amperes to minus 10 amperes.

The resulting field at instant 2 is now established upward and to the right as shown by the arrow NS. The major part of the field is produced by phase A (full strength) and the weaker parts by phases B and C (half strength).

At instant 3, the current in phase C is plus 10 amperes, and the field extends vertically upward. At instant 4 the current in phase B becomes minus 10 amperes, and the field extends upward and to the left. At instant 5, the current in phase A becomes plus 10 amperes, and the field extends downward and to the left. At instant 6, the current in phase C is minus 10 amperes, and the field extends vertically downward. In instant 7 (not shown), the current corresponds to instant 1 when the field again extends downward and to the right.

Thus, a full rotation of the two-pole field has been done through one full cycle of 360 electrical degrees of the three-phase currents flowing through the stator windings.

SYNCHRONOUS SPEED

The number of poles in the motor will determine how many times the magnetic field in the stator revolves for any given generated frequency. The term "pole" should bring to mind the terms used in Chapter 2 on magnetism. The following definition of a motor pole gives it a practical application value: A motor pole is the completed circuit of a motor stator winding that, when energized by a current, will produce a magnetic field concentration, or polarity.

The speed of the revolving stator field is called synchronous speed. The synchronous speed depends on two factors:

- The number of poles.
- The frequency of the power source.

The synchronous speed, in turn, determines the speed of the motor rotor. Just as with the generator prime mover speed, the generated frequency and rotor speed are directly related. The number of poles in the motor determines how fast the revolving field will move around the inside periphery of the motor housing at a given frequency. The more poles a motor has, the longer it takes to energize all the sets of poles and the slower the motor field will revolve at 60 hertz.

The table shows the speed of the revolving field (or synchronous speed) for a 60-hertz generated power supply.

Number of Poles in the Motor	Stator Revolving Field Speed (Synchronous Speed)
2 poles	3,600 RPM
4 poles	1,800 RPM
6 poles	1,200 RPM
8 poles	900 RPM

DIRECTION OF ROTATION

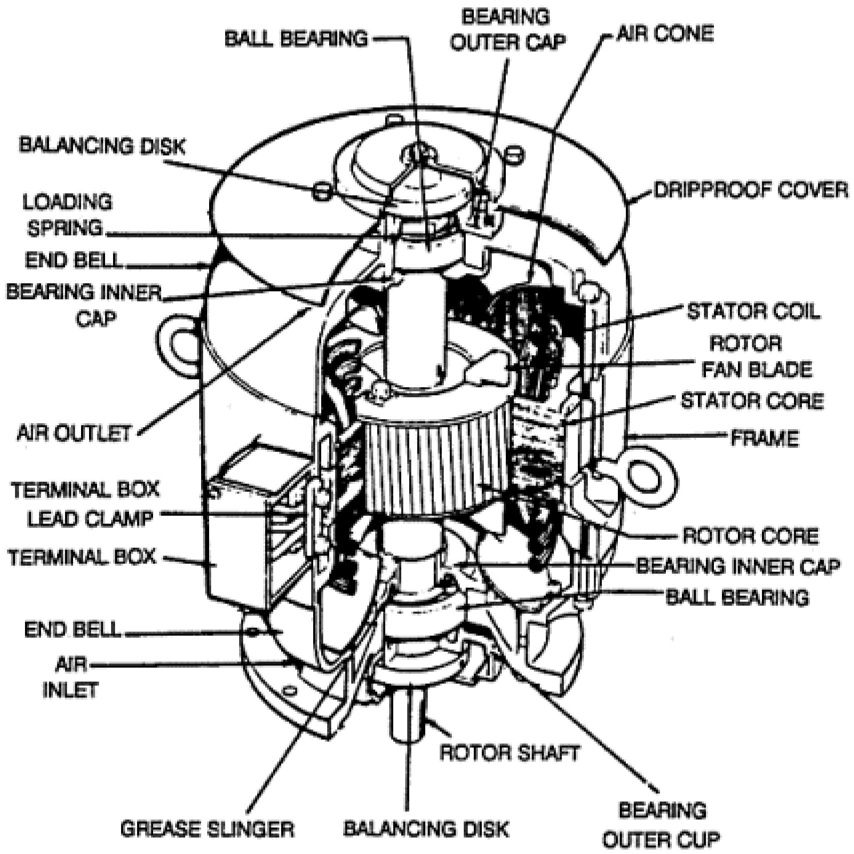
The direction of rotation of three-phase machines are determined by the phase sequence. Normal phase sequence on board Army vessels is A-B-C. This can be verified from the switchboard. A set of lights indicates the phase sequence from the power source.

As the generator rotates, current flow is induced in the armature. Each phase in the armature becomes electrically active. The order in which the phases become electrically active determines the order in which the motor's stator receives the current. The motor that receives current A-B-C-A-B-C will rotate in a given direction. If any two leads change places, then the two affected phases change their sequence of arrival. If phases B and C are exchanged, then phase C will follow phase A. This reverses the direction of the revolving magnetic field in the stator. Current arrives at the motor C-BA-C-B-A. When the revolving field in the motor's stator changes direction, the motor's rotor changes direction. Reversing the generator's output will turn the motor's rotor in the opposite direction as well. If the generator's output is reversed, then it is known as C-B-A phase sequence.

