Section 8:  
AC Motors, motor control and motor protection  
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Introduction

Electric motors are an important part of any electrical system. Because they convert electrical energy to mechanical energy, they are the interface between the electrical and mechanical systems of a facility. This creates unique challenges for control and protection which have, in turn, led to unique solutions.

This section gives background on various AC motor types, and the control and protection practices commonly used for these.

AC motor types

Motors generally consist of two basic assemblies: The stator, or stationary part, and the rotor, or rotating part. Motors have two sets of windings: armature windings, to which the power is applied, and field windings, which produce a magnetic field that interacts with the magnetic field from the armature windings to produce torque on the rotor. This torque causes the rotor to rotate. For most AC motors, the armature windings are located on the stator, and the field windings are located on the rotor (one exception is the field exciter for a brushless synchronous motor, as described below). For this reason, in most cases the armature windings are known synonymously as the stator windings.

AC motors in common use today may be divided into two broad categories: Induction (asynchronous) or synchronous. These two types of motors differ in how the rotor field excitation is supplied. For induction motors, there is no externally-applied rotor excitation, and current is instead induced into the rotor windings due to the rotating stator magnetic field. For synchronous motors, a field excitation is applied to the rotor windings. This difference in field excitation leads to differences in motor characteristics, which leads in turn to different protection and control requirements for each motor type.

A.) Induction motors

Induction motors are the “workhorses” of modern industry. Because they have no applied field excitation, the rotor windings can be made to be very simple and rugged. The most common motor type is the squirrel-cage motor, which has rotor windings consisting of copper or cast-aluminum bars solidly connected to conducting end rings on each end, forming a structure which resembles a squirrel cage [1]. Due to the simple rotor construction, the squirrel cage motor is rugged and durable, and is the most common type. Wound-rotor motors are also available, usually for special application where external resistance is applied to the rotor for speed control, as described later in this section.

An important concept in the application of induction motors is the fact that due to the lack of field excitation, the motor speed will vary with the torque of the load. Synchronous speed for a given motor is given by the equation:

\[ n_s = \frac{120f}{p} \]  

(8-1)

where

- \( n_s \) is the synchronous speed, in RPM
- \( f \) is the frequency in Hz
- \( p \) is the number of poles of the motor, which can be defined as 2 x the number of different magnetic field orientations around the stator per phase. The minimum number of poles is 2 and the number of poles is always even.

For an induction motor, the speed will always be less than synchronous speed by a factor known as the slip of the motor. The motor speed can be expressed as:
\[ n = (1 - s) \cdot n_s \]  \hspace{1cm} (8-2)

where

\[ n \] is the speed of the motor, in RPM
\[ s \] is the slip
\[ n_s \] is the synchronous speed of the motor per (8-1) above

Induction motors are classified by application with a design letter which gives an indication of key performance characteristics of the motor. Table 8-1 gives typical design letter characteristics for induction motors. These are typical characteristics only – for further details consult the specific performance standards for the complete requirements [2,3].

### B.) Synchronous motors

Synchronous motors have a DC field excitation applied to the field windings on the rotor. This has the effect of allowing the motor to run at synchronous speed. However, the motor produces torque only at synchronous speed, so for starting the rotor is also equipped with damper windings that allow the motor to be started as an induction motor.

**Table 8-1: Typical characteristics and applications of fixed frequency medium AC squirrel cage motors (Essentially same as [2] table 10-1 and [3] table 3)**

<table>
<thead>
<tr>
<th>Polyphase Characteristics</th>
<th>Locked-rotor torque (percent rated load torque)</th>
<th>Pull-up torque (percent rated load torque)</th>
<th>Breakdown torque (percent rated load torque)</th>
<th>Locked-rotor current (percent rated load current)</th>
<th>Slip (%)</th>
<th>Typical Applications</th>
<th>Relative Efficiency</th>
</tr>
</thead>
<tbody>
<tr>
<td>Design A</td>
<td>Normal locked rotor torque and high locked-rotor current</td>
<td>70-275(^a)</td>
<td>65-190(^a)</td>
<td>175-300</td>
<td>Not Defined</td>
<td>0.5-5</td>
<td>Fans, blowers, centrifugal pumps and compressors, motor-generator sets, etc., where starting torque requirements are relatively low</td>
</tr>
<tr>
<td>Design B</td>
<td>Normal locked rotor torque and normal locked-rotor current</td>
<td>70-275(^a)</td>
<td>65-190(^a)</td>
<td>175-300a</td>
<td>600-800</td>
<td>0.5-5</td>
<td>Fans, blowers, centrifugal pumps and compressors, motor-generator sets, etc., where starting torque requirements are relatively low</td>
</tr>
<tr>
<td>Design C</td>
<td>High locked-rotor torque and normal locked-rotor current</td>
<td>200-285(^a)</td>
<td>140-195(^a)</td>
<td>190-225a</td>
<td>600-800</td>
<td>1-5</td>
<td>Conveyors, Crushers, stirring machines, agitators, reciprocating pumps and compressors, etc., where starting under load is required</td>
</tr>
<tr>
<td>Design D</td>
<td>High locked-rotor torque and high slip</td>
<td>275</td>
<td>Not Defined</td>
<td>275</td>
<td>600-800</td>
<td>≥5</td>
<td>High peak loads with or without flywheels such as punch presses, shears, elevators, extractors, winches, hoists, oil-well pumping and wire-drawing machines</td>
</tr>
<tr>
<td>IEC Design H</td>
<td>High locked rotor torque and high locked rotor current</td>
<td>200-285(^a)</td>
<td>140-195(^a)</td>
<td>190-225(^a)</td>
<td>800-1000</td>
<td>1-5</td>
<td>Conveyors, Crushers, stirring machines, agitators, reciprocating pumps and compressors, etc., where starting under load is required</td>
</tr>
<tr>
<td>IEC Design N</td>
<td>Normal locked-rotor torque and high locked rotor current</td>
<td>70-190(^a)</td>
<td>60-140(^a)</td>
<td>160-200(^a)</td>
<td>800-1000</td>
<td>0.5-3</td>
<td>Fans, blowers, centrifugal pumps and compressors, motor-generator sets, etc., where starting torque requirements are relatively low</td>
</tr>
</tbody>
</table>

\(^a\) Higher values are for motors having lower horsepower ratings
Synchronous motors may be further classified as brush or brushless type. The field exciter for a brush-type motor is typically a DC generator with its rotor mounted on the motor shaft. The output of the DC generator is fed via brushes and slip rings to the motor field windings. The field exciter for a brushless synchronous motor typically consists of an AC generator with the field windings on its stator, armature windings on its rotor, and with its rotor mounted on the motor shaft. The output of the generator is rectified by solid-state rectifier elements also mounted on the rotor shaft and fed directly to the motor field windings without the need for brushes or slip rings. Because of the proliferation of solid-state power electronic technology, and because the brushless-type motors require less maintenance almost all new synchronous motors are brushless-type [1], although many existing installations do have older brush-type motors in service. In either design the field excitation to the exciter may be varied to vary the power-factor operation of the motor, and in fact power factor correction is one common use of synchronous motors since they can be made to operate at leading power factors.

C.) Enclosure types, cooling methods and other general application information

Please refer to [3] for more information on motor enclosure types and cooling methods, as well as additional general application information for motors.

**Motor torque and driven load characteristics**

Motors are rated in **horsepower** (hp; 1hp = 746W) or, occasionally, in watts or kilowatts. In either case, this is the rated output power of the motor at the motor shaft when the motor is running at full speed. Due to losses in the motor, the input power will be higher. Due to the motor power factor and these losses, the full-load current of the motor will be larger than would be otherwise anticipated by looking only at the hp or kW rating. This will be discussed further later in this section.

At the motor shaft, the rated output power is related to the shaft rotational speed as follows:

$$P = \frac{T \cdot n}{5252} \quad (8-3)$$

where

- $P$ is the shaft output power in hp
- $T$ is the shaft output torque in ft-lbf
- $n$ is the motor speed in RPM

Further, the shaft rotational acceleration is related to the output torque and the inertia of the load as follows:

$$T = \frac{J \alpha}{18424} \quad (8-4)$$

where

- $T$ is the output accelerating torque in ft-lbf
- $J$ is the total moment of inertia of the motor shaft and rotor plus the driven load, in lb-ft$^2$ (also referred to as wk2), is the shaft acceleration in rpm/min.

