

IEEE Guide for AC Motor Protection

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Abstract: Generally accepted methods of protection for ac motors are provided. This guide identifies and summarizes the functions necessary for adequate protection of motors based on type, size, and application. This guide does not purport to detail the protective requirements of all motors in every situation.

Keywords: ac motor protection, adjustable-speed drive motor protection, induction motor protection, microprocessor-based motor protection, motor, rotating machinery protection, synchronous motor protection, wound rotor motor protection

The Institute of Electrical and Electronics Engineers, Inc.
3 Park Avenue, New York, NY 10016-5997, USA

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Introduction

(This introduction is not part of IEEE Std C37.96-2000, IEEE Guide for AC Motor Protection.)

The following changes have been made in this revision of the AC Motor Protection Guide:

- A glossary of component and terminology definitions has been added as Clause 3.
- Clause 6 has been modified to include more application guidance for the protection of adjustable-speed drives and motor systems.
- Clause 8 has been added to discuss the advantages, benefits, and issues regarding the application of the multifunction, microprocessor-based protection systems because of their widespread use on motor applications. These benefits are discussed in generic terms and are generally obtained when applying this type of protection system. The areas are thermal modeling capability, integration of functions into one package, control, data collection/reporting/remote communications, and certain application issues. Additionally, Clause 8 was added to provide more guidance for the application of multifunction, microprocessor-based protection systems.

Participants

At the time this guide was completed, the AC Motor Protection Guide Working Group had the following membership:

Jonathan D. Gardell, *Chair*
Munnu Bajpai, *Vice Chair*

A. N. Darlington
S. Easterday-McPadden
E. C. Fennell
S. Mazumdar
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R. V. Rebbapragada
D. W. Smaha

S. M. Usman
W. P. Waudby
K. J. Khunkhun
M. Yalla
S. E. Zocholl

The following members of the balloting committee voted on this standard:

Alexander P. Apostolov
John Appleyard
Michael P. Baldwin
E. A. Baumgartner
Farouk D. Baxter
Robert W. Beckwith
G. Benmouyal
John Boyle
B. Bozoki
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IEEE Guide for AC Motor Protection

1. Scope

This application guide presents generally accepted methods of protection for ac motors. It identifies and summarizes the functions necessary for adequate protection of motors based on type, size, and application. This guide does not purport to detail the protective requirements of all motors in every situation. What it does provide is enough information and guidance for the user to implement adequate protection for particular applications.

The recommendations in this guide are based on typical types of installations. However, sufficient background information relating to protection requirements, applications, and setting philosophy is provided to enable the reader to determine required protective functions for motor installation. The protective functions discussed in this guide can also be implemented with multifunction, microprocessor-based protection systems (digital systems). A complete discussion of this type of protection system's attributes is included in this guide.

Relay protection of squirrel-cage, wound-rotor induction motors, and synchronous motors is presented herein, with a review of the generally accepted forms of motor protection. This guide also summarizes the uses of relays and devices, individually and in combination, so the user may select the necessary equipment to obtain adequate motor protection.

This guide is concerned primarily with the protection of three-phase, integral horsepower motors and adjustable-speed motors where specifically indicated. Its recommendations are of a general nature, designed to cover typical motor installations. Sufficient background information on objectives, application, and setting philosophy is presented.

The following outline describes the order in which information is presented in this guide:

- a) Clause 2 lists applicable references.
- b) Clause 3 contains a glossary of terminology.
- c) Clause 4 gives a brief description of the design of induction and synchronous motors. It also discusses various types of switching and control devices used to interrupt low- and medium-voltage motors, and provides schematics that show how these devices are controlled and protected.
- d) Clause 5 gives a brief description of the damaging effect on a motor of abnormal voltage, current, temperature, and incorrect operating conditions or procedures. A clear understanding of the electrical and mechanical response of the motor to these abnormalities will greatly assist the user in evaluating the need for, and the means of obtaining, adequate motor protection in any situation.

- e) Clause 6 presents detailed recommendations for good engineering practice in a series of tables and diagrams. The tables and diagrams are classified according to type of switching, normal source voltage, and motor and circuit ratings; they show the combinations of devices normally applied for an associated protective function. See Table 7 for a complete listing of all device designations [both American National Standard Institute (ANSI) and National Electrical Manufacturer's Association (NEMA)] used in this guide. Also included in this clause is application guidance for protection of adjustable-speed drive applications.
- f) Clause 7 includes a discussion of the various factors that must be considered in determining the setting of each relay, protective function, or device. Whenever it is applicable, information is provided on the desirability of using a device to actuate an alarm or a trip.
- g) Clause 8 includes a discussion of the important aspects of multifunction, microprocessor-based motor protection systems. Five areas are covered that illustrate the enhancements in functionality and the additional features these types of protection systems provide.

2. References

This guide shall be used in conjunction with the following publications. When the following standards are superseded by an approved revision, the revision shall apply.

ANSI C37.06-1997, American National Standard for Switchgear—AC High-Voltage Circuit Breakers Rated on a Symmetrical Current Basis—Preferred Ratings and Related Capabilities.¹

ANSI C37.16-1997, American National Standard for Switchgear—Low-Voltage Power Circuit Breakers and AC Power Circuit Protectors—Preferred Ratings, Related Requirements and Application Recommendations.

ANSI C50.10-1987, General Requirements for Synchronous Machines (IEC 34-1-1969).

ANSI C50.41-1982, American National Standard for Polyphase Induction Motors for Power Generating Stations.

ANSI/NEMA ICS 1-Rev. 2 (1990), General Standards for Industrial Control and Systems.

ANSI/NEMA ICS 2-1988, Industrial Control Devices, Controllers, and Assemblies.

ANSI/NFPA 70-1999, National Electrical Code[®] (NEC[®]).

IEEE Std C37.010-1999, IEEE Application Guide for AC High-Voltage Circuit Breakers Rated on a Symmetrical Current Basis.²

IEEE Std C37.2-1996, IEEE Standard Electrical Power System Device Function Numbers and Contact Designations.

IEEE Std C37.13-1990 (Reaff 1995), IEEE Standard for Low-Voltage AC Power Circuit Breakers Used in Enclosures.

IEEE Std C37.90-1989 (Reaff 1994), IEEE Standard for Relays and Relay Systems Associated with Electric Power Apparatus.

¹ANSI publications are available from the Sales Department, American National Standards Institute, 11 West 42nd Street, 13th Floor, New York, NY 10036, USA (<http://www.ansi.org/>).

²IEEE publications are available from the Institute of Electrical and Electronics Engineers, 445 Hoes Lane, P.O. Box 1331, Piscataway, NJ 08855-1331, USA (<http://standards.ieee.org/>).

IEEE Std C37.100-1992, IEEE Standard Definitions for Power Switchgear.

IEEE Std C37.101-1993, IEEE Guide for Generator Ground Protection.

IEEE Std C37.102-1995, IEEE Guide for AC Generator Protection.

IEEE Std C62.2-1987 (Reaff 1994), IEEE Guide for the Application of Gapped Silicon-Carbide Surge Arresters for Alternating Current Systems.

IEEE Std C62.22-1997, IEEE Guide for the Application of Metal-Oxide Surge Arresters for Alternating-Current Systems.

IEEE C62.92.1-1987 (Reaff 1993), IEEE Guide for the Application of Neutral Grounding in Electrical Utility Systems, Part I—Introduction.

IEEE Std 242-1986 (Reaff 1991), IEEE Recommended Practice for Protection and Coordination of Industrial and Commercial Power Systems (IEEE Buff Book).

IEEE Std 522-1992 (Reaff 1998), IEEE Guide for Testing Turn-to-Turn Insulation on Form-Wound Stator Coils for Alternating-Current Rotating Electric Machines.