By reversing any two phase wires, either at the generator's armature or the motor's terminals, the phase sequence will change at that point. Reversing any two leads, at the same point, will restore normal phase sequence. Industry standard dictates configuration control by identifying the conductors to be exchanged: the A and C phase for generators, P1 and P3 for feeders, L1 and L3 for branch circuits, or T1 and T3 for motor terminals.

CONSTRUCTION AND OPERATION

The next figure shows a cutaway view of a three-phase induction motor. There is very little difference between the AC motor and the AC generator. The rotor is supported by bearings at each end. The stator is freed in position to the inside of the motor frame. The frame encloses all the components of the motor.



Frame

The motor frame, among other considerations, is a determining factor in the placement of the motor. Each motor frame enclosure has certain characteristics and specific vessel applications. There are seven basic types of enclosures:

In an open-type enclosure, the end bells are open and provide for maximum motor ventilation. This is the lowest cost motor enclosure.

In a semiguarded enclosure, the end bells are open, but screens are provided to prevent objects from falling into the motor. There is no protection against water or liquids.

In a guarded enclosure, screens and guards exist over any opening in the motor housing. Limited openings are provided to limit access to live and rotating components within the motor enclosure. Generally, the holes must prevent a 1/2-inch diameter rod from entering the enclosure.

In a drip-proof enclosure, the end bells are covered to prevent liquid from entering the enclosure at an angle not greater than 15 degrees from the vertical.

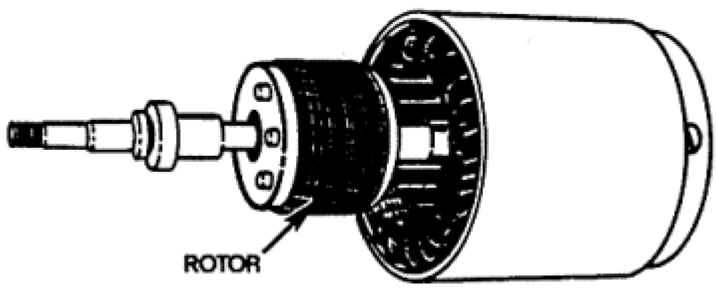
In a splash-proof enclosure, the motor openings are constructed to prevent liquid drops or solid particles from entering the motor at any angle not greater than 100 degrees from the vertical.

A waterproof enclosure prevents any moisture or water leakage from entering the motor and interfering with its successful operation.

A watertight enclosure prevents a stream of water from a hose (not less than 1 inch in diameter, under a head of 35 feet, from a distance of 10 feet) from any direction from entering the motor for a period of at least 15 minutes.
Electric equipment exposed to the weather or in a space where it is exposed to seas, splashing, or similar conditions must be watertight or in a watertight enclosure. Electric motors, however, must be either watertight or waterproof (Code of Federal Regulations, Title 46, Subpart 111.01-9).

Stator Windings

The motor stator is the stationary winding bolted to the inside of the motor housing. The stator windings have a very low resistance. The three-phase AC generator armature is built very similar to the three-phase AC motor stator. Each machine has the stationary conductor winding insulated its entire length to prevent turn-to-turn shorts. The winding is also insulated from the frame. The motor stator winding is identical to a generator armature that has a like amount of poles. Each winding is overlapped and is electrically and mechanically 120 degrees out of phase.

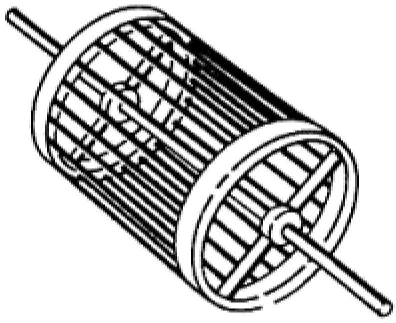


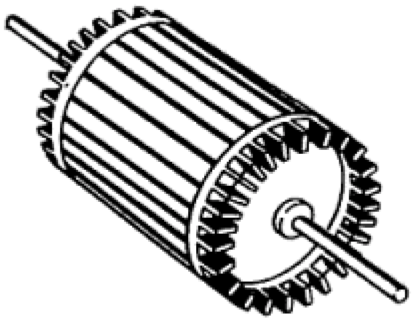
The figure above shows an end view of the stationary windings. Each of the three-phase windings are divided into many additional coils uniformly distributed throughout the stator. This even distribution allows more effective use out of the magnetic fields that will be developed within the stator windings when current is present. This also produces a more even torque (pulling and pushing by magnetic forces) for the rotor.

Rotor Windings

The rotor looks like a solid cylinder supported at each end by bearings (Figure 16-6). Upon closer examination, you may see thin bars embedded in the laminated cylinder at an angle almost parallel to the rotor shaft. At each end of the cylindrical rotor core, there are shorting rings. Each end of a bar is connected to the shorting rings.