Because $a = \frac{dn}{dt}$, the speed of the motor shaft can be written as:

$$n = \int_0^t \alpha \, dt = \int_0^t \frac{18434 \cdot T}{J} \, dt \quad (8-5)$$
The inertia of the load (and rotor), then, is crucial to the acceleration rate of the motor shaft (and the load) and thus to the output speed of the shaft. A typical design B induction motor torque-speed characteristic is as shown in figure 8-1, along with pertinent characteristics from table 8-1 labeled:

![Figure 8-1: Typical NEMA design B induction motor speed-torque characteristic](image)

Figure 8-1 shows the motor output torque as a function of shaft speed with full rated voltage applied to the motor. To show the performance of a motor when connected to a load, a typical speed-torque-characteristic for a fan is plotted along with the motor speed-torque characteristic in figure 8-2. The load speed-torque characteristic is a plot of the torque required to drive a load at a given speed. Several points can be made regarding the motor and load of figure 8-2:

- The motor locked-rotor torque is greater than the load torque at zero speed. This means the motor can start with the load connected.
- The motor pull-up torque is greater than the load torque during the acceleration period. This means that the motor can successfully accelerate the load.
- The steady-state speed of the motor is where the motor-torque and load-torque curves cross – the steady-state operating point – approximately 98.5% synchronous speed. The motor slip is therefore approximately 1.5%

The difference between the motor output torque and the load torque is the accelerating torque for the motor-load system. The accelerating torque is the same as given in eq. (8-1) above. A plot of the accelerating torque is given in figure 8-3.

![Figure 8-2: Example motor and load speed-torque characteristics](image)

![Figure 8-3: Accelerating torque for motor and load of figure 8-2](image)
With the accelerating torque known, the motor (and load) shaft speed can be calculated from eq. (8-4) and (8-5). In practice, this is best left to computer simulation. A typical plot of the approximate shaft speed, is shown in figure 8-4.

As can be seen from figure 8-4, for the example shown the motor accelerates to steady-state speed in approximately 14 seconds. The motor breakdown torque and load and motor moments of inertia (typically referred to as motor wk2 and load wk2, respectively) must be known to obtain this speed vs. time characteristic.

The importance of the above analysis lies in the fact that for successful motor starting the motor must be able to successfully support the load torque during acceleration. If the motor cannot do this, it will stall during starting. Proper motor selection, considering both the HP and torque characteristics, is essential for proper starting. Further, for an induction motor the slip is determined by the torque characteristics of the motor and load.

**Motor starting methods**

Several methods exist for starting motors. The most common methods are outlined here.

In addition, a discussion of motor-starting and control devices is given.

**A.) Motor starting devices**

The most common motor starting device is the low voltage motor-starting contactor. A contactor is defined in [4] as “a two-state ON-OFF device for repeatedly establishing and interrupting an electric power circuit.” Contactors are designed for optimum performance and lifetime when switching loads; they are not designed for interrupting short-circuit currents and therefore motor circuits require separate short-circuit protection. Because contactors are closed magnetically via their control coils, the use of contactors is typically referred to as magnetic control. For small motors, typically fractional-horsepower, manual control switches are also available. Motor starting contactors and switches in the United States are typically designed and manufactured per NEMA ICS-1 [4], NEMA ICS-2 [5], and UL 508.

A controller is defined by [6] as “a device or group of devices that serves to govern, in some pre-determined manner, the electric power delivered to the apparatus to which it is connected.” Motor starting contactors are available as integral units with externally-operable switching means, defined by [4] as a combination controller. A starter is defined by [4] as “a form of electric motor controller that includes the switching means necessary to start and stop a motor in combination with suitable overload protection.”; a combination starter, which includes the motor switching contactor as well as overload protection (described further below) and an integral disconnecting device, is a type of combination controller. Low Voltage manual and magnetic controllers are classified by [5] as Class A, B, or V according to their interrupting medium and their ability to interrupt currents:

**Class A:** Class A controllers are AC air-break, vacuum break, or oil-immersed manual or magnetic controllers for service on 600 V or less. They are capable of interrupting operating overloads but not short circuits or faults beyond operating overloads.
**Class B**: Class B controllers are DC air-break manual or magnetic controllers for service on 600 V or less. They are capable of interrupting operating overloads but not short circuits or faults beyond operating overloads.

**Class V**: Class V controllers are AC vacuum-break magnetic controllers for service on 1500 V or less, and capable of interrupting operating overloads but not short circuit or faults beyond operating overloads.

Low voltage NEMA-rated contactors are designated in sizes 00 (smallest) through 9 (largest) for various duty applications per [5]. Figure 8-5 shows a NEMA-rated low voltage contactor along with a manual motor starting switch, a starter, and a combination starter.

![Figure 8-5](image)

**Figure 8-5**:  
*a.*) Motor starting contactor,  
*b.*) Manual motor starter,  
*c.*) Motor starter with contactor and overload relay,  
*d.*) Combination starter with magnetic-only circuit breaker, contactor, thermal overload relay and pilot devices

Control of contactors using maintained-contact devices is referred to as **two-wire control**. Use of momentary-contact devices in the control of contactors is referred to as **three-wire control**. Three-wire control has the advantage of allowing the contactor to open and remain open if the line voltage should fail; this arrangement is typical to provide undervoltage protection for motors and prevent inadvertent re-energization after a power failure. Two-wire and three-wire control are shown in figure 8-6.

![Figure 8-6](image)

**Figure 8-6: Low voltage contactor control: (full-voltage non-reversing control shown):**  
*a.*) Contactor nomenclature,  
*b.*) Two-wire control,  
*c.*) Three wire control

Medium voltage contactors are typically use vacuum as the interrupting means. Unlike a circuit breaker, a medium voltage vacuum contactor is specifically designed for long life in load-interrupting duty rather than for short-circuit interrupting duty. However, unlike their low voltage counterparts a medium voltage contactor may be able to interrupt short-circuit currents beyond operating overloads.
Medium voltage air-break, vacuum, or oil-immersed controllers are classified by [7] as class E. Class E controllers are further divided into class E1 and E2 as follows:

**Class E1:** Class E1 controllers employ their contacts for both starting and stopping the motor and interrupting short circuits or faults exceeding operating overloads.

**Class E2:** Class E2 controllers employ their contacts for starting and stopping the motor and employ fuses for short circuits or faults exceeding operating overloads.

Above 7200 V, motor control is generally accomplished using circuit breakers.

**B.) Across-the-Line Starting**

The most common method for starting an induction motor is *across-the-line starting*, where the motor is started with full voltage applied to the stator windings. Across-the-line starting uses contactors to energize the motor at full line voltage. The motor acceleration will be as described above, and is dependent upon the line voltage, motor output torque, and load torque characteristics. Across the line-starting is also known as *full-voltage starting*.

Across-the-line starting at 600 V or less employs a single low voltage contactor, connected as shown in figure 8-7. Note that the short-circuit protection and disconnecting devices are not shown.

![Figure 8-7: Low voltage across-the-Line starting implementation](image)

Another form of across-the-line starting is full voltage reversing starting, in which the motor may be made to turn in either direction. This arrangement utilizes a *full voltage reversing contactor* with six poles, interlocked so that only one set of contacts may be closed at a given time. The contacts are connected so that in the reverse direction the motor has two phases swapped, forcing it to run in the opposite direction.

Across-the-line starting is the least expensive method, but it has the disadvantage that the full locked-rotor current will be drawn during starting. This can cause voltage sags. Also, since the motor acceleration is dependent only upon the motor output torque and load torque characteristics (along with the line voltage level), the acceleration is not as smooth as can be attained with other starting methods.

**C.) Reduced-voltage autotransformer starting**

Reduced-voltage autotransformer starting consists of initially starting the motor with an autotransformer, then removing the autotransformer from the circuit as the motor accelerates. This method results in a lower inrush current as the motor starts, but also results in less available output torque when the autotransformer is in the circuit. Autotransformer windings typically are tapped at 80, 65, and 50% voltage levels; the available output torque is related to the output torque when at full voltage by the equation:

\[
T_{RV} = T_{FV} \cdot \left(\frac{\text{%autotransformer tap}}{100}\right)^2
\]  

(8-6)

where

- \(T_{RV}\) is the motor output torque at reduced voltage when the autotransformer is in the circuit
- \(T_{FV}\) is the motor output torque with full voltage applied
Therefore, the motor output torque at the 80% autotransformer tap is 64% of the full-voltage torque value, at 65% tap the torque is 42.25% of the full-voltage torque, and at 50% tap the torque is 25% of the full-voltage value. Care must be taken to insure that the motor can be started at the tap value selected. Also, the thermal duty capabilities of the autotransformer per NEMA ICS-9 must be taken into account; these will generally limit the lowest tap to which the motor may be connected without damage to the autotransformer during starting.