IEEE Std 620-1996, IEEE Guide for the Presentation of Thermal Limit Curves for Squirrel Cage Induction Machines.

NEMA AB1-1993, Standards for Molded Case Circuit Breakers.³

NEMA FU1-1986, Standards for Low-Voltage Cartridge Fuses.

NEMA MG1-1998, Motors and Generators.

NEMA MG10-1994, Energy Management Guide for Selection and Use of Polyphase Motors.

NEMA SG3-1995, Standards for Low-Voltage Power Circuit Breakers, Section SG3, 28-9.5, Application of Fused Circuit Breakers to Full-Voltage Motor Starting and Running Duty of Three-Phase, 60 Hz Motors.

3. AC motor terminology glossary

For purposes of this guide, the following terms and definitions apply. These terms and definitions are commonly used in the industry and found in both IEEE 100-1996 [B152]⁴ and NEMA MG-1-1998. IEEE 100-1996 should be referenced for terms not defined in this clause.

3.1 accelerating thermal limit (loci): The time-current relationship limit based on the allowable temperature limit of the rotor during the accelerating (starting) process.

3.2 accelerating time-current curve: The characteristic starting current vs. time curve representing the motor acceleration at a given applied voltage.

3.3 accelerating torque: The net torque between the motor capability torque and load torque during the starting process, which accelerates the motor and load to operating speed.

³NEMA publications are available from Global Engineering Documents, 15 Inverness Way East, Englewood, Colorado 80112, USA (<http://global.ihs.com/>).

⁴The numbers in brackets correspond to those of the bibliography in Annex B.

3.4 breakdown torque: The maximum torque that a motor will develop with rated voltage at rated frequency, where an abrupt drop in speed will not occur.

3.5 damper winding limited: A synchronous motor that is thermally limited by its damper winding.

3.6 field winding: The rotor circuit on an ac synchronous motor, which consists of winding connected to a dc source and produces the main electromagnetic field of the motor.

3.7 high-inertia load: A load that has a moment of inertia that exceeds normal values, as described in NEMA MG-1-1993, and for which the motor needs to be designed to have both thermal and mechanical capability to accelerate the load to operating speed without exceeding its limits.

3.8 load torque: The torque required by mechanically driven equipment across the operating speed range.

3.9 locked-rotor current: The steady-state motor current with the rotor locked, when supplied from a source at rated voltage and frequency.

3.10 locked-rotor impedance: The impedance at the motor terminals during the locked-rotor condition.

3.11 locked-rotor thermal limit (permissible locked-rotor time): The maximum permissible safe time vs. locked-rotor current flowing in the windings at rated voltage and frequency.

3.12 locked-rotor torque: The minimum torque that a motor will develop at rest, for all angular positions of the rotor, at rated voltage and frequency.

3.13 loss of synchronism (out of step): A condition that exists when the synchronous machine has lost synchronism with respect to the supply system.

3.14 motor torque capability: The torque capability of the motor, supplied with rated voltage and frequency across the operating speed range, during the starting and running processes.

3.15 pull-in torque: The maximum constant torque of a synchronous motor under which the motor will pull its connected inertia load into synchronism, at rated voltage and frequency, when its field excitation is applied.

3.16 pull-up torque: The minimum torque developed by the motor during the period of acceleration from rest to the speed at which breakdown torque occurs.

3.17 rotor: The rotating component of an ac motor that contains the field winding, which may be wound or of the squirrel-cage type. In the case of the synchronous motor, the field winding may be energized from a dc source.

3.18 rotor limited: A motor that is thermally limited by its rotor system.

3.19 running thermal capability: A plot of maximum permissible time vs. percent of rated current flowing in the motor winding when the motor is running.

3.20 service factor: A multiplier which, when applied to the rated horsepower, indicates a permissible horsepower loading that may be carried under the conditions specified for the service factor.

3.21 slip cycle: When a synchronous motor slips out of step (loss of synchronism) a complete 360° with respect to the supply source.

3.22 slip frequency: The frequency of a induction motor rotor's voltage and current when the rotor is rotating at some value of slip.

3.23 starting current: The current required by the motor during the starting process to accelerate the motor and load to operating speed. Maximum starting current at rated voltage is drawn at the time of energizing.

3.24 starting time: The time required to accelerate the load to operating speed.

3.25 starting torque: The rated motor torque capability during start at rated voltage and frequency.

3.26 stator: The stationary component of an ac motor that contains the armature winding and stator core.

3.27 stator-limited: A motor that is thermally limited by its stator system.

3.28 squirrel-cage winding: A rotor circuit that consists of conducting bars, connected with an end ring on each end, which constitute the rotor winding. Voltages are induced on this circuit which, in turn, produces current flow. Interaction between the stator and rotor fields creates the electromagnetic torque of the motor.

3.29 thermal limit curve (cold): A plot of maximum permissible time vs. percent of rated current flowing in the motor winding when the motor is started from ambient temperature.

3.30 thermal limit curve (hot): A plot of maximum permissible time vs. percent of rated current flowing in the motor winding when the motor is started from rated operating temperature.

3.31 wound rotor winding: The rotor circuit on a wound rotor induction motor, which consists of a polyphase winding that carries the alternating current produced by induction.

4. Equipment description

4.1 Induction motors

The stator winding (armature windings) of an induction motor is connected to the power line. The winding in the rotor slots is not connected to any power lines, but receives its current by means of induction. Energy is transferred to the rotor by means of the magnetic field. Depending on the type of power supply, the stator winding is either polyphase (usually three-phase) or single-phase. The rotor winding is designed as either a polyphase winding (wound rotor winding, usually three-phase) or a squirrel-cage winding. In the wound rotor induction motor, the conductors of the rotor winding are insulated and are brought out to slip rings, which are connected to a starting or control device. In the squirrel-cage induction motor, the conductors of the rotor are not insulated, but consist of bare conductors set into the slots. These conductors are connected together solidly by a conducting metallic ring at each end that is compatible with the conductor alloy.

4.2 Synchronous motors

Polyphase synchronous motors have stators and stator windings (armature windings) similar to those of induction motors. The rotor of the synchronous motor, however, differs considerably from that of the induction motor. The rotor has poles, usually salient, corresponding to the number of stator winding poles. The poles are wound with many turns of wire, and a direct current is circulated through the winding to create alternately north and south magnetic flux poles.

The dc excitation may be applied to the field windings through brush rigging and slip rings, or by means of a brushless excitation system consisting of an ac exciter, rectifier, and control equipment mounted on the rotating element.

To start a synchronous motor, it is normally necessary to have a number of bars embedded in the face of each pole, short-circuited at each end to form a squirrel cage (called amortisseur or damper winding) similar to that found in the induction motor. Furthermore, the field winding must be disconnected from the dc supply and shorted, usually by means of an appropriate starting and field-discharge resistor during starting (that is, the synchronous motor is normally started as an induction motor).

The differences between control and motor protection of the synchronous motor, as compared to the induction motor, are related to the rotor construction. Since dc excitation is required for synchronous operation, and synchronous operation is fundamental to the synchronous motor, protection against both loss of field and loss of synchronism should be provided. During starting, the control equipment generally is required to ensure, automatically and accurately, that the rotor speed has reached a proper value before the dc excitation is applied. The synchronous motor rotor thermal capability and its allowable stall time (permissible locked-rotor time) are generally much less than for an induction motor, and special protection for the damper winding must be provided.

However, since the synchronous motor's stator, bearings, and enclosure variations are essentially the same as those of the induction motor, protection schemes for these parts are basically the same.