These rotor windings are similar in construction to the amortisseur or damper windings found in the generator.





Rotor Current

These short-circuited rotor bars become a transformer secondary. The magnetic field established in the stator induces an EMF in the rotor bars. The rotor bars and the shorting rings complete a circuit, and a current flow is then established in these rotor bars. Remember, whenever a current flow is established so is a magnetic field. Since this magnetic field is the property of induction and induction opposes that which creates it, the magnetic field pole in the rotor is of the opposite polarity of the stator field pole that generated it. Magnetism principles apply, and the rotor's polarity is attracted to the stator's opposite polarity. The revolving field of the stator, in effect the revolving magnetic polarity, pulls and pushes the initially established rotor field in the rotor. The pulling and pushing produces torque, and the motor rotor turns.

Short-Circuited Rotor Bars

Words often used to describe the solid bar windings found in the induction motor rotor are "short-circuited bars." A short circuit is a very low resistance situation that has very little restraint in reducing current flow. A short circuit condition can have devastating effects on the entire electrical environment. The rotor bars are designed for very low resistance to obtain certain motor operating characteristics. The rotor bars themselves are not entirely the cause for the short circuit condition. The great inrush of motor current is initiated because of the relative motion between the stationary rotor winding and the revolving stator field. This is part of the maximum current the motor will draw initially from the distribution system. Through transformer-like action, the great difference in relative motion induces a large EMF and resulting current flow in the rotor.

The inrush will be dramatically reduced as the rotor speed increases. The closer the rotor RPM is in relation to the speed of the revolving stator magnetic field, the less relative motion exists. Less relative motion means less induced EMF and a reduction in rotor and stator winding currents. Shortly after power is applied to the motor, the current is reduced to as little as 10 percent. Once the motor is operating at normal speed, the full-load current (FLC), stipulated on the data plate, is maintained. Large motors installed on Army watercraft can have an increase in current 6 to 12 times greater than the data plate FLC rating. Mechanically overloading a motor slows the rotor and increases current. It is the increase in current, no matter how little, that results in heating sufficient to destroy motors.

SLIP

If the rotor could turn at synchronous speed, then there would be no relative motion between the magnetic field of the stator and the rotor conductor bars. This would end the induction process in the rotor, and the rotor would lose its magnetic field.

This is not possible with an induction motor. If rotor speed equaled synchronous speed, the rotor would stop. However, as soon as the rotor slowed, even slightly, induced EMF and current would again flow in the rotor winding. Rotor speed would be maintained somewhere below synchronous speed. Slip is the difference between the synchronous speed and the actual speed of the rotor. Slip is more often expressed as a percentage:

Percent slip = (synchronous speed - rotor speed) x 100 synchronous speed

Percent slip = (1,800 RPM - 1,785 RPM) x 100 1,800 RPM

Percent slip = 15 x 100 1,800

Percent slip = 0.8 percent

An induction motor will always have a difference in speed between the rotor and the stator field. Without this difference, there would be no relative motion between the field and rotor and no induction or magnetic field in the rotor.

Rotor and therefore motor speed is determined by the number of poles, the frequency, and the percentage of slip.

ROTOR RESISTANCE

Induction motor rotors are designed to have a specific amount of resistance. The resistance in the rotor determines the comparative ease with which the magnetic field in the rotor becomes established. The motor starting current, slip, and torque are modified by the rotor resistance. By developing a motor with a high rotor resistance, a larger slip is developed because the magnetic field of the rotor cannot develop very quickly. A step-by-step sequence of events portrays the actions between the stator and rotor in a relatively high rotor resistance induction motor:

- Alternating current in the revolving stator field induces an EMF in the rotor bars.

- The high resistance in the rotor prevents the rapid building of the rotor's magnetic field.

- The inability of the rotor to rapidly build a magnetic field fails to allow the rotor to increase in speed rapidly.

- Because the rotor does not increase in speed rapidly, there is a greater relative motion between the revolving stator field and the slow-moving rotor.

- The greater relative motion, from a slow-moving rotor, increases the EMF into the rotor bars.

- The increased rotor EMF generates an increased current flow in the short-circuited rotor bars.

- The increased current increases the rotor's magnetic field.

- The increased magnetic field increases the magnetic attraction of the rotor to the stator's revolving field.

- The rotor develops a greater torque to operate heavier loads.

However, extra torque does not come without some complications. Increased torque means an increased current demand on the distribution system. There is also an increase in slip at full load. Higher resistance rotors are not acceptable for all applications. This is the reason for the many rotor designs.

The rotor resistances are identified by the National Electrical Manufacturers Association (NEMA) and designated by design.

MOTOR CHARACTERISTICS

The resistance of the stator windings is very low. The less resistance a component has, the greater the current from the generator. Motor current requirements can be, among others, attributed simply to size. The larger the stator winding diameter is, the larger the motor itself is constructed. A motor, with its low resistance stator windings, initially reacts as a short circuit. It is not until the expanding and contracting magnetic fields cut the many turns of wire adjacent to each conductor in the stator winding that the current is further reduced. This momentary inrush of current, combined with the transformer-like action, described in Short-Circuit Rotor Bars, accounts for the overall current needed for a motor.