A typical low voltage implementation of the reduced-voltage autotransformer starter is shown in figure 8-8.

![Figure 8-8: Low voltage implementation of a reduced-voltage autotransformer starter](image)

In figure 8-8 there are three contactors, labeled R, 1S, and 2S. The control scheme is designed so that the first contactor to close is 1S, connecting the two autotransformers in open-delta. Once contactor 1S is closed, contactor 2S closes, connecting the motor to the output of the autotransformer, in this case set to 50%. After a pre-set time delay or current transition level, contactor 1S opens, leaving the motor energized through the non-common autotransformer windings. Once contactor 1S is open, contactor R closes, energizing the motor at full voltage. This is a closed-transition scheme; open transition schemes exist also.

D.) Reduced-voltage reactor or resistor starting

Reduced-voltage reactor or resistor starting consists of adding a resistor or reactor in series with the motor at the beginning of the starting cycle, then shorting the resistor or reactor as the motor accelerates. This is generally a less expensive method than the reduced-voltage autotransformer method, but suffers the same limitations due to the reactor or resistor thermal limits.

E.) Wye-delta starting

Motors that have windings in which both ends of each stator windings are brought to terminals and are configurable in either wye or delta candidates for wye-delta starting. Wye-delta starting starts the motor in a wye configuration, which supplies 57.7% of the line-to-line voltage to each winding. During the starting process the motor is connected in delta, supplying 100% of the line-to-line voltage to each winding. Both normally-open and normally-closed transition schemes are available. This starting method typically uses three contactors.

F.) Part-winding starting

Motors which have stator windings in two parts with at least six terminal leads may be started with part-winding starting. Part-winding starting energizes part of the transformer windings, typically 1/2 or 2/3 of the entire winding per phase, to allow a lower inrush and smoother acceleration. This scheme typically uses two contactors and is a closed-transition scheme. Separate overload relays are provided for each part of each winding.
G.) Solid-state soft-starting

Solid-state soft-starting ramps the voltage at the motor terminals linearly, producing a smooth acceleration. Recent innovations include motor output torque-control models which linearly ramp the motor output torque, which can result in even smoother, almost linear, acceleration.

Central to the operation of a solid-state soft-starter is the silicon-controlled rectifier, or SCR (also known as a thyristor). An SCR is a device which conducts current in one direction when current is injected into its gate terminal, and blocks current in the other direction. The circuit symbology and nomenclature for an SCR, including the direction of current flows, is given in figure 8-10. In figure 8-10, if $i_g$ flows in the direction shown and $V_{ak}$ has the polarity shown, the SCR current $i$ will flow in the indicated direction. If the gate current becomes zero, the SCR will turn off; this is known as natural commutation. To stop the flow of current in the absence of a natural current zero, the SCR must be reversed-biased by applying $V_{ak}$ with a polarity the opposite to that shown in the figure. This is referred to as forced commutation. For AC circuits, SCR's are employed in back-to-back pairs. Reference [8] contains much background material on SCR operating theory and application.

A typical low voltage implementation of a solid-state soft-start controller is shown in figure 8-9. In figure 8-9 the in-line contactor IC closes first. The firing circuit then causes the SCR’s to vary the motor voltage as required by the starting parameters. Once the motor has accelerated to full speed, the shorting contactor SC closes, bypassing the SCR’s and connecting the motor directly to full voltage.

The soft-start controller can also decelerate the motor in the same manner using the SCR’s.

Because the SCR’s dissipate heat, the equipment heat dissipation and the ambient temperature are concerns when applying soft-start controllers and must be considered carefully.

Dedicated motor power factor correction capacitors must be switched out of the circuit during starting when adjustable-speed drives are employed, due to the harmonic voltage interactions that could cause them to fail. Surge capacitors should not be used at motors which are soft-started for the same reason.

Because soft-starters are microprocessor-based devices, they are typically supplied with communications and internal diagnostic capabilities, making them a truly cutting-edge motor starting (and stopping) solution.
H.) Rotor resistance starting
Applicable only to wound-rotor motors, this starting method employs an adjustable external resistance which is connected to the rotor via brushes and slip rings. The resistance in the rotor circuit dramatically alters the speed-torque characteristics of the motor during starting. The resistance in the rotor circuit is generally adjusted to be highest during starting and is gradually lowered throughout the starting process.

A variation on this method is the use of solid-state circuitry to switch the rotor current and vary the effective value of the external rotor circuit resistance.

These methods offer running speed control also. However they have been supplanted in recent years by adjustable-speed drives where speed control is required and by soft-starters where speed control is not required.

I.) Adjustable-speed drive starting
Adjustable-Speed Drives, discussed in more detail below, have the benefit of providing soft-starting for a motor, with starting advantages similar to the soft-starter described above. Unless speed control of the motor is required, the soft-starter is a more economical solution for starting. If speed control is required, however, an adjustable-speed drive is among the best solutions available.

Because an adjustable-speed drive is not bypassed after starting, unlike a soft-starter, the harmonic currents it causes to flow can affect the system power quality on a continuous basis. Also, power factor correction capacitors must not be used at the drive output to the motor.

J.) Medium voltage starting method implementations
All of the starting methods mentioned above are generally available at the medium voltage level. However, the disadvantages attributed to a given starting method are often exponentially more so when that method is applied at the medium voltage level.

Because medium voltage contactors generally employ vacuum technology, they are more expensive than low voltage contactors. They are also larger, and the vacuum interruption technology has a tendency to produce larger transients than air-break technology. This can create issues in such starting methods as the reduced-voltage autotransformer, which at the medium voltage level typically employs a three-phase autotransformer with three windings connected in open-wye rather than two in open-delta as shown for the low voltage implementation in figure 8-8. The voltage transients developed during starting force the use of surge arrestors to protect the autotransformer when the motor voltage is switched from reduced-voltage to full voltage.

K.) Which starting method to use?
The selection of a motor starting method will be dictated both by the requirements of the driven machinery and the requirements of the electrical system. Across-the-line starting will be sufficient in a great number of situations. However, in some cases one of the starting methods discussed above must be employed. Table 8-2 gives a list of the general advantages and disadvantages for each of the starting methods discussed above.

Motor speed control methods
It is often desirable to control the motor speed, usually for reasons process control for such variables as flow or pressure. Such applications as fans and pumps often have varying output requirements, and control of the motor speed is more efficient than mechanically limiting the process output with such devices as throttling valves or dampers. The reason for this is due to the fact that for centrifugally-based processes (such as fans and centrifugally-based pumps), the following relationships exist [1]:

\[ \text{Torque} \propto \text{RPM}^2 \quad (8-7) \]

\[ \text{Power} \propto \text{RPM}^3 \quad (8-8) \]
So, for these types of processes the torque required to turn them is proportional to the square of the speed. But, the power required to turn them is proportional to the cube of the speed, and this is what makes motor speed control economically attractive [3]. To further this argument, consider the energy wasted when mechanical means such as the throttling valves or dampers are used to control a process which is being driven from a motor running at full speed. It is clear that motor speed control can be used to save energy by reducing wasted energy used to mechanically control the process.

A.) Adjustable-speed drives

By far the most commonly-used AC motor control method is the use adjustable-speed drives. In most commercial and industrial environments these have supplanted virtually every other motor speed control method.