4.3 Switching and control

All motors require the following functions to be incorporated into their control and switching equipment:

- a) Stator disconnection means
- b) Stator fault-interrupting devices
- c) Stator switching means

Various devices used for these functions are described in 4.3.1, 4.3.2, and 4.3.3. All three functions may be provided in a single device. In some applications, two or three devices may be required. In addition, a synchronous motor must have some means of field switching.

In this subclause, the general types of stator and field interrupting and control devices are described. These devices have been primarily specified with the protection of the motor in mind. In some cases, the question of interruption to production is a very vital consideration for the user, and protection of certain motors may be secondary. In this case, see 5.7.2.1.1 and 5.7.2.1.2.

4.3.1 AC line-interrupting control devices

Since the protective device generally provides only for the detection of an abnormality, it is necessary to consider the interrupting device in selecting the overall protection package. Although a detailed review of such devices is beyond the scope of this guide, a summary of their application and limitations is essential.

4.3.1.1 Low-voltage magnetic contactor with circuit breaker or fuses (up to 600 V)—motor control center (MCC)

These controllers consist of a magnetic contactor used for starting or stopping the motor. The controller is equipped with thermal overload (heaters) and loss-of-voltage protection. Loss-of-voltage protection is inherent with magnetic contactors when used with integral control power supply and three-wire control circuits. Loss-of-voltage protection in this context indicates that the supply power is interrupted and the disconnection is maintained. The voltage must fall sufficiently to permit the contactor to open and break the seal-in

circuit, and may not protect the motor against undervoltage operation. Short-circuit protection may be provided either by the magnetic trip of the circuit breaker or by fuses. The circuit breaker may also serve as the disconnecting means, whereas a separate disconnecting means is required in fused starters.

4.3.1.2 NEMA Class E1 high-voltage motor controllers (2200–4800 V)

Standards for these motor controllers are given in ANSI/NEMA ICS 2-1988, and the ratings are listed in Table 2-324-2 of that document. These controllers consist of a medium-voltage magnetic contactor used for starting and stopping the motor, with thermal overload and undervoltage protection similar to that listed for the low-voltage units. In addition, fault protection is provided by instantaneous overcurrent (IOC) relays to trip a circuit breaker. Other relaying is added as described in Clause 6. The circuit breaker may also serve as the disconnecting means.

4.3.1.3 NEMA Class E2 high-voltage motor controllers (2200–4800 V)

These motor controllers are similar to the Class E1 controllers described in 4.3.1.2, except that the short-circuit protective relays are omitted and fault-interrupting fuses are added. The fuses operate for fault-current magnitudes above the interrupting capability of the main contactor. Special care is required in applying instantaneous relaying so that the contactor does not attempt to interrupt current magnitudes above the contactor rating. In many cases, the contactor opening time is greater than the maximum clearing time for the fuse. However, when large motors (2000 hp and above) are supplied by fused contactors, fuse clearing times are increased, which may require delaying contactor opening.

4.3.2 Switchgear-type motor control

Power circuit breakers can be used for motor control of all stator-disconnecting, fault-interrupting, and switching functions. Standards are available that cover the application and limitations of ac power circuit breakers for these functions. For example, ANSI C37.16-1988 shows the application of low-voltage ac power circuit breakers for full-voltage motor starting and running duty of three-phase, 60 Hz, 40 °C rise motors; whereas ANSI C37.16-1988 covers the limitations related to repetitive duty and normal maintenance. ANSI C37.06-1987 shows the number of operations for various operating conditions that can be performed on medium-voltage circuit breakers before maintenance is required.

4.3.3 Field switching equipment

All synchronous motors are provided with some form of field application equipment to apply the dc source at the appropriate point (time or speed). The control of this power supply must be integrated with the stator control. For smaller motors, contactors are used to switch the power supply to the field. On larger ratings, field circuit breakers may be needed. Two methods are commonly used to apply the dc supply to brushless synchronous motor fields. In one method, an ac power supply is applied to a rotating transformer whose output is rectified and supplied to the field. The other method uses a dc supply to an ac exciter whose output is rectified and supplied to the field. The equipment that rectifies ac power to the dc field is contained on the rotating element.

4.4 Effect of ac and dc control equipment

Synchronous motors require both stator and field control circuits. The control circuit requirements for induction motors depend on the type; for example, a squirrel-cage induction motor requires only stator control, and the wound rotor type requires, additionally, a rotor circuit control. A variety of ac or dc control circuits are used for these purposes. Some examples of stator control schematics are shown in the simplified circuits of Figure 1, Figure 2, and Figure 3.

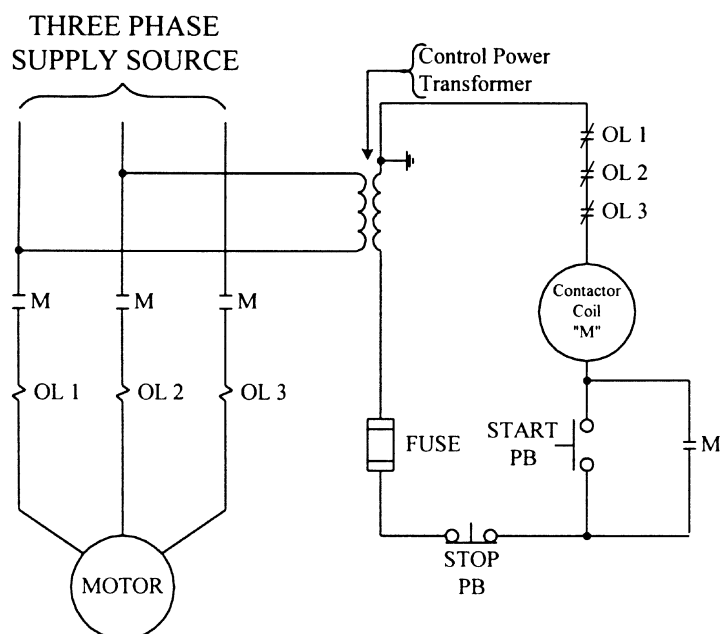


Figure 1—Three-wire control circuit with loss-of-voltage protection (field control not shown)