When the vessel is initially started, a ship's electrical distribution system may have only lights in operation. There is very little current registering on the switchboard ammeters. This is because the resistance in the light bulbs is so high. The high resistance keeps current down.

As soon as a motor is connected to the line, the current draw becomes excessive. The ammeter will register more than six times the normal operating current of the motor. This is what happens: The motor's internal wiring is of negligible resistance. Since all electrical components are connected in parallel in the distribution system, the parallel circuit rules apply. Resistance in a parallel circuit is always less than the smallest resistor. (This is why the largest idle motor is of considerable concern when designing a ship's distribution system.) The motor wire resistance is now the only determining factor for the generator's current output. The current immediately supplied by the generator is called inrush current. If the rotor is mechanically prevented from moving, the current is then called locked rotor current.

Westinghouse developed a program to investigate motor circuit protection. A power source and cabling system was designed to handle LRC levels far in excess of that normally found on Army watercraft. The objectives of the test was to determine how much the fault current would exceed the normal full-load current if a rotor was mechanically prevented from rotating. Results show that lock rotor current progresses in steps. Approximately 44 cycles after the initial LRC, LRC almost doubled in value. This double LRC was maintained for an additional 42 cycles until the LRC increased again. This time the LRC was stepped up to three times initial LRC. The LRC continued to increase in steps of similar values with fewer cycles between steps. Test results hold little consolation in the knowledge that at no time did the fault current exceed 50 times the FLC. The test established that motor failures start at relatively low values (6 x FLC) and cascade quickly in mere seconds. A current draw of the observed magnitude would devastate the current-producing capacity of the generating system and effectively terminate the operation of the distribution system if not interrupted rapidly. Remember, all improperly protected circuits are fire hazards!

The induction motor poses many problems for the electrical system environment. The motor's great current draw can tax the electrical system to the extent that the generated voltage will drop. (There is internal resistance in the generator, too. The greater the current through the generator's conductors, the greater the voltage dropped in the entire electrical system, E = IR). When this generated voltage drops below a certain point, relays, contractors, and other electrical holding coils become de-energized, and their associated equipment stops operating.

A complete understanding of motor operating characteristics is necessary to understand the effects of the motor on the electrical system and the requirements for protecting a motor against overload conditions. The two most prominent effects from the motor are --

- Inductive reactance.
- High rotor EMF.

Inductive Reactance

The discussion on transformers explained the properties of induction on a coil of wire. Except for the minimal resistance of the wire itself, there appears to be nothing to prevent a power source from restricting the majority of its current. As it turns out, induction opposes a change in current. A back voltage or counter EMF (CEMF) is developed and pushes back on the power supply. In the DC system, the CEMF restricts current flow. In AC, the CEMF impedes current flow change. The AC system with its various amplitudes and current directions creates a generator out of any inductor. This shuttle power is inductor-generated and must be overcome by the generator. When the inductive reactance (shuttle power), the motor's load, and assorted losses are overcome, the generator supplies only enough additional current to keep the motor rotor turning. The only problem exists with the inductive reactance. This generated CEMF and its resulting current are there to be overcome. Inductive reactance, therefore, is not consumed.

Whenever inductance is involved in the electrical system, a lagging power factor results. The power factor is extremely poor when the motor is first started. The lower the power factor, the greater the increase in current needed to operate the motor. A power factor of .5 can be expected when a motor is first started. At the motor's rated speed, a power factor of .8 is normal. Unity or 1.0 is the best use of power. Not only does the generator have to supply current for overcoming the wire resistance, but it must overcome the inductive reactance from the motor itself.

Never select a motor that is overrated for its application. Contrary to popular belief, when a motor is not operated at its rated capacity, the electrical system efficiency is decreased. The power factor is decreased, goes further away from unity, and more power is required to operate the motor than would have normally been required for a motor operating at the designated rated capacity.

Never operate a motor above its rated capacity. It will not operate long. Motors and generators can easily operate at many times their normal current ratings for a short period of time. Even so, excess heat is generated. If this heat is not permitted to dissipate rapidly, insulation damage will result.

High Rotor EMF

Inductive reactance is always an important consideration when choosing motors for the electrical system. But the induction motor has another characteristic that influences the electrical environment even more. This is called the rotor EMF.

The motor acts much like a transformer. The stator winding becomes the primary winding, and the rotor becomes the secondary winding. If the secondary winding of a transformer becomes shorted out, the primary winding effectively becomes the generating source. The primary winding, an extension of the generator, provides as much current as possible according to the Maximum Power Transfer Theorem.

At the instant when the rotor has not yet begun to move and current is applied to the stator, there is a maximum slip. There is maximum relative motion between the stator and the rotor and a maximum induced voltage into the low-resistance rotor bars. These rotor bars act like a short circuit drawing very large currents from the source because there is negligible resistance to restrict the current flow.

The stator windings have extremely large currents because of the large induced rotor EMF. Both the rotor and the stator develop maximum magnetic fields from maximum current flows.