An adjustable-speed drive works on the principle of varying the frequency to vary the speed of the motor. Recall that from eq. (8-1) the synchronous speed of a motor is a function of both the system frequency and the number of poles of the motor. By varying the frequency, the motor speed may be varied so long as the motor is equipped to dissipate the heat at reduced speeds. Unlike soft-starting, specialized definite-purpose inverter-rated motor designs are preferred since reduced-speed operation can cause thermal issues and

**Table 8-2: Motor starting methods summary**

<table>
<thead>
<tr>
<th>Method</th>
<th>Advantages</th>
<th>Disadvantages</th>
</tr>
</thead>
<tbody>
<tr>
<td>Across-the-Line</td>
<td>Simple</td>
<td>High Current Inrush</td>
</tr>
<tr>
<td></td>
<td>Cost-Effective</td>
<td>High Starting Torque</td>
</tr>
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<td></td>
<td></td>
<td>Abrupt Start</td>
</tr>
<tr>
<td>Reduced-voltage</td>
<td>High output torque vs. starting current</td>
<td>Limited duty cycle</td>
</tr>
<tr>
<td>autotransformer</td>
<td>Some Flexibility in starting characteristics due adjustable taps on autotransformers</td>
<td>Large equipment size due to autotransformers</td>
</tr>
<tr>
<td>Reduced-Voltage</td>
<td>High output torque vs. starting current</td>
<td>Limited duty cycle</td>
</tr>
<tr>
<td>Resistor or Reactor</td>
<td></td>
<td>Limited flexibility in starting characteristics</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Higher inrush current than with reduced-voltage autotransformer</td>
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<tr>
<td></td>
<td></td>
<td>Large equipment size due to resistors/reactors</td>
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<tr>
<td>Wye-Delta</td>
<td>Relatively low inrush current</td>
<td>Relatively low output torque vs. starting current</td>
</tr>
<tr>
<td></td>
<td>Relatively simple starter construction</td>
<td>Limited flexibility in starting characteristics</td>
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<tr>
<td></td>
<td>Good for long acceleration times</td>
<td>Requires special motor construction</td>
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<tr>
<td>Part-Winding</td>
<td>Relatively Simple starter construction</td>
<td>Relatively low output torque vs. starting current</td>
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<tr>
<td></td>
<td></td>
<td>Not suitable for frequent starts</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Requires special motor construction</td>
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<tr>
<td>Solid-state soft starter</td>
<td>Smooth Acceleration</td>
<td>Relatively Expensive</td>
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<tr>
<td></td>
<td>Low inrush current</td>
<td>Sensitive to power quality</td>
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<td></td>
<td>High flexibility in starting characteristics</td>
<td>Heat dissipation and ambient temperature are a concern</td>
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<tr>
<td></td>
<td>Typically offers deceleration control also</td>
<td></td>
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<tr>
<td></td>
<td>Typically integrates with industrial automation</td>
<td></td>
</tr>
<tr>
<td></td>
<td>infrastructure</td>
<td></td>
</tr>
<tr>
<td>Rotor Resistance</td>
<td>Smooth acceleration available</td>
<td>Complicated controller design</td>
</tr>
<tr>
<td></td>
<td>Good flexibility in starting characteristics</td>
<td>Requires expensive wound-rotor motor construction</td>
</tr>
<tr>
<td></td>
<td>Can be used for speed control also</td>
<td></td>
</tr>
<tr>
<td>Adjustable Speed Drive</td>
<td>Smooth Acceleration</td>
<td>Cost-prohibitive unless speed control is required also</td>
</tr>
<tr>
<td></td>
<td>Low inrush current</td>
<td>Sensitive to power quality</td>
</tr>
<tr>
<td></td>
<td>High flexibility in starting characteristics</td>
<td>Heat dissipation and ambient temperature are a concern</td>
</tr>
<tr>
<td></td>
<td>Offers deceleration and speed control also</td>
<td>Continuous harmonic currents can create power quality issues</td>
</tr>
<tr>
<td></td>
<td>Typically integrates with industrial automation</td>
<td></td>
</tr>
<tr>
<td></td>
<td>infrastructure</td>
<td></td>
</tr>
</tbody>
</table>
overspeed operation can result in safety issues. Further, pulse-width modulated (PWM) drive outputs can cause repetitive voltage overshoots referred to as ringing, which can reduce the life expectancy of a general-purpose motor. As per [3], the motor manufacturer should be consulted before applying a general-purpose motor in an adjustable-speed drive application.

Various designs exist for adjustable-speed drives, however for low voltage drives the most prevalent is the voltage-source pulse-width modulated design. As its name implies, the output is pulse-width modulated to reduce the output harmonic and noise content. The AC input to the drive is typically a diode rectifier. A simplified circuit topology for a voltage-source PWM drive is given in figure 8-11.

![Figure 8-11: Voltage-source PWM adjustable-speed drive: simplified circuit topology for low voltage implementation](image)

The output stage for the circuit in figure 8-11 consists of Insulated-Gate Bipolar Transistors (IGBT’s), which are commonly used in low voltage PWM adjustable-speed drives instead of SCR’s due to their superior switching rate capability.

Adjustable speed drives offer superior speed control for motors through 10,000hp, depending upon the system voltage [1]. They usually incorporate protection for the motor as well, allowing the omission of separate motor protective relays if desired. Due to the high switching frequencies involved and their interaction with the cable capacitance, the length of the cable runs between the output of the drive and the motor are limited, and, as mentioned above for soft-starters, power factor correction capacitors and surge capacitors should not be used at the output of an adjustable speed drive. Also due to the high switching frequencies, common-mode noise on the grounding conductors can be an issue when these drives are employed.

On the incoming line, adjustable speed drives produce harmonics which must be taken into account in the over-all system design. This topic is addressed in a later section of this guide.

Adjustable speed drives, like soft-starters, are microprocessor-based devices. Therefore, they can interface with the automation infrastructure of a facility.

With the exception of a few isolated cases, for most industrial and commercial facilities adjustable speed drives are the speed control of choice for AC motors.

**B.) Older methods**

Various other methods exist for AC motor speed control. A few of these are:

- Rotor-resistance speed control – similar to rotor-resistance starting, this method consists of varying the effective resistance in the rotor of a wound-rotor induction motor to vary the speed. Variants of this method include rotor power recovery systems using a second machine or an auxiliary solid-state rectifier and converter.

- Multi-speed motor – This type of motor is typically a squirrel-cage motor which has up to four fixed speeds.

- Primary voltage adjustment using saturable reactors – This method is only applicable to NEMA Design D motors and offers a very narrow range of speed control.

Because of the limitations of these methods and the fact that they do not fit a wide range of motors, the adjustable speed drive is typically the solution of choice for most commercial and industrial facilities.
Motor stopping devices

Several methods for motor stopping exist. Which, if any, is to be used is dependent upon the application.

A.) Dynamic braking

On form of dynamic braking involves the disconnection of AC power an induction motor and connecting DC power to one stator phase. The kinetic energy of the motor and load is dissipated in the rotor circuit resistance.

An alternative method, which is frequently used in adjustable-speed drives, allows the motor to supply energy back to the drive, where it is dissipated via a braking resistor.

B.) Plugging

Plugging is the reversal of the phase sequence on an induction motor via switching two phase connections to the motor, which will cause the motor to come to a very rapid stop due to torque developed on the rotor in the opposite direction from the current running direction. A zero-speed switch should be used to prevent reversal of the motor.

C.) Mechanical braking

Unlike the methods mentioned above, mechanical brakes can hold a motor at standstill after power is removed. Various forms of mechanical braking, such as DC solenoid, AC solenoid, AC torque-motor, and AC thruster type, are available. These are typically spring-set and electrically released, allowing them to be fail-safe in the event of an electrical power failure.

D.) Adjustable speed drive and soft-start controller deceleration

For those applications not require fast deceleration times but a controlled deceleration is required, the speed ramping capabilities inherent in most adjustable speed drives and soft-start controllers may be used. For faster stopping with an adjustable-speed drive dynamic braking is required.

Motor protection

Motor protection involves protection of a motor from abnormal conditions. The most common abnormal condition is an overload, which can produce damaging heating effects in the motor. For this reason, overload relays are the primary means of motor protection. However, short-circuit protection is also required to minimize damage to the motor from an internal short-circuit. Other protective devices are also available, their use depending upon the size of the motor and the cost of protection vs. the cost of the motor.

A.) Nameplate values

While these are not the only values marked on a motor nameplate, the following are the nameplate values most important to motor protection:

**Rated Volts:** The rated voltage of the motor

**Rated Full Load current (FLA):** The rated full-load current of the motor when running at full output capacity.

**Time Rating:** 5, 15, or 30 minutes, or continuous.

**Rated Horsepower or KW:** This is the output rating of the motor, not the input rating

**Code Letter or Locked-Rotor Current (LRA):** The locked-rotor current is the current that will be drawn by the motor at zero speed. It is the initial current upon full-voltage energization of the motor. If given as a code letter, the code letter may be used to determine the locked-rotor kVA per hp of the motor from NEC Table 430.7(B) [6].

**Service Factor (SF):** This is the factor by which the rated hp or kW may be multiplied to determine the maximum continuous output of the motor without exceeding a defined temperature rise in the motor.
B.) Low voltage motor protection

Low voltage motor protection typically involves overload and short-circuit protection.