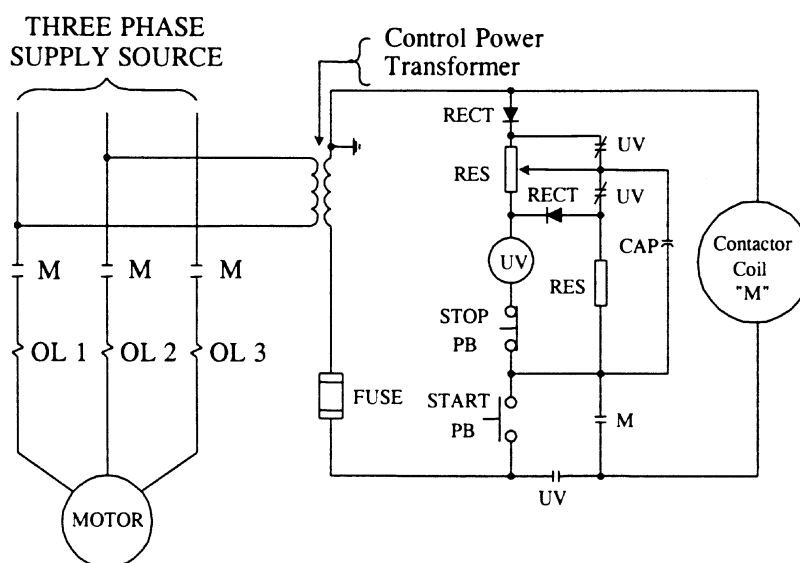


Figure 2—Three-wire control circuit with time-delay loss-of-voltage protection

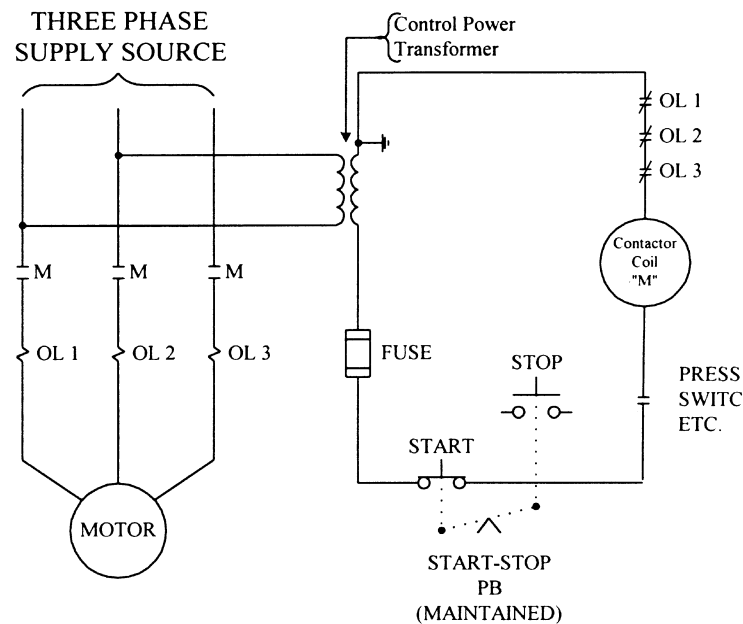


Figure 3—Two-wire control circuit with loss-of-voltage release

4.4.1 Stator control equipment

Protection from extremely low or complete loss of line voltage is an inherent feature of the nonlatched type of ac motor controllers. These devices are not designed to release at any specific level of voltage. A measure of protection against low line voltage is available because the contactors are maintained closed by potential taken directly from the motor line or from a control power transformer. The line contactors must be closed at 85% of rated line voltage, according to ANSI/NEMA ICS 2-1988, 110.41 (b), while the dropout point is not defined and may vary from 20% to 70% of rated voltage (typically 70%). The line contactor will drop open if a severe voltage dip or complete loss of line voltage should occur while a motor is running.

4.4.1.1 Three-wire control with loss-of-voltage protection

When the circuit shown in Figure 1 is used, the contactor (M) is maintained through an auxiliary contact in parallel with the start pushbutton. If the contactor should open due to low line voltage, the coil circuit is broken by the auxiliary control contact, and the motor cannot restart until the start pushbutton is operated. This type of protection is referred to as three-wire control with loss-of-voltage protection. During a condition of low line voltage, a synchronous motor acts as a source of reactive power for a short period of time and, therefore, tends to maintain its ac terminal voltage for a considerably longer period than an induction motor. Voltage-sensitive contactors cannot be relied upon in this instance, since the motor may generate sufficient voltage to prevent the contactor from dropping out. See 5.7.2.1.2 for information on the protection of the motor for this condition.

4.4.1.2 Three-wire control with time-delay loss-of-voltage protection

When it is desired to ensure that the motor will continue to operate during voltage dips or outages of short duration, a control circuit similar to that shown in Figure 2 can be used. This is referred to as three-wire control with time-delay loss-of-voltage protection; it consists of a time-delay undervoltage (UV) relay that maintains a sealing contact for a definite period after a voltage failure. It should be noted that the contactor (M) may drop out during the voltage dip, but will pick up again when the voltage is restored if the undervoltage time delay has not been exceeded.

4.4.1.3 Two-wire control

When the auxiliary control contact (M) of Figure 1 is omitted, and the start-stop pushbutton is replaced with a toggle or latched switch and a knife switch, pressure switch, or other type of maintained contact sensing device, the two-wire control of Figure 3 results. With this scheme, the line contactor opens on any low voltage below the dropout value to disconnect the motor. The motor automatically restarts when sufficient voltage is restored to close the line contactor. This arrangement is referred to as two-wire control with loss-of-voltage release. This two-wire control arrangement has the disadvantage that several motors on the same power system will attempt to restart simultaneously when voltage is restored. Such a strain on a system may depress the voltage to the point where the motors would never be able to accelerate to full speed (less than 80% to 90% of motor rated voltage). This is because the starting torque of a motor is proportional to square of the applied voltage to the motor terminals. In addition, unexpected automatic restarting after restoration of voltage may not be desirable. When the two-wire control is used, overload relays with automatic reset should not be applied. When the automatic reset overload relays are installed in this arrangement, an overload causes the motor to shut down, but the motor is restarted when the relays reset. The cycle could continue until the motor is damaged.

Synchronous motors would probably pull out of step if restored automatically; therefore, the scheme in Figure 3 is not recommended for them.

4.4.1.4 Circuit breaker control

When circuit breakers are used for motor control, no inherent tripping occurs for low (or zero) line voltage. These devices are latched and must be tripped by operating a specific device or contact.

4.4.2 Field-control equipment

Switching the field of a synchronous motor is complicated by the fact that the field may be any of the following:

- a) A brush-type field (i.e., one supplied power through slip rings on the shaft and associated brushes) that derives its direct current from
 - 1) A shaft-driven dc excite.
 - 2) A separate motor-generator set.
 - 3) A separate static rectifier.
- b) A brushless-type field that requires
 - 1) DC excitation for the field of a rotating ac exciter.
 - 2) AC excitation for the primary of a rotating transformer.

Generally, the field application circuit must

- 1) Provide a discharge path for the alternating current induced in the motor field during starting. This circuit may require opening of the field-discharge-resistor circuit when excitation is applied to the motor field.
- 2) Apply field at a suitable speed (95% to 99%) and (with some equipment) at a favorable position of the rotor poles with respect to the rotating flux.
- 3) Automatically remove field on impending pullout.
- 4) Automatically resynchronize upon restoration of favorable conditions, or provide shutdown, whichever is desired.

4.4.2.1 Brush-type (slip rings)

A typical low-voltage, brush-type synchronous motor control is shown in Figure 4. The details of operation vary with the particular equipment supplied by different manufacturers and with different motor applications. The general sequence of operation is as follows: closure of the start pushbutton energizes the line-contactor coil (M), connecting the motor stator to the ac line and sealing in around the pushbutton.