The rotor's magnetic field, from induction, is of the opposite polarity of the stator's magnetic field. The rotor starts to move. As the rotor speed increases, the relative motion between the two windings decreases. The decreasing relative motion decreases the EMF and the resulting current flow in the rotor bars. The power source demand decreases as does the current flow to the stator.

This phenomenon is readily observable by using an induction ammeter and an AC motor. Simply place the jaws of the ammeter around one insulated conduct or (not all). Start the motor and observe the meter readings. The current will start very high and then taper off quite rapidly as the motor increases in speed.

Load Changes

Counter electromotive force developed in the stator windings could restrict current flow to moderation, except for the overwhelming EMF induced in the rotor. Many other factors affect the operation of the motor, such as impedance, changes in torque, and the angle in degrees separating the stator and rotor magnetic fields. The table below is a simple reference to the factors affecting a motor and the electrical environment under three motor operations.

	STARTING UP	OPERATING SPEED	UNDER LOAD
Motor RPM	0	highest	dropping
CEMF	0	highest	dropping
Power factor	lowest	highest	droppong
Rotor EMF	highest	lowest	increasing
Current I	highest	lowest	increasing
Torque	highest	lowest	increasing

The following is a brief outline on the motor-operating characteristics under several conditions:

- When the motor is operating at no-load conditions, the rotor speed gets very close to synchronous speed. Very little EMF is induced in the rotor bars, just enough to overcome mechanical losses. Current draw is low.

- As the motor becomes increasingly more loaded, the slip increases, and relative motion increases. Induced rotor EMF increases and with it a resulting increase in current flow in both the rotorand stator windings. The increased magnetic fields increase torque and the ability of the motor to return to its proper speed. Current automatically increases as the rotor slows down.

- During an overload condition, the rotor is slowed excessively. The EMF induced in the rotor and its subsequent current flow in both the rotor and stator can burn up the insulation windings and destroy the motor. Current becomes destructive.

MOTOR PROTECTION

Motor requirements for current vary widely with the load. In addition, the current actually exceeds the normal operating range when the motor is first started. How then can the motor be protected against the excessive currents outside the normal parameters of operation and still be protected from small prolonged current increases?

Fuse Protection

Fuses have several disadvantages in protecting the motor. If a fuse is used to protect the motor for its full-load current rating, then the fuse would open during the initial inrush of current. A fuse designed to pass inrush current would not protect the motor against currents less than the inrush but greater than the normal full-load current. For every 1C rise over normal ambient temperature ratings for insulation, it has been estimated that the life expectancy of a motor can be reduced almost a

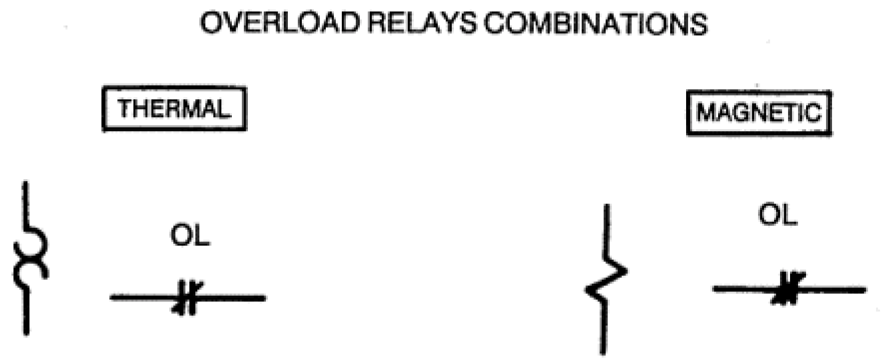
year. Current generates heat in a motor. Heat destroys the motor insulation.

Time-delay fuses have been used for motor protection in the past. However, another problem develops when using three fuses for the protection of the three-phase motor.

Should only one of the three fuses open when the motor was operating, the motor would not stop immediately. It would continue to operate. The operation of three-phase motors on only two lines constitutes a single-phase condition. The three-phase motor cannot operate single phasing for long without internal damage. This would not become apparent until enough damage was incurred that the motor would be irreparable. The fuse was not the answer for protecting three-phase motors.

Magnetic Motor Starters

The magnetic motor starter is a magnetic contactor with an overload protection device. Unlike the fuse, the magnetic motor starter does not have to be replaced. It can be reset repeatedly.