Overload protection is the protection from the thermal effects of overloads. As mentioned above, the motor input current is always larger than would normally be dictated by the output power due to losses and the motor power factor. NEC Article 430 [6] gives typical full-load currents where a machine's actual full-load current is not known. However, for overload protection purposes the motor nameplate full-load current rating must be used ([6] Article 430.32 (A) (1)). The NEC basic requirement for overload protection is 125% of the nameplate rating for motors with service factors of 1.15 or greater and with a marked temperature rise of 40 C or less, and 115% for all others. This NEC requirement takes into account the maximum long-time setting of the overload relay, but for low voltage motors fine-tuning of the relay selection should be made according to the motor manufacturer's recommendations.

Typically, overload relays for low voltage motors are classified as melting alloy, bimetallic, or solid-state. In general, melting alloy relays are hand-reset devices, whereas bimetallic relays can be self-resetting or hand-resetting. Bimetallic relays are available as temperature-compensated or non-compensated; non-compensated is an advantage when the relay and motor are in the same ambient temperature since the relay opening time changes with the temperature in a similar manner to the motor [2]. Temperature compensated relays are designed for operation where the motor is at a constant ambient temperature but the relay is at a varying ambient temperature. While melting-alloy and bimetallic overload relays must be selected to suit the motor, for a solid-state relay the same physical relay may be used for several different types of motors, with the settings adjusted on the relay to match the motor it is protecting. Some solid-state relay models also have the advantage of providing phase-loss protection.

Note that NEMA ICS 2-2000 classifies motor overload relays into three classes, Class 10, 20, and 30, depending upon the time delay to trip on locked-rotor current. NEMA Class 10 overload relays will trip in 10s at 6x the overload rating of the relay, Class 20 will trip in 20s at 6x the overload rating, and Class 30 will trip in 30s at 6x the overload rating.

Short-circuit protection generally involves fuses or magnetic-only circuit breakers (also known as motor circuit protectors). Short-circuit protection is constrained by NEC article 430-52 [6] gives limits for various types of motor/protective device combinations. In general, however, the lowest rating that does not cause nuisance tripping due to motor inrush will give the best protection.

In addition to protecting the motor, the short-circuit protection also protects the motor circuit conductors and the contactor. Note that the motor circuit conductors, per NEC Article 430.22 (A), must be sized to have an ampacity not less than the 125% of the motor full-load current as determined from the tables in Article 430, not from the full-load current marked nameplate rating. The purpose of this is avoid undersized cables should the motor be replaced in the future with a different make and model of the same hp rating, since the hp rating does not clearly define the full-load current of the motor. Unlike conventional branch circuits, overcurrent protective devices in motor branch circuits do not dictate the conductor sizes. For this reason, care must be taken to insure that the motor branch circuit short-circuit protection protects the motor conductors for short-circuits.

To show how the overload and short-circuit protective devices coordinate with the motor and motor cable damage curves, consider a 480 V, 300 hp squirrel-cage induction motor with a full-load current nameplate rating of 355 A. The NEC Table 430.250 [6] full-load current rating for sizing the motor branch-circuit conductors is 361A. From NEC table 310-16 [6], (1) 500kcmil cable per phase, with an ampacity of 380 A, is selected to supply the motor. A Class 10 melting-alloy overload relay, sized for the motor per the manufacturer's recommendations, is selected for overload protection. A magnetic-only circuit breaker, sized at 800 A, which is in accordance with the 80% of motor full-load current per NEC Table 430.52 [6], is used for short-circuit protection. The motor switching devices is a NEMA size 6 contactor. A one-line representation of this motor branch circuit is shown in figure 8-12.
The resulting time-current coordination is shown in figure 8-13. Note that in figure 8-13 the purple curve to the right of the overload relay curve is the motor thermal damage curve, obtained from the motor manufacturer. If this curve is not available the relay or motor manufacturer’s selection tables should be used for selection of the overload relay. The thermal overload relay protects the motor from overloads, while at the same time not opening the motor inrush current or full-load current, as denoted by the purple “MOTOR” current curve to its left. Note the high-current region (with current equal to the motor locked-rotor current) with an acceleration time of approximately 9 seconds; this curve is dependent upon the connected load and must also obtained from the motor manufacturer unless the motor acceleration time can be determined. In many cases the motor starting current curve will not be available; for most cases a Class 10 overload relay will clear the locked-rotor current, with Class 20 relays applied for higher service-factor motors such as NEMA design T-frame motors and Class 30 applied for high-inertial loads [2]. The magnetic-only circuit breaker protects the cable for short-circuits, as denoted by the red “CABLE” short-circuit characteristic to the right of the circuit breaker characteristic. Finally, while it is not shown on the curve the contactor can break up to 10 x its motor FLA rating, or 5400A, up to 10 times without servicing per [5] which is more than the maximum trip current of the circuit breaker; the contactor is therefore adequately protected. The motor and its branch circuit is, therefore, adequately protected.

For larger motors on solidly-grounded systems low voltage ground-fault protective devices may also be required to allow coordination with upstream ground-fault protective devices. The application of these falls under the same guidelines as given in “System protection” section (section 7 in this guide).
In addition to the overload protection described above, thermostats are commonly installed in three-phase industrial-service 460 V motors from 11 kW through 150 kW (14-200hp) [2]. These are bimetallic devices that operate at one fixed temperature and serve to de-energize the motor if the temperature setpoint is exceeded.

Low voltage motors are also occasionally provided with undervoltage relays, either to trip or prevent energization when an undervoltage condition exists.

C.) Medium voltage motor protection

The protection of medium voltage motors is typically more complex than for their low voltage counterparts. Multi-function microprocessor-based relays are typically used, which provide overload and overcurrent protection as well as a host of other protection features which protect the motor from other abnormal conditions. R-rated fuses are typically used for short-circuit protection.

Some of the additional protective elements utilized for medium voltage motors include:

- RTD’s – Resistance Temperature Detectors are typically made of platinum, nickel, or copper and exhibit an increasing resistance with increasing temperature. The RTD resistance is used to monitor the temperature at various points in the motor, typically in the stator windings. The temperature is used to provide precise overload protection for the motor. Per [2], RTD’s should be specified for all motors 370 kW (500 hp) and above.

- Negative-Sequence Overcurrent (Device 46) – This is used to protect against damaging negative-sequence currents, which can be caused by unbalanced voltages.

- Phase sequence (Device 47) – This is used to prevent the single-phasing of three-phase motors, which can cause thermal damage if not detected.

- Differential (Device 87) – This is used to provide sensitive, high-speed protection for motor internal faults. Typically only larger motors are provided with differential protection. In addition to traditional differential protection, motors can also be equipped with self-balancing differential protection in which only one CT is used for each phase, with both ends of each winding passing through that phases’ CT. Both are shown in figure 8-14. Note that both ends of each stator winding must be brought to terminals to utilize differential protection. Traditional differential protection may utilize either percentage differential (preferred) or high-impedance differential relays. Self-balancing differential protection typically utilizes a standard overcurrent relay element.

- Ground Fault Protection (Device 50G): Almost all medium voltage motors on solidly-grounded or low-resistance-grounded systems are provided with ground-fault protection. This is accomplished with a zero-sequence CT and is almost always instantaneous.

![Figure 8-14: Motor differential protection:](image)

a.) Traditional

b.) Self-balancing
Typical overload and short-circuit protection for a medium voltage motor may be illustrated by considering the following: A 750 hp, 4160 V motor is to be protected. The motor has a nameplate full-load current value of 96 A and a locked-rotor current of 576 A, and a service factor of 1.15. A microprocessor-based motor protection relay is to be utilized. The motor is to be provided with R-rated fuses for short-circuit protection. NEC Article 430.224 [6] states that for motors over 600V the conductors shall have an ampacity no less than that at which the motor overload protective device(s) are to trip. The pickup value for the overload protection is to be set equal to the service factor times the nameplate full-load current, which is 110.4 A; the cables are copper in underground conduit, therefore the cable size selected is #2AWG, with an ampacity of 145A per NEC table 310.77 [6]. The CT primary ratings for the motor protection relay are typically selected as no less than 1.5 times the motor full load current to avoid saturation (must be checked!) – in this case 200:5. To coordinate with the overload protection and protect the motor branch circuit cables and motor, a 6R fuse is chosen (note that per NEC Article 430.225 [6] the motor overcurrent protection must be coordinated to automatically interrupt overload and fault currents in the motor, but there is not specific constraint given for the short-circuit protection, unlike the requirements for motors under 600 V per above). The motor switching device is a vacuum contactor rated 5.5 kV with an interrupting rating of 5000A. A one-line representation of the motor branch circuit is shown in figure 8-15, excluding ground-fault protection.