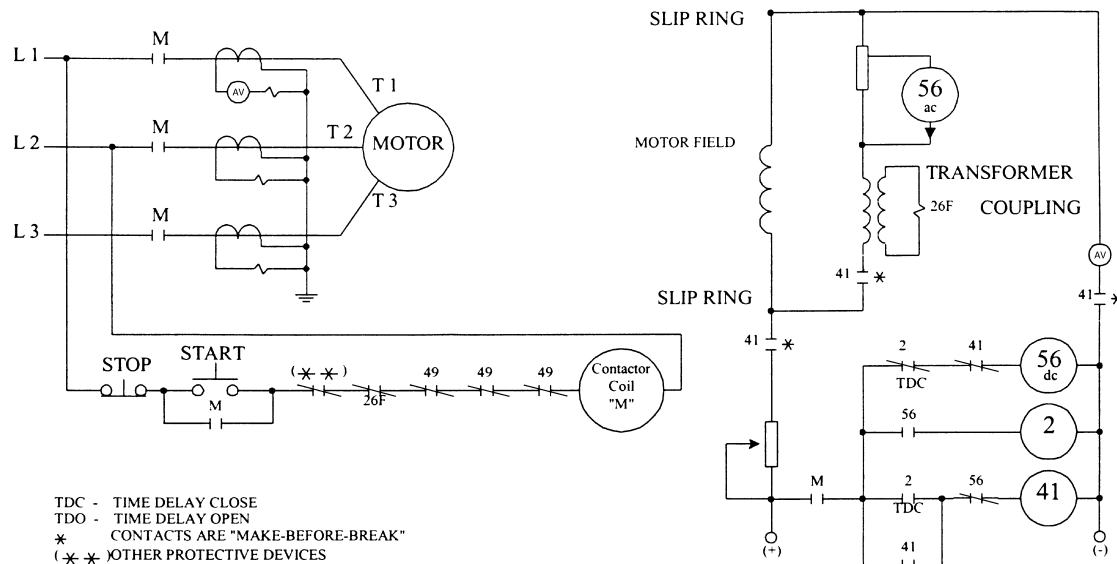


Figure 4—Typical brush-type synchronous motor control

The motor accelerates as an induction motor with its field connected across its starting (and discharging) resistor. A thermal relay (26F) for damper winding protection is in series with this resistor. Should the motor fail to start and accelerate, the relay operates to open the line-contactor coil circuit. This protection is discussed in 3.3. It is frequently important that the field be applied at the proper speed and at a favorable position of the rotor with respect to the rotating flux in the machine. To accomplish this, coordination is required between the field application or synchronizing relay (56 dc) and an ac holding coil (56 ac). When the line contactor (M) closes, its auxiliary contact energizes the closing coil (56 dc), which energizes the timing relay (2) and opens the field contactor (41) coil circuit. The timing relay is used to prevent the application of field until the proper time. When the timer reaches its actuating position, the field application relay closing coil (56 dc) is de-energized, leaving the operation of this relay dependent upon the variable ac voltage signal appearing across the starting resistor, as detected by the holding coil (56 ac). This relay will drop out when the time interval between half waves of the rectified induced field current exceeds the relay setting. This occurs at 94% to 98% of synchronous speed, at which time its contacts will close, energizing the field contactor (41).

4.4.2.2 Brushless-type

In brushless-type synchronous motor control, the motor field and the field application circuit are mounted on the motor shaft. Alternating current is still required for the line contactor and the exciter field. These circuits

are, in general, similar to those for the brush-type motor and need not be repeated. A typical control circuit, inherent in a brushless-type motor and mounted with the rotating equipment, is shown in Figure 5 and operates as follows. The SCR2 is fired during a synchronous motor startup (induction motor stage) for activating the field-discharge resistor. The control circuit holds the rectifier SCR1 from firing until the slip frequency becomes very small, which is approaching synchronous speed; it then fires the rectifier SCR1 at the proper time, and thus applies excitation to the synchronous motor field. At the same time, the field-discharge resistor is removed from the circuit (deactivating) by removing the gate signal of the rectifier SCR2. This frequency-sensitive part of the control circuit ensures that the field excitation is applied at the proper pull-in speed for successful synchronizing.

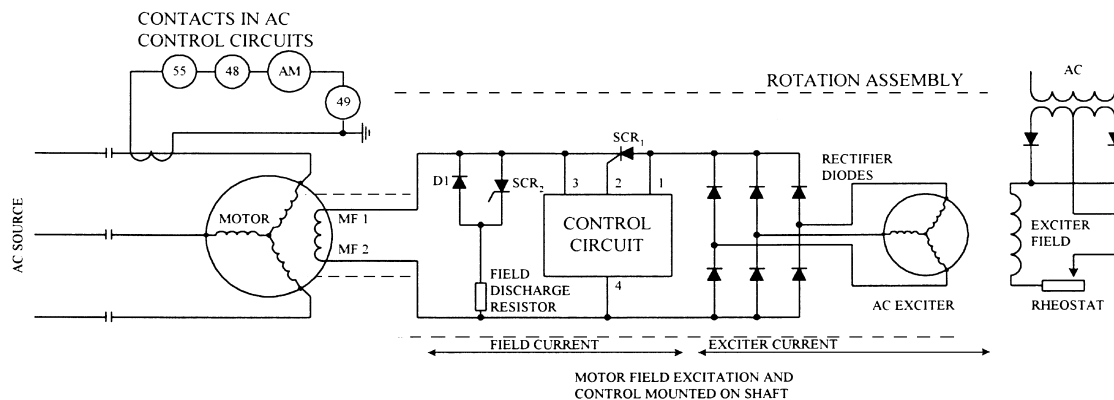


Figure 5—Typical brushless-type synchronous motor control

5. Motor protection requirements

5.1 Pullout and stall protection

5.1.1 Induction-motor stalling

An induction motor stalls when the load torque exceeds the breakdown torque and causes its speed to decrease to zero, or to some stable operating point well below rated speed. This occurs when the applied shaft load is greater than the producing motor torque due to the suppression of the motor terminal voltage. Also, a stall condition can occur when an excessive mechanical load is applied beyond motor torque capability. This condition will develop motor current equal to or approaching locked-rotor current.

5.1.2 Synchronous motor loss of synchronism (pullout)

When a synchronous motor loses synchronism with respect to the system frequency with which it is connected, it is referred to as “out of step.” This condition occurs when the following actions take place individually or in combination:

- Excessive load is applied to the shaft
- The supply voltage is reduced excessively
- The motor excitation is too low

Torque pulsations applied to the shaft of a synchronous motor are also a possible cause of loss of synchronism, if the pulsations occur at an unfavorable period relative to the natural frequency of the rotor with respect to the power system.

A prevalent cause of loss of synchronism is a fault occurring on the supply system. Fault-clearing time, fault location, fault type, and system configuration are significant factors relating to the stability of the motor. Fast fault clearing, multiple ties, and remoteness of faults favor stability.

Underexcitation of the machine is a common cause of out-of-step operation. This may be caused by incorrect tripping of the rotor field circuit breaker (or contactor), or by opening or short circuiting the field circuit. When loss of synchronism (pullout) occurs, and the motor is not separated from the system on the first pole slippage, field excitation must be disconnected and the field connected to the discharge resistor immediately. This minimizes the current that flows until the motor can be isolated. The motor should then be isolated as quickly as possible, because this is not an acceptable long-term operating condition.

5.1.3 Electrical quantities change during a stall

For an induction motor to stall during normal operation, the load torque must exceed the breakdown torque as described in 5.1.1. During this process, the motor current will increase rapidly (which is called “inrush current” or “locked rotor”) until the breakdown torque is reached. Beyond breakdown torque, the motor current continues to increase approaching locked-rotor current. Along with the increase in current, the speed of the motor decreases and the impedance of the motor approaches the locked-rotor impedance.

There are two types of stall causes, as follows:

- a) Excess shaft load torque prior to a motor startup (e.g., failure to open the pump’s discharge gate)
- b) Sudden change of increased shaft load torque during normal operation (e.g., bearing failures)

For a synchronous motor, loss of synchronism is a gradually evolving phenomenon rather than an instantaneous occurrence, as described in 5.1.2. During the initial phase of pullout, stator current increases, terminal voltage decreases, and a voltage is induced in the rotor circuit at the slip frequency. Power flow into the motor increases until approximately a 90° angle is reached between the equivalent machine voltage and the system voltage. At approximately the 180° point, current is maximum and lags the system voltage by the angle of the total impedance between the motor and the system (including the stator resistance and transient reactance of the motor). Also at this point, the direction of power flow reverses, with the motor mass supplying energy to the system. When resistance is significant, this reversal occurs prior to the 180° point. The reactive power flow for virtually the full slip cycle is into the motor, but it may be provided by the motor for a small part of the slip cycle, depending on the machine excitation.