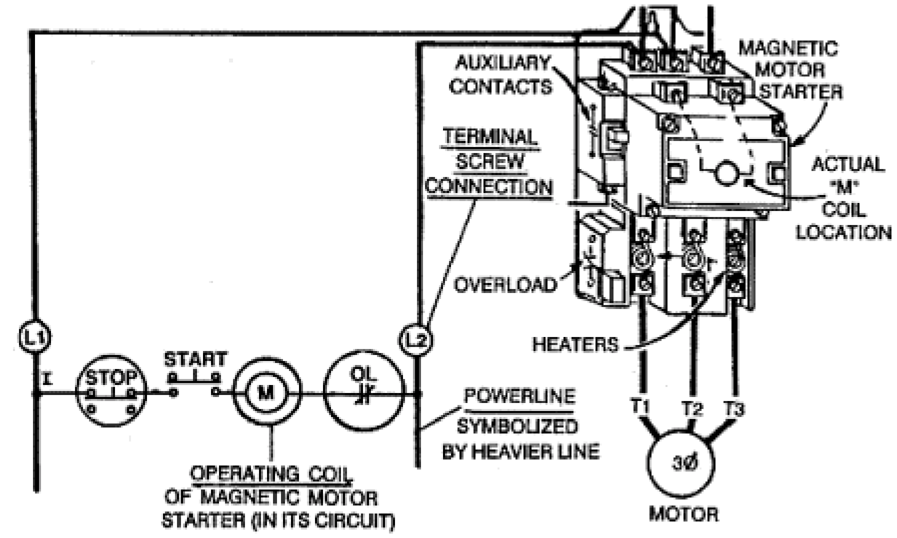
The Motor Circuits

Larger current-demanding motors use two circuits for operation. One circuit is the three-phase power circuit supplied from the distribution power panel. The other electrical circuit is the control circuit.

The figure shows the magnetic motor starter and the power circuit from the distribution power panel. The heavy, dark lines provide the three-phase, high current-carrying power to the motor.

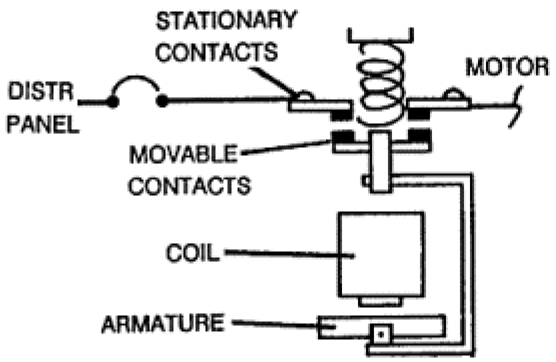
Inside the magnetic motor starter, directly under the coil, are three large main contact sets. These contacts are in series with the power panel A, B, and C phase terminals and the T1, T2, and T3 motor terminals. As long as these contacts are closed, current from the power distribution panel can operate the motor. This is one circuit.

The other circuit controls the three large contact sets explained above. The coil in Figure 16-9 actually moves the contacts. The figure shows the control circuit that the coil is actually in. M represents the coil in the figure.

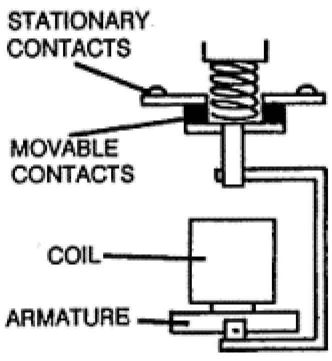


The M coil is supplied single-phase power from the magnetic motor starters A and B phase terminals (also known as L1 and L2 terminals). The figure above shows two M coils: one in its true physical position in the magnetic motor starter and the other in the line diagram to explain its function electrically. There is actually only one M coil. The same applies to the NC overload contacts.

When the START button is pressed, a complete circuit from A phase through the M coil, through the NC overload contacts, to the B phase is completed in the control circuit. The M coil energizes and moves a bar, known as an armature, that is in physical contact with the three large power contacts in the motor's three-phase power circuit. The figure below illustrates this action.



A



B

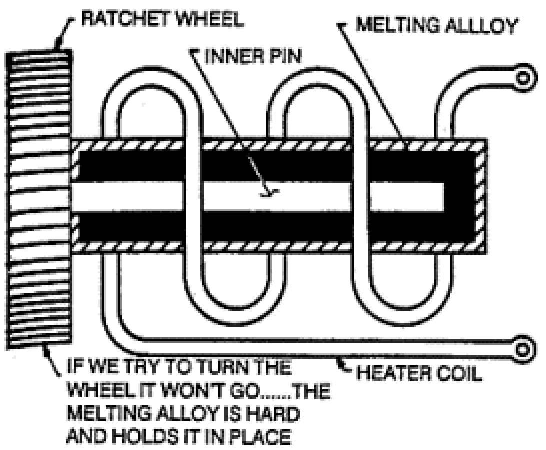
The main power circuit contacts for the motor are held open by spring tension (see Figure view A). When the coil becomes energized, the magnetic attraction between the armature and the magnet overcomes spring tension, and the main contacts for the motor close (Figure view B). The motor now operates.

When the current to the motor is too great, the overload heaters get hot. The heaters are in series with the motor terminals and the main contacts for the motor. The heaters directly control what happens to the NC overload contacts in the control circuit. When the heaters get hot enough, the overload contacts open, and the M coil de-energizes. The loss of the magnetic field allows spring pressure to open the three main contacts in series with the motor, and the motor stops operating. By de-energizing the one coil (M), all three sets of main contacts open. Detrimental single phasing is avoided.

A minor disadvantage of the thermal overload device is its need to cool off before being reset. The Figure shows a magnetic motor starter and the overload heater and NC overload contact section separately.