![Figure 8-15: Example medium voltage motor circuit, excluding ground-fault protection](image)

The resulting time-current coordination for this circuit is shown in figure 8-16. Note that the purple “MV MOTOR” load current curve is to the left and below the green overload relay characteristic, therefore the motor inrush and full-load current does not trip the overload relay. Unlike the case for a low voltage motor, this is typically available from the manufacturer, who has analyzed the motor’s performance when connected to the driven load. Note also that the purple motor thermal damage curve is to the left and above the relay overload curve, indicating the motor is protected for overloads. The same applies for the red “MV CABLE” rated full-load current marker at the top of the plot. The motor thermal damage curve is obtained from the motor manufacturer; if the entire curve is not available, the motor hot safe-stall time provides one point on the curve. The red “MV CABLE” short-circuit damage curve is to the right and above the blue “MV FUSE” characteristic, therefore the cable is protected for short-circuits by the fuses. Finally, note that the fuse total clearing and overload relay curves cross at approximately 900 A; this is well above the inrush of 576 A, but well below the contactor rating of 5000 A. The fuse will therefore clear faults above the contactor’s 5000 A rating before the contactor opens.

**NEC requirements for motors**

The following are highlights from the NEC [6] requirements for motors. This is not intended to list all NEC requirements for motors, but to illustrate the major points that apply in the most common motor installations and affect the power system design. For the full text of the complete NEC requirements for motors, consult the NEC.

### A.) General

The NEC basic requirements for motors, motor circuits, and controllers are given in NEC Article 430 [6], and are supplemented by additional articles for specific motor-driven equipment. Article 430 is divided into 14 parts. The requirements which apply to each part of a motor circuit are illustrated in figure 8-17.
One of the main premises of Article 430 is the fact that the hp or kW rating of a motor is the output rating, as discussed above. The motor electrical input characteristics will vary based upon the motor design. The requirements in Article 430 are designed around this fact, as will be illustrated below.

Several definitions are given in Article 430 for terms unique or have meanings unique to that article:

**Adjustable Speed Drive:** A combination of the power converter, motor, and motor mounted auxiliary devices such as encoders, tachometers, thermal switches, and detectors, air blowers, heaters, and vibration sensors.
**Adjustable-Speed Drive System:** An interconnected combination of equipment that provides a means of adjusting the speed of a mechanical load coupled to a motor. A drive system typically consists of an adjustable speed drive and auxiliary electrical apparatus.

**Controller:** For purposes of Article 430, this is any switch or device that is normally used to start and stop the motor by making and breaking the motor circuit current.

**Motor Control Circuit:** The circuit of a control apparatus or system that carries the electric signals directing the performance of the controller but does not carry the main power current.

**System Isolation Equipment:** A redundantly monitored, remotely operated contactor-isolating system, packaged to provide the disconnection/isolation function, capable of verifiable operation from multiple remote locations by means of lockout switches, each having the capability of being padlocked in the “off” position.

**B.) Ampacity and motor rating determination (Article 430.6)**

NEC motor ampacity table values, rather than motor nameplate full-load current values, must be used to determine the motor ampacity for all purposes other than for overload protection, per Article 430.6. This does not apply to low-speed (less than 1200 RPM) motors, motors built for high torques, multispeed motors, equipment employing a shaded-pole or permanent-split capacitor type fan or blower motor and marked with the motor type, or listed factory-wired motor-operated appliances marked with both hp and full-load current. The NEC motor ampacity tables (Tables 430.248, 430.248, 430.29, and 430.250) are referenced in hp; for motors marked in amperes, the horsepower must be determined by finding the hp corresponding with the nameplate ampacity, using interpolation if necessary.

The motor nameplate full-load current rating must be used for determination of overload protection.

The basis of this requirement is the fact that the motor horsepower alone is not enough to define the input current requirements of the motor, yet it is possible that a replacement for a given motor would be selected based only upon horsepower.

**C.) Motor circuit conductors [Article 430 Part II]**

For a single motor used in a continuous duty application, Article 430.22 (A) dictates that the motor circuit conductors be rated not less than 125% of the motor’s full-load current rating per the motor ampacity tables.

For a multispeed motor, the requirement is that the branch circuit conductors on the line side of the controller must be based upon the highest of the full-load current ratings shown on the motor nameplate, with the branch-circuit conductors between the controller and the motor based upon the current rating of the winding(s) that the conductors energize. [430.22 (B)]

For a wye-start, delta-run connected motor, the selection of branch circuit conductors must be based upon the motor full-load current. The conductors between the controller and the motor must be based upon 58% of the motor full-load current. [430.22 (C)]

For a part-winding connected motor, the selection of branch-circuit conductors on the line side of the controller must be based upon the motor full-load current. The selection of conductors between the controller and the motor must be based upon 50% of the motor full-load current. [430.22 (D)]

For motors with other than continuous duty, the motor branch circuit conductors must have a rating not less than as shown in table 430.22 (E), which gives percentages of the nameplate full-load current rating for various classifications of service and motor duty ratings. [430.22(E)]

For continuous-duty motors with wound-rotor secondaries, conductors between the secondary (rotor) to the controller must have an ampacity no less than 125% of the full-load secondary current of the motor. For other than continuous duty motors, the percentages in table 430.22 (E) apply. If there is a resistor separate from the controller, Table 430.23 (C), which is based upon the resistor duty classification, contains percentages of full-load secondary current to which the conductors between the controller and the resistor must be compared. [Article 430.23].
Conductors that supply several motors or a motor(s) and other loads must have an ampacity not less than 125% of the full-load current rating of the largest motor in the group plus the sum of all the full-load currents of all other motors in the group, plus the ampacity required for other loads. Various exceptions apply, and the authority having jurisdiction may grant permission for a lower ampacity, provided the conductors have the ampacity for the maximum load determined in accordance with the sizes and number of motors supplied and the character of their loads and duties. [430.24, 430.25]

Where a motor installation includes a capacitor connected on the load side of the motor overload device, the effect of the capacitor must be disregarded in sizing the motor circuit conductor. [460.9, referenced in 430.27]

D.) Motor and branch-circuit overload protection (Part III)

Continuous-duty motors over 1hp must be protected against overload by means of a separate overload device that is responsive to motor current or a thermal protector integral with the motor that will protect from dangerous overheating and failure to start. Motors that are part of an approved assembly that does not subject the motor to overloads may be protected by an integral device that protects the motor against failure to start. Motors larger than 1500 hp must be protected by a protective device with imbedded temperature detectors that cause current to the motor to be interrupted when the motor attains a temperature rise greater than marked on the motor nameplate in an ambient temperature of 40˚C. [430.32]

The “separate overload device” per the above can be recognized to be an overload relay as discussed above. The “protective device having imbedded temperature detectors” typically refers to RTD’s and their associated relay(s).

If overload relays are used, for motors with a marked service factor of 1.15 or greater or a marked temperature rise of 40˚C or less may be set at a maximum of 125% of the motor nameplate full-load current rating. For all other motors the maximum overload relay setting is 115% of the motor nameplate full-load current rating. If these values do not allow the motor to start or carry the load, higher-size sensing elements or incremental settings may be permitted to be used so long as they do not exceed 140% of the motor nameplate full-load current rating for motors with a service factor of 1.15 or greater or a temperature rise of 40˚C or less, or 130% for all other motors. Part-winding motors must have overload protection for each winding, set to half of these values.[430.32(A), 430.32(C), 430.4]

Overload requirements for motors 1hp or less vary depending upon whether the motor is automatically started or non-automatically started. [430.32(B), 430.32 (D)]

Motors for intermittent and similar duty may be protected against overload by the branch-circuit and ground-fault protective device. [430.33]

Motor overload devices for non-automatically started motors may be shunted or cut out of the circuit during starting. With some exceptions, an automatically-started motor cannot have their overload devices shunted or cut out of the circuit. [430.35]

A motor controller may be permitted to serve as overload protection. [430.38]. This allows a separate relay which causes the motor contactor to be used, or the use of adjustable-speed drive built-in overload protection capabilities.