5.1.4 Protective devices for detecting abnormal motor conditions

Stall detection for an induction motor is usually provided by an overcurrent relay, with an inverse characteristic set to detect current above the breakdown torque level. Since motor starting can result in a stall or locked-rotor condition, this protection is usually covered by setting the motor-starting relays above the motor-starting time-current curves and below the running and accelerating thermal limit for the motor. In cases where motors are applied to high-inertia loads, overcurrent protection may need to be combined with speed switches, distance relays, or additional rotor thermal protection to fully protect the motor (see 5.2.7).

Out-of-step detection devices for synchronous motors usually operate on the stator power-factor angle. Impedance-type devices are available for detecting loss of field, and they may also be set to operate on out-of-step conditions without field failure, where the motor transient reactance exceeds the system impedance viewed from the motor terminals (the usual case).

For very large synchronous motors or synchronous condensers, a loss-of-field relay is often used to detect VAR flow into the machine. Accidental tripping of the rotor field circuit breaker (or contactor) or loss-of-field current can be accurately detected by this device (see 7.2.5). There have also been successful applications of rotor field current devices operating from a rotor field current shunt and of notching relays that count pole slips based on power reversals.

A device sensing alternating current in the rotor field circuit may also detect the motor out-of-step condition. These devices used in the rotor field circuit usually consist of a current transformer (CT) with an ac relay on its secondary. When the machine is operating synchronously, there is no ac component of rotor field current and, therefore, no relay current. If the machine is out-of-step with the system, a current of slip frequency exists; if it is of sufficient magnitude, the relay picks up. During the starting period, this relay must be blocked. This scheme is not adaptable to motors with a brushless excitation scheme. For such a scheme, a power-factor relay may be used (see 7.2.12).

5.2 Stator winding protection

5.2.1 General

Deterioration of the electrical insulating system of stator windings is a common cause of reduced motor life and failure. This may result from numerous causes, such as subjecting the insulation to moisture, excessive dielectric stress, and mechanical or thermal damage.

The physical and dielectric properties of an insulation system deteriorate with age, and like other chemical activity, this process is accelerated by an elevation in temperature. A rule of thumb has been developed from tests and experience to indicate that the life of an insulation system is approximately halved for each 10 °C incremental increase of winding temperature, and approximately doubled for each 10 °C decrease (the range of 7 °C–12 °C is indicated for modern insulation systems). Thus, insulation life is related to the length of time the insulation is maintained at a given temperature.

In practice, winding failures resulting from dielectric breakdown are usually attributed to conditions such as impulse or switching surge voltage, moisture, penetration, or conducting contaminants. Mechanical stresses, such as vibration or distortion forces, can also cause winding failures. These forces occur most often when starting the motor, or possibly during a transfer to another electrical source. Regardless of the reason associated with the failure, the effect of elevated temperature is to reduce the ability of the insulation to withstand electrical or mechanical abuse.

The temperature level at which an insulation system should be protected is subject to engineering judgment and applicable standards. (For limits established by the motor industry, see NEMA MG1-1998, Articles 12.41, 12.42, and 12.52. For induction motors, see NEMA MG1-1998, Article 20.40. For synchronous motors, see NEMA MG1-1998, Article 21.40.)

It should be noted that deriving increased output at the price of higher temperatures for any given motor means accepting a shorter life. However, when motors are used in essential or critical service, such as for fire pumps or boiler-feed pumps, it is often desirable that the operator be given time to correct an overload condition before a motor is stopped. Such service may require the motor to run overloaded for prolonged periods, in situations where the overload does not exceed the breakdown torque rating of the motor. In these cases, the cost of reduced motor life due to the overload conditions must be weighed against the expense and damage that would result from a service interruption.

5.2.2 Motor overloading

Overloads can produce stator total hot spot temperatures in excess of the designed thermal limits of the winding insulation system. However, in all cases of operation that result in overtemperature, time is an

important factor. The heat storage capacity of an induction motor is relatively large. Slight overloading for short periods of time does not result in damaging temperature excursions, because the extra heat is stored in the mass of the conductor, core, and structural members. In contrast, for locked-rotor conditions, the rate of temperature increase is very rapid due to the large currents. Since very little heat is transmitted (in this short time interval) from the conductors to the more massive parts of the motor, the thermal limits of the winding insulation may be reached within seconds.

5.2.3 National Electrical Code® (NEC®) (ANSI/NFPA 70-1999)⁵ and OSHA

The National Electrical Code® (NEC®) (ANSI/NFPA 70-1999) has as its purpose the practical safeguarding of persons, buildings, and their contents from hazards arising from the use of electricity. It contains provisions considered necessary for safety. Its scope includes the electric conductors and equipment installed, for example, within or on public or private buildings, industrial substations and mobile homes. It does not cover installations under the exclusive use of electric utilities, mines, and certain other exceptions. The NEC as a recommendation for safe practice is adopted by most of the states, cities, and towns in the United States as the governing electrical code, and is enforced by the local or state-approved authority.

OSHA, 29 CFR, Chapter XVII, Part 1910 is concerned with all establishments engaged in the manufacture of products for interstate commerce. Part 1910 (Subpart S—Electrical) of the regulation has essentially adopted the NEC and incorporates its requirements for electrical installations. The edition of the NEC adopted by OSHA is not generally the same as that enforced by local authority. NFPA Std 70E is generally the standard that influences the OSHA changes.

The adoption of the NEC in the public and private sector, even though excluding installations under the exclusive control of electric utilities when used in connection with the generation, transmission, and distribution of electric energy, essentially represents requirements for practically all residential, commercial, and industrial installations. For this reason, NEC requirements, as they apply to motors and motor circuits, are included.

The NEC specifies overload devices used to protect motors, motor-control apparatus and motor branch-circuit conductors against excessive heating due to overload and failure to start (see ANSI/NFPA 70-1996, Article 430, Part C). The NEC further specifies devices intended to protect the motor, motor-control apparatus, and branch-circuit conductors against overcurrents due to short circuits and grounds (see ANSI/NFPA 70-1996, Article 430, Part D). In motor branch circuits, it is customary to provide for these functions separately, where the running overload protective device protects against motor overloads and locked rotor, and the overcurrent protective device (as a separate device) provides protection against short circuits and ground faults.

The NEC specifies maximum current rating or setting in relation to motor nameplate full-load current for the motor running overload protective device, since the requirement includes the need to monitor the maximum continuous motor branch-circuit current. Of the several means recognized for providing motor running overload protection, the two basic approaches in common use are a separate overcurrent device that is responsive to motor current, and a thermal protector integral with the motor (see ANSI/NFPA 70-1996, Articles 430–432).

For continuous duty motors, a separate overload device responsive to motor current is specified in ANSI/NFPA 70-1996, Articles 430–432, to be rated or selected to trip at no more than 125% of rated full-load current for motors with a marked temperature rise not over 40 °C, or with a service factor not less than 1.15 and not higher than 115% of full-load current rating for all other motors.

For continuous duty motors having a thermal protector integral with the motor, ANSI/NFPA 70-1996, Articles 430–432 specify that the thermal protector shall be approved for use with the motor that it protects on

⁵National Electrical Code and NEC are both registered trademarks of the National Fire Protection Association, Inc.

the basis that it will prevent dangerous overheating of the motor due to overload and failure to start. For motors rated more than 1 hp, in addition to protecting against excessive temperature, the thermal protector is specified to limit the combination of motor and protector to an ultimate trip current in the following manner. Where full-load current does not exceed 9 A, the trip current should not exceed 170% of motor full-load current. For motors with full-load current values between 9.1 A and 20 A, the trip current should not exceed 156% of motor full-load current. For motors with a full-load current value of 20 A, the trip current should not exceed 140% of motor full-load current.