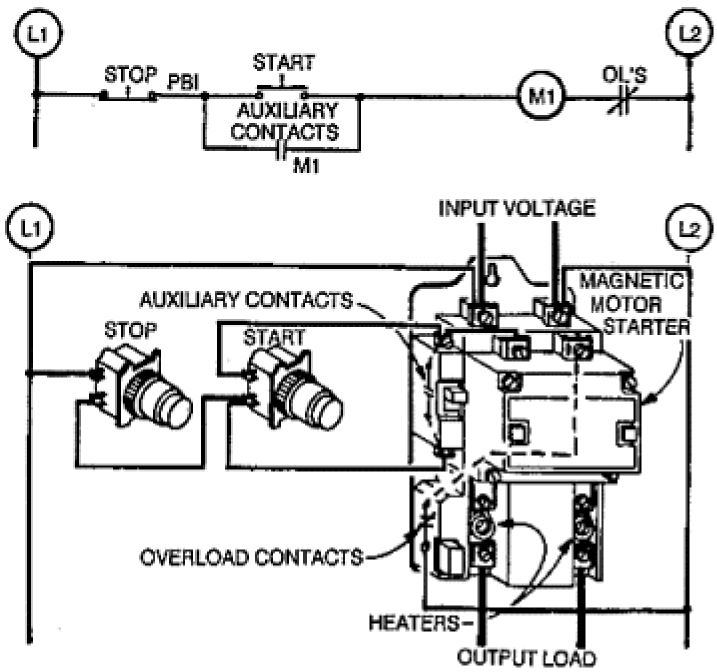
Thermal Heater and NC Overload Operation

The common thermal overload uses heater coils in the main power line in series with the main contractors and the motor stator windings. The current going to the motor must go through the overload heaters first. These heater coils surround a eutectic alloy solder pot. Eutectic means it has a very low melting point. Characteristically, a eutectic solder goes from solid to liquid and back again without developing a mushy condition.



The solidified solder holds a ratchet wheel and pin assembly firmly in place (Figure 16-14). The ratchet wheel is under tension and holds a set of contacts closed. These contacts have the ability to interrupt the magnetic coil circuit that opens and closes the main contacts. When the magnetic coil is de-energized, the main contacts open. The main contacts no longer supply power to the motor, and the motor stops.

The thermal overloads effectively monitor motor current by developing a comparative heat in the heater coils. The more current that flows though the heaters, the faster the heaters become hot. When the motor is first started, the heat from the momentary high inrush current is dissipated rapidly by the heater coils. The operation of the motor is not interrupted. If, however, the high current should last but another moment longer, the contacts would open, and the motor would stop. If a small overcurrent condition exists, the heaters will still get hot enough to melt the eutectic alloy, but it will take longer. Once enough heat is generated in the heaters and the eutectic alloy melts, the ratchet wheel and pin assembly move under spring pressure. As a result, the contacts in the control circuit of the magnetic motor starter open. This de-energizes the coil in the magnetic motor starter and opens the main contacts, disconnecting the motor from the line. Notice in the figure below that the overload contacts are not in the motor power supply line. They are in the control circuit that operates the main contactors. The main contractors and the overload heaters are in the motor's main three-phase supply line.



The protection afforded by the overload device is determined by the heater coil selection. By using different heater coils, a variety of overcurrent protection can be selected. This must be based on the full-load current rating of the motor. The temperature surrounding the motor and the magnetic motor starter must also be considered. Heat and current have the same destructive nature toward electrical equipment. Electrical components in engine compartments are exposed to greater heat than those in the ward room. Likewise, the controller, which houses the magnetic motor starter, must be in the same area as the motor it protects. Only in this manner will the heater be affected by the same ambient temperature as the motor windings.

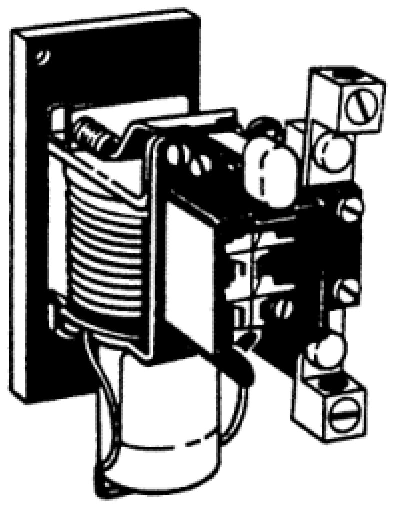
Proper motor protection is required in the motor control centers in the engine room. The MCC is air conditioned, and the motors in the engine compartment are not.

If adequate motor protection selection is not provided, additional investigation is necessary.

Every motor starter manufacturer has specific overload guidelines supplied with the equipment. Magnetic motor starters are provided with heater selection charts because magnetic motor starters do not come with overload heaters. Each heater must be identified for the specific motor application, full-load current, and ambient temperatures. The manufacturer guides are self-explanatory. Additional information is available in the Code of Federal Regulations, Title 46, Subpart 111.70, and the National Electrical Code (NEC), Article 430.