A motor overload device that can restart a motor manually after overload tripping shall cannot installed unless approved for use with the motor it protects, and must not be installed if it causes injury to persons [430.43]. This requirement is to insure that proper cooling time is given before a motor is automatically restarted.

If immediate automatic shutdown of a motor by a motor overload protective device(s) would introduce additional or increased hazard(s) to a person(s) and continued motor operation is necessary for a safe shutdown of equipment or process, the motor overload protection may be permitted to be connected to a supervised alarm rather than causing an immediate shutdown. [430.44]

Part-winding motors must have overload protection for each winding, set to half of that specified by 430.52. [430.4]

Where a motor installation includes a capacitor connected on the load side of the motor overload device, the rating or setting of the motor overload device must be based upon the improved power factor of the motor circuit. [460.9, referenced in FPN to 430.32].
E.) Motor branch circuit short-circuit and ground fault protection (Part IV.)

Motor branch circuit short-circuit and ground fault protective devices must comply with Table 430.52, which gives maximum ratings, in percentage of the motor full-load current, which can be used for various motor and protective device types. If the value for the protective device rating does not correspond with a standard size for a fuses, nonadjustable circuit breakers, thermal protective devices, or possible settings of adjustable circuit breakers, the next higher standard size is permitted. If the value for the protective device rating is no sufficient for the starting current of the motor, various exceptions apply depending upon the protective device type. [430.52 (C) (1)].

Where maximum branch-circuit short-circuit and ground-fault protective device ratings are shown in the manufacturer’s overload relay table for use with a motor controller or are otherwise marked on equipment, they must not be exceeded even if otherwise permitted by Table 430.52. [Table 430.52 (C) (2)]

Instantaneous-trip circuit breakers may only be used if adjustable and if part of a listed combination motor controller having coordinated motor overload and short-circuit and ground-fault protection in each conductor. Exceptions apply. [Table 430.52 (C) (3)]

For a multi-speed motor, a single short-circuit and ground-fault protective device is permitted for two or more windings, so long as the rating of the protective device does not exceed the percentage per Table 430.52 of the smallest winding protected. Exceptions apply. [430.52 (C) (4)]

So long as the replacement fuse size is marked adjacent to the fuses, suitable fuses are permitted in lieu of the devices listed in Table 430.52 for power electronic devices in a solid state motor control system. [430.52 (C) (5)]

A listed self-protected combination controller is permitted in lieu of the devices specified in Table 430.52 so long as the adjustable instantaneous trip settings do not exceed 1300% of full-load motor current for other than Design B energy-efficient motors and 1700% of full-load current for Design B energy-efficient motors. The same applies for a motor short-circuit protector, so long as it is part of a listed motor controller having coordinate motor overload protection and short-circuit and ground-fault protection. [430.52 (C) (6), 430.52 (C) (7)]

Torque motors must be protected at the motor nameplate current rating in accordance with 240.4 (B). [430.52 (D)]

Two or more motors or one or more motors and other loads are permitted to be connected to the same branch circuit if:

- The motors are not over 1hp, the branch circuit is 120 V and protected at not over 20 A 600 V or less protected at not over 15 A, the full-load rating of each motor does not exceed 6 A, the rating of the branch-circuit short-circuit and ground-fault protective device marked on any of the controllers is not exceeded, and individual overload protection confirms to 430.32, OR,

- If the branch circuit short-circuit and ground-fault protective device is selected not to exceed the requirements of 430.52 for the smallest rated motor, each motor has individual overload protection, and it can be determined that the branch-circuit short-circuit and ground-fault protective device will not open under the most severe normal conditions of service that might be encountered, OR,

- The motors are part of a group installation complying with 430.52 (C) and (D). [430.53]

For multimotor and combination load equipment, the rating of the branch-circuit and ground-fault protective device must not exceed the rating marked on the equipment. [430.54]

Motor branch circuit and ground-fault protection may be combined into a single protective device where the rating or setting of the device provides the overload protection specified in 430.32. [430.55]

F.) Disconnecting means (Part IX.)

An individual disconnecting means must be provided for each controller. The disconnecting means must be in sight from the controller location unless the circuit is over 600 V, in which case a controller disconnecting means capable of being locked in the open position is permitted to be out of sight of the controller if it is marked with a warning label giving the location of the disconnecting means. A single disconnecting means is permitted for a
group of coordinated controllers that drive several parts of a single machine or piece of apparatus. In this case the
disconnecting means must be located in sight from the controllers, and both the disconnecting means and the
controllers must be located in sight from the machine or apparatus. [430.102]

A motor disconnecting means must be located in sight from the motor location and the driven machinery location
unless the controller disconnecting means is individually capable of being locked in the open position and either
a.) such a location of the disconnecting means is impracticable or introduces additional or increased hazards to
persons or property, or b.) the motor is in an industrial installation where conditions of maintenance and
supervision ensure that only qualified persons service the equipment. The controller disconnecting means per
above may be permitted to serve as the disconnecting means for the motor if it is located in sight from the motor
location and the driven machinery location. [430.102]

The disconnecting means must open all ungrounded supply conductors and must be designed so that no pole can
be operated independently. The disconnecting means is permitted to be in the same enclosure with the controller.
The disconnecting means must clearly indicate whether it is in the open (off) or closed (on) position. The
disconnecting means may be a listed motor circuit switch rated in horsepower, a listed molded case circuit
breaker, a listed molded case switch, or an instantaneous trip circuit breaker that is part of a listed combination
controller. Listed manual motor controllers additionally marked as “suitable as motor disconnect” are permitted as
disconnecting means where installed between the final motor branch-circuit short-circuit protective device and
the motor. [430.103, 430.104, 430.109 (A)]

System isolation equipment must be listed for disconnection purposes. Where system isolation equipment is used
it must be installed on the load side of the overcurrent protection and its disconnecting means. The disconnecting
means must be a listed motor-circuit switch rated in horsepower, a listed molded case circuit breaker, or a listed
molded-case switch. [430.109 (A) (7)]

Stationary motors of 1/8 hp or less may use the branch-circuit overcurrent device as the disconnecting means.
Stationary motors rated 2hp or less and 300V or less may use a general-purpose switch with an ampere rating not
less than twice the full-load current rating of the motor, a general-use AC snap switch for use only on AC, or a
listed manual motor controller with a hp rating not less than the motor hp and marked “suitable as motor
disconnect” as the motor disconnecting means. [430.109 (B), 430.109 (C)]

For stationary motors rated at more than 40hp up to and including 100hp, the disconnecting means is permitted to
be a general-use or isolating switch where plainly marked “do not operate under load.” [430.109(E)]

Cord-and-plug connected motors with a horsepower-rated attachment plug and receptacle having ratings no less
than the motor ratings may use the attachment plug and receptacle and the disconnecting means. Cord-and-plug
connected appliances per 422.32, room air conditioners per 440.63, or a portable motor rated 1/3 hp or less do
not require the hp-rated attachment plug and receptacle. [430.109 (F)]

The ampere rating of the disconnecting means must not be less than 115% of the full load current rating of the
motor, unless it is rated in hp and has a hp rating not less than the hp of the motor. For torque motors the
disconnecting means must have an ampere rating of at least 115% of the motor nameplate current. A method
for determining the required disconnect rating for combination loads is given in 430.110 (C). [430.110]

Each motor must be provided with its own disconnecting means, unless a number of motors drive several parts of
a single machine or piece of apparatus, a group of motors is under the protection one set of branch-circuit
protective devices as permitted by 430.53 (A), or where a group of motors is in a single room within sight from the
location of the disconnecting means. [430.112]

Where a motor or motor-operated equipment receive electrical energy from more than one source, each source
must be provided with a disconnecting means from each source of electrical energy immediately adjacent to the
equipment served. The disconnecting means for the main power supply to the motor is not required to be
immediately adjacent of the controller disconnecting means can be locked in the open position.