Other overload protection recognized by ANSI/NFPA 70-1996, Articles 430–432(a) (4), involves the use of embedded temperature detectors used in conjunction with intermediate devices that cause motor current to be interrupted.

5.2.4 Inadequate ventilation

Inadequate ventilation results from a reduction of coolant flow to the motor parts from which heat is to be removed. Motors operated with clogged or partially clogged ventilating passageways may have restricted airflow and thus run hot. Similarly, screens, filters, or devices in the motor air stream may become clogged and reduce coolant flow. With ventilation blocked, a motor operating even at no load may be subject to destructively high temperatures. Ventilation inadequacy can be detected by airflow, pressure, or devices sensing the temperature of the motor winding, and alarming or tripping action can be initiated.

5.2.5 Unusual ambient conditions

Motors and controls, such as separate overload devices, are ordinarily rated for use in a maximum ambient temperatures no higher than 40 °C. In areas where the ambient temperature at the motor, controls, or both exceeds, or is appreciably lower than, the rated maximum ambient, special consideration may be required, as described in the following paragraphs.

When a motor's ventilating medium increases in temperature, the motor winding and rotor temperatures also increase. Operating the motor at a higher-than-rated ambient temperature, even though at or below rated load, can subject the motor windings to overtemperature similar to that resulting from overloaded operation in a normal ambient. The motor rating may have to be appropriately reduced for operation in such high ambient temperatures.

Locations that may see higher-than-normal ambient temperatures are those in direct sunlight during a hot summer day or in boiler room installations. Additionally, excessive motor temperature may result if the discharge air is misdirected so as to re-enter the inlet ports. Installing motors too close to a wall or to each other can also cause this to occur.

Motors installed at high altitudes operate in an atmosphere of lower-than-normal air density with reduced cooling effectiveness. This again can result in a higher-than-normal temperature rise, and the motor rating may have to be reduced. Motors designed for special applications, such as sealed motors on submersible pumps that have their rotors in the path of the fluid being pumped, involve unusual ambient conditions that require special consideration in selecting and setting thermal devices, and should be evaluated on an individual basis with input from the manufacturer.

When the ambient temperature is considerably lower than the nominal 40 °C, it would appear that a motor could be loaded beyond its rating. This is not necessarily true. Other considerations besides the thermal limitations of motor components must be taken into account. Mechanical parts, such as shafts and bearings, must be suited for increased loading. Margins on pullout torque may be cut dangerously close. Thus, it is not recommended to load motors beyond their ratings in lower-than-normal ambient temperatures without careful investigation.

In some instances, a motor and its thermal overload device(s) may be installed in two different locations, each with its own ambient conditions. For such cases, special consideration must be given to the protective relay setting(s), or ambient-compensated thermal overload devices may be specified. Further details are given in 5.2.10.2.

Totally enclosed motors, which are cooled by internal recirculation of water-cooled air (heat-exchanger-type motors), can experience overheating because of higher-than-normal water temperature or restricted water flow. By monitoring the temperature of the air discharged from the heat exchanger, excessive temperature of the recirculated air can be detected. In some cases, it may be practical to monitor the flow or temperature of the water through the heat exchanger. For these applications, consideration should be given to whether some other critical component, such as a separately driven fan, should be monitored in addition to the water temperature. Various types of detectors are available that may be used for visual instrumentation, signaling, or shutdown.

Whenever operation under specific abnormal ambient conditions is anticipated, special studies should be conducted and/or special operating information (e.g., derating guidelines) should be obtained from the motor manufacturer.

5.2.6 High and low voltage and frequency

According to NEMA MG1-1998, Article 20.45, motors are generally expected to operate successfully under running conditions at rated load with a variation of $\pm 10\%$ of rated voltage, $\pm 5\%$ of rated frequency, or a combination of the two, provided the sum of the absolute values of the deviations does not exceed 10% and the frequency variation does not exceed $\pm 5\%$. For synchronous motors, rated excitation current is to be maintained.

Variation in voltage or frequency, or both, usually results in an increase in stator winding temperature over that expected at rated nameplate conditions. Within the defined limits, the increase in operating temperature is permissible, because it is characteristically of short duration and, therefore, is considered not damaging to the insulation. The motor can be protected against such overloads by devices that sense line current, but otherwise are independent of frequency.

The selection and application of overload protection devices must be related to the higher than rated current, which can occur at the extremes if the motor is to be permitted to operate at rated load over the range of voltage and frequency variations. The overload protection devices can be set for 115% of rated current to prevent nuisance tripping for most motors. The minimum tripping value of the overload protection should factor in this extra current. However, if these voltage and frequency variations are expected to occur frequently, or to continue for extended periods of time, motor insulation life expectancy is shortened. In such instances, obtain motors with lower than normal temperature rises at rated condition to compensate for the adverse operating conditions.

Motors may be operated from solid state or other types of variable frequency, or variable voltage power supplies, for adjustable-speed drive applications. For these applications, the motors should be individually evaluated for these conditions and appropriately designed so that the maximum temperature rise over its expected operating range does not exceed values acceptable to the insulation system used. In these applications, stator thermal protection is generally obtained by devices that sense winding temperature rather than motor current alone.

5.2.7 Locked rotor or failure to accelerate

Failure of a motor to accelerate when its stator is energized can be caused by several types of abnormal conditions, including mechanical failure of the motor or load bearings, low supply voltage, or an open circuit in one phase of a three-phase voltage supply. When a motor stator winding is energized with the rotor stationary, the motor performs like a transformer with resistance-loaded secondary winding. Typically, stator

winding currents may range from three to seven or more times the rated full-load value, depending on motor design and supply system impedance. The motor controller must be capable of interrupting locked-rotor current. See Figure 6(a) and Figure 6(b) for typical examples of time-current curves indicating starting (accelerating) time-current, locked-rotor thermal limit, accelerating thermal limit, and running overload curve. In Figure 6(a), the locked-rotor thermal limit is a single point for the 100% motor terminal voltage condition.

During starting, the skin effect due to slip frequency operation causes the rotor resistance to exhibit a high locked-rotor value, which decreases to a low running value at rated slip speed. Using a typical locked-rotor current of six times the rated current and a locked-rotor resistance of three times the normal running value, the I^2R heating effect is estimated at $6^2 \times 3$, or 108 times that at normal current. I^2R defines the heating effect and I^2t defines the thermal capability. Consequently, an extreme temperature must be tolerated for a limited time to start the motor. Overtemperature can be prevented by sensing the line-current magnitude and interrupting the power when the starting time is excessive. Since motors require and can tolerate high current for a limited time during acceleration, an appropriate time delay must be incorporated in the current sensing device. To provide locked-rotor or failure-to-accelerate protection, the protective device must be set to disconnect the motor before the stator insulation suffers thermal damage, or the rotor conductors melt or suffer damage from repeated stress and deformation.