A less common protective device is the magnetic overload relay. This device uses a current coil that creates a magnetic field in

proportion to the current carried in it. Once the magnetic field is strong enough, the contacts are opened, and the circuit is de-energized. The main benefit to this type of overload device is its ability to be reset immediately.



THREE-PHASE ALTERNATING CURRENT MOTORS - Free Online Tutorial Part 3

MOTOR NAMEPLATE DATA

Motors are designed and developed for specific applications. Identifying their proper usage may be difficult. To ensure the correct component for the correct application, all government regulatory societies require a minimum of specific information to be printed on the motor's nameplate. Additional information may be obtained in IEEE Standard 45, Section 24, and (NEC) Article 430. This data includes:

- Manufacturer's name.

- Motor frequency. This may be represented as Hz for hertz or as CPS for cycles per second. This is always an indication of AC application.

- Phases (either three phase or single phase). This is also an indication of AC application.

- Voltage. The motor is designed to operate at this voltage or within a specified voltage range. Two voltages separated by a slash, such as 450/225, indicate a two-voltage system. Either voltage may be used by connecting the electrical stator leads as directed in the manufacturer's manual or on the data plate.

- Full-load current (FLC). This is the current required to operate the motor at its rated load and speed. This is not the current draw when the motor is started. If two current values are given, this indicates the current when supplied with one of the two possible voltage connections. When the higher voltage is used, less current is necessary to operate the motor.

- Full-load speed. This is the speed in revolutions per minute the rotor will turn under full load.

- C rise. This Celsius value plus the motor's rated ambient temperature add together to determine the maximum temperature range the motor can obtain under full-rated load (40C equals 104F).

- Time rating. This is the time the motor can operate continuously without stopping. Usually 5, 15, 30, or 60 minutes or continuous ratings are specified.

- Rated horsepower.

- Code letter. This indicates the highest current the motor will draw when the rotor is physically prevented from moving initially. The current is rated in kVA per horsepower. This is a measurement of locked rotor amperage. Table 16-3 lists code letters from the National Electrical Code.

- Design. This provides starting kVA, running kVA, and running KW characteristics. This is a product of the internal resistance of the rotor. Generally, designs B, C, and D are used:

-- Design A is of limited usage. This motor has extremely high starting kVA, as much as 50 percent higher than the B, C, or D design motors.

-- Design B is a standard rotor design. This type of rotor has a low internal resistance. It has normal starting torque, low starting current, and low slip at full load.

-- Design C has a higher internal rotor resistance. This improves the rotor power factor at the start, providing more starting torque. Fully loaded, the extra resistance creates a greater slip.

-- Design D has more resistance. The starting torque is maximum.

-- Serial number. The serial number or identification number is extremely useful when dealing with the manufacturer. The serial number and appropriate information is maintained on file with the company.

-- Type. This is the manufacturer's specific application information. This will also identify the housing characteristics (waterproof, drip-proof, and so forth).

--Service factor. This is an allowable overload above the full-load current. It is expressed as a decimal. Multiplying the full-load current by the service factor establishes the maximum allowable current acceptable above full-load current for a short period of time.

-- Frame. Many of the dimensions found on a blueprint are incorporated in the frame identification. Some of these specifications may include the rotor shaft length, diameter, and machining the motor housing and bolting placements; and so forth.

CODE LETTERS	STARTING kVA/HP	COMMONLY USED ON:
A	0 - 3.14	
B	3.15 - 3.54	
C	3.55 - 3.99	
D	4.0 - 4.49	
E	4.5 - 4.99	
F	5.0 - 5.59	15 HP and up
G	5.6 - 6.29	10 HP
H	6.3 - 7.09	7.5 and 5.0 HP
J	7.1 - 7.99	3 HP
K	8.0 - 8.99	2.0 and 1.5 HP
L	9.0 - 9.99	1 HP
M	10.0 - 11.19	Less than 1 HP
N	11.2 - 12.49	
P	12.5 - 13.99	
R	14.0 - 15.99	
S	16.0 - 17.99	
T	18.0 - 19.99	
U	20.0 - 22.39	
V	22.4 and up	

When a motor is ordered, all the data plate information must accompany the supply document. There is no substitute for the correct electrical component. Universal equipment does not exist in a marine distribution system unless the specifications can be matched exactly.

The table below provides a sample of some three-phase mot or starting characteristics for design B, C, or D. Design A motors may have starting kVA values that are as much as 50 percent higher. Many 3,600

HP	RPM	Running KW	Running kVA	Starting kVA
1	3,600	1.05	1.3	13
	1,800	1.06	1.4	12
	1,200	1.02	1.5	12
2	3,600	1.9	2.2	19
	1,800	1.9	2.3	13
	1,200	2.0	2.7	18
3	3,600	2.9	3.2	25
	1,800	2.8	3.4	24
	1,200	2.8	3.7	24
7.5	3,600	6.7	7.5	48
	1,800	6.9	7.9	46
10	3,600	8.8	9.8	62
	1,800	8.8	10.1	60
15	1,800	13.0	14.7	84
	1,200	12.9	15.2	82
20	1,800	17.2	19.4	112
	900	17.4	21.6	110

RPM motors are design A.