G.) Motor controllers and control circuits (Parts VI and VII)

Each controller must be capable of starting or stopping the motor it controls and must be capable of interrupting
the locked-rotor current of the motor. An autotransformer controller must provide an “off” position, a running
position, and at least one starting position, and designed so that it cannot rest in the starting position or in any
position that will render the overload device in the circuit inoperative. Motor starting rheostats must be designed so that the contact arm cannot be left on intermediate segments. [430.82]

Stationary motors of 1/8 hp or less which are normally left running and is constructed so that it cannot be damaged by overload or failure to start, the branch-circuit protective device is permitted to serve as the controller. Portable motors rated 1/3 hp or less may have an attachment plug and receptacle serve as the controller. [430.81]

Controllers, other than inverse time circuit breakers and molded case switches, must have horsepower ratings at the application voltage not lower than the horsepower rating of the motor. A branch circuit inverse time circuit breaker or molded case switch is permitted as a controller for all motors. For stationary motors 2hp or less and 300 V or less, a general-use switch having an ampere rating not less than twice the full-load current rating of the motor or an AC – only snap switch where the motor full-load current rating is not more than 80% of the ampere rating of the switch may serve as the controller. For torque motors, the controller must have a continuous-duty, full-load current rating not less than the nameplate current rating of the motor. [430.83]

A controller with a straight voltage rating, for example 240 V or 480 V, is permitted to be applied in a circuit in which the nominal voltage between any two conductors does not exceed the controller’s voltage rating. A controller with a slash rating, for example, 480 Y/277 V, may only be applied on a solidly-grounded circuit where the nominal voltage to ground from any conductor does not exceed the lower of the two values of the controller’s voltage rating and the nominal voltage between any two conductors does not exceed the higher value of the controller’s voltage rating. [430.83 (E)]

A controller need not open all conductors to the motor, unless it also serves as a disconnecting means [430.84]. The controller must only open enough conductors as is necessary to stop the motor.

A controller is permitted to disconnect the grounded conductor, so long as the controller is designed so that the pole which disconnects the grounded conductor cannot open without simultaneously opening all conductors of the circuit. [430.85]

Each motor must have its own individual controller, unless a number of motors drive several parts of a single machine or piece of apparatus, a group of motors is under the protection one overcurrent device as permitted by 430.53 (A), or where a group of motors is in a single room within sight from the location of the disconnecting means. An air-break switch, inverse time circuit breaker, or oil switch may be permitted to serve as the controller and disconnecting means if it complies with the requirements for controllers in 430.83, opens all ungrounded conductors to the motor, and is protected by an overcurrent device in each ungrounded conductor. An autotransformer type controller must be provided with a separate disconnecting means. Inverse-time circuit breakers and oil switches are permitted to be both hand and manually operable. [430.111]

Motor control circuits must be provided with overcurrent protection in accordance with 430.72. [430.72]

Motor control circuits must be arranged so that they will be disconnected from all sources of supply when the disconnecting means is in the open position. The disconnecting means may be two separate adjacent devices, one to disconnect the motor circuit, the other to disconnect the control circuit. Various exceptions apply to the requirement to the need for the two disconnecting means to be adjacent to each other. Control transformers in controller enclosures must be connected to the load side of the disconnecting means for the motor control circuit. [430.74]

Where damage to a motor control circuit would constitute a hazard, all conductors of such a remote motor control circuit that are outside the control device itself must be installed in a raceway or otherwise suitably protected from physical damage. Where one side of the motor control circuit is grounded, the motor control circuit must be arranged so that an accidental ground in the control circuit remote from the motor controller will not start the motor or bypass manually operated shutdown devices. [430.73]

H.) Adjustable-speed drive systems

Branch/feeder circuit conductors that supply power conversion equipment included as part of an adjustable-speed drive system must have an ampacity not less than 125% of the rated input to the power conversion equipment. For an adjustable speed drive system that utilizes a bypass device, the conductor ampacity must not be less than required by 430.6 (see above). [430.122]
Where the power conversion equipment is marked to indicate that motor overload protection is included, additional overload protection is not required. If a bypass circuit is utilized, motor overload protection as described in part III (see above) must be provided in the bypass circuit. For multiple-motor applications individual motor overload protection per part III is required. [430.124]

Adjustable speed drive systems must protect the motor against overtemperature conditions by means of a motor thermal protector per 430.32, an adjustable speed drive controller with load and speed-sensitive overload protection and thermal memory retention upon power loss, overtemperature protection relay utilizing thermal sensors embedded in the motor and meeting the requirements of 430.32 (A)(2) or (B)(2), or a thermal sensor embedded in the motor that is received and acted upon by an adjustable speed drive. Motors that utilize external forced-air or liquid cooling systems must be provided with protection that will be continuously enabled or enabled automatically if the cooling system fails. For multiple motor applications, individual motor overtemperature protection must be provided. The provisions of 430.43 and 430.44 apply to motor overtemperature protection means. [430.24]

The disconnecting means is permitted to be in the incoming line conversion equipment and must have a rating of not less than 115% of the rated input current of the conversion unit. [430.128]

I.) Motor control centers (Part VIII.)

Motor control centers must be provided with overcurrent protection with parts I, II, and IX of article 240. The ampere rating or setting of the overcurrent protective device must not exceed the rating of the common power bus. This overcurrent protection may be provided by an overcurrent protective device located ahead of the motor control center or a main overcurrent device located within the motor control center. [430.94]

J.) Motor feeder short-circuit and ground-fault protection (Part V.)

A feeder supplying a specific fixed motor load(s) and consisting of conductor sizes based upon 430.24 must be provided with a protective device having a rating or setting not greater than the largest rating or setting of the branch-circuit short-circuit and ground-fault protective device for any motor supplied by the feeder, plus the sum of the full-load currents of the other motors of the group. The largest rating or setting of the branch-circuit short-circuit and ground-fault protective device is based upon the maximum permitted size per Article 430.52. and Table 430.52. Where one or more instantaneous trip circuit breakers or motor short-circuit protectors are used for motor branch-circuit and ground fault protection as permitted in 430.52(C), each instantaneous trip circuit breaker or motor short-circuit protector must be assumed to have a rating not exceeding the maximum percentage of motor full-load current permitted by Table 430.52 for the type of feeder protective device employed. Where the feeder overcurrent protective device also provides overcurrent protection for a motor control center, the provisions of 430.94 apply. [430.62]

Where a feeder supplies a motor load and, in addition, a lighting or lighting and appliance load, the feeder protective device must have a rating sufficient to carry the lighting and appliance load, plus the rating permitted by 430.52 for a single motor, the rating permitted by 440.22 for a single hermitic refrigerant motor-compressor, or the rating permitted by 430.62 for two or more motors. [430.63]

K.) Over 600 V, nominal (Part XI.)

Certain requirements mentioned above are amended or added to above 600V, as follows:

Conductors supplying motors must have an ampacity not less than the current at which the motor overload protective device(s) is selected to trip [430.224]

Each motor circuit must include coordinated protection to automatically interrupt overload and fault currents in the motor, the motor circuit conductors, and the motor control apparatus. This may be a thermal protector integral to the motor or external current-sensing devices, or both. The secondary circuits of wound-rotor AC motors are considered to be protected against overcurrent by the motor overload protection means. Operation of the overload interrupting device must simultaneously disconnect all ungrounded conductors. Automatic reset of overload sensing devices is prohibited after trip unless resetting does not cause automatic restarting or there is no hazard to persons due to automatic restarting. Where a motor is vital to operation of the plant and the motor should
operate to failure if necessary to prevent a greater hazard to persons, the sensing device(s) are permitted to be connected to a supervised annunciator or alarm instead of interrupting the motor circuit [430.225]

Fault current protection must be provided by either a circuit breaker, arranged so that it can be serviced without hazard, or fuses. A circuit breaker must open each ungrounded conductor. Fuses must be placed in each ungrounded conductor and must be furnished with a disconnecting means (or be of the type that can serve as the disconnecting means) and arranged so that they cannot be serviced while energized. Automatic reclosing of the fault-current interrupting device is not permitted unless the circuit is exposed to transient faults and such automatic reclosing does not create a hazard to persons. Overload and fault-current protection may be provided by the same device. [430.225]

The ultimate trip current of overload relays or other motor-protective devices must not exceed 115% of the controller’s continuous current rating. Where the motor branch-circuit disconnecting means is separate from the controller, the disconnecting means current rating must not be less than the ultimate trip setting of the overcurrent relays in the circuit.

The controller disconnecting means must be capable of being locked in the open position.

L.) Other articles

Other NEC [6] articles which apply to motors and augment or amend the provisions in article 430 are given in table 430.5. Chief among these are Article 440, “Air-Conditioning and Refrigerating Equipment,” Article 610 “Cranes and Hoists,” Article 620 “Elevators, Dumbwaiters, Escalators, Moving Walks, Wheelchair Lifts and Stairway Chair Lifts” and Article 695 “Fire Pumps.”

References


[7] Industrial Control and Systems: Medium Voltage Controllers Rated 2001 to 7200V AC.