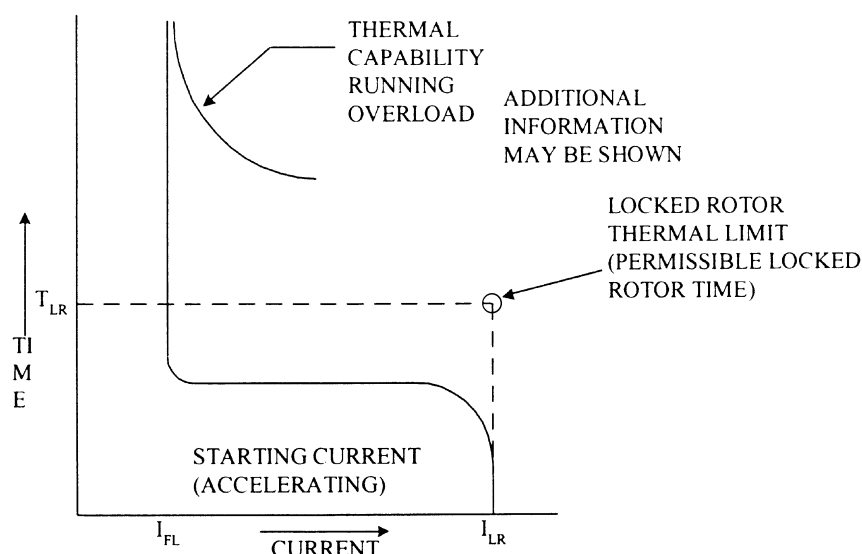


**Figure 6 (a)—Typical motor-starting and capability curves
(applies for a particular motor terminal voltage and cold start)**

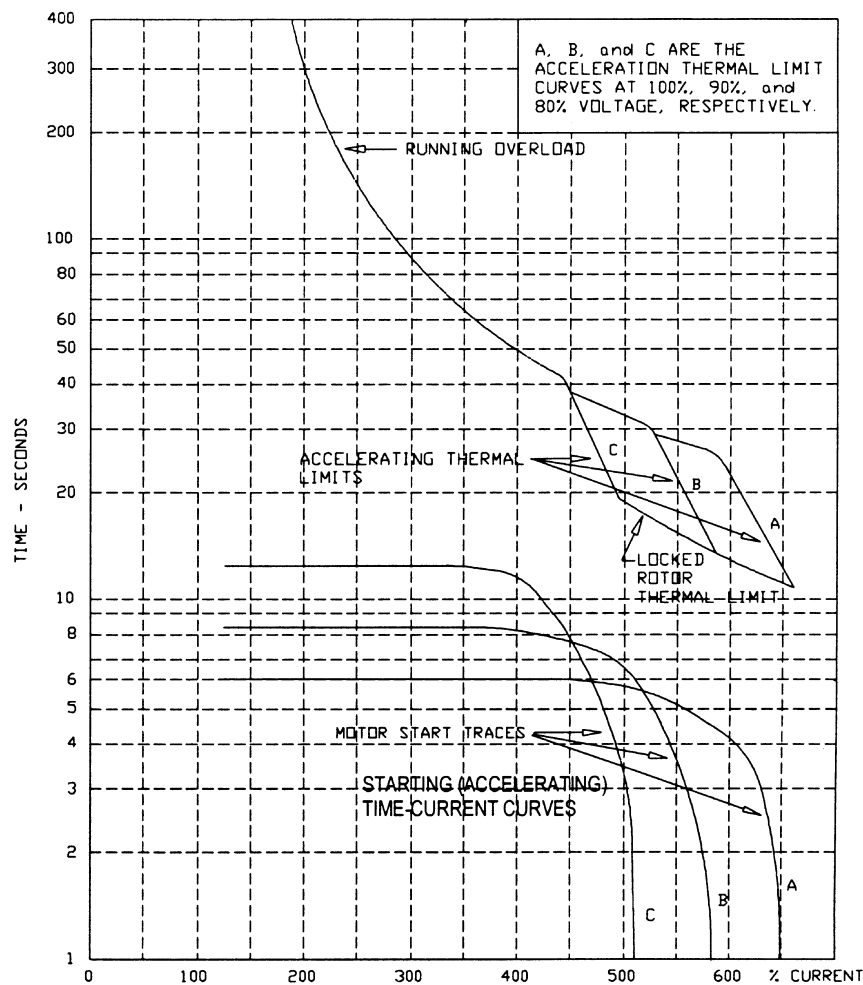


**Figure 6 (b)—Typical time-current and thermal limit curves
(adapted from IEEE Std 620-1996, Figure 1)**

Depending on the design, a motor may be limited thermally by the stator or rotor during accelerating or locked-rotor conditions. In high-horsepower designs, frequent rotor heating and the resulting temperature rise are the limiting factors. The motor designer must address the locked-rotor thermal limit requirement in the design. This allowable locked-rotor thermal limit is usually given for rated locked-rotor current. It can also be given in the form of accelerating thermal limit curves as part of the motor time-current curve, as shown in Figure 6(b). The allowable locked-rotor thermal limit and the accelerating thermal limit curves should be obtained for starting from both rated ambient (cold start) and rated operating (hot start) temperature. It is required that the time-current accelerating (starting) curve be plotted on the same graph as the thermal limit curves for at least 80% and 100% voltage (see IEEE Std 620-1996).

Starting times vary depending on motor design and load torque characteristics. Times may vary from less than two seconds to more than 60 seconds and must be determined for each application. Overload relays applied to detect the locked-rotor conditions must be able to carry full starting current for the entire acceleration period without operating. Although the starting current does drop off near full speed, this effect is normally neglected, providing some margin of safety from relay operation during acceleration.

Care must be exercised in applying overcurrent relays for locked-rotor conditions. The starting current characteristic, as usually plotted, is a trace of current vs. time. Overcurrent relay operation may occur even though coordination studies show the overcurrent relay characteristic is at all points above the starting characteristic of the motor. The reason for this is that the overcurrent relay curve is a locus of single-current and time values, and the motor-starting current is a dynamic time-current characteristic. A longer time margin should be allowed for the motor accelerating time. Ramsaur [B159] sheds light on the performance of overcurrent relays subject to decreasing current. Proper application of this information allows a satisfactory setting to be chosen.

The starting current at zero time of an induction motor nearly equals the locked-rotor current magnitude, but has a lesser heating effect. This occurs because rotor resistance is a function of slip, and it decreases as the motor accelerates to rated speed. When at rest, the rotor is swept by the rotating field set up by the stator current. The field travels at synchronous speed relative to the stationary rotor and induces a voltage at line frequency. At line frequency, the reactance of the rotor cage causes the current to flow at the outer edge of the bars, occupying only approximately one third of the conductor cross-sectional area. For this condition, the apparent resistance is at a maximum, as is the corresponding I^2R heating. When the rotor accelerates, the rotor conductors catch up with the stator field. The conductors are then subjected to the low-slip frequency, and the current can occupy more of the conductor area. For this condition, the apparent resistance can decrease as much as two-thirds at rated slip, as does the corresponding heating.

The terminal voltage of a large motor may be significantly reduced during starting. An induction motor's starting current varies proportionally with the applied voltage. Because the starting current is reduced, thus reducing the corresponding I^2R heating effect, the allowable accelerating time increases. Allowable accelerating times are commonly specified for 100%, 90%, and 80% starting voltages. Special applications may require motor starting at 70% or even lower voltages. The user should request the specific allowable accelerating time for reduced voltage starting from the manufacturer. The acceleration time of the motor will also change due to the starting voltage. The approximate effect on the motor torque capability is an inverse relationship with the square of the voltage; thus, at 90% voltage, approximately 81% of rated starting (locked rotor) torque capability will be available from the motor. Since the load torque characteristics are not changed, the acceleration time is increased. Figure 6(b) (from IEEE Std 620-1996) is as an example of typical thermal limit and accelerating (starting) time-current curves.

High-inertia loads, such as induced draft fans, require long acceleration times. The starting time may exceed the allowable locked-rotor thermal limit. This is permitted because the rotor resistance is a function of slip and decreases as the motor accelerates. The accelerating (starting) time may exceed the allowable locked-rotor time without excessively heating the rotor. This condition is shown in Figure 7 with the accelerating thermal limit for the applied voltage. The lower end of the curve is the allowable locked-rotor thermal limit (Powell [B92]). For this case, an overcurrent relay set to coordinate with the locked-rotor thermal limit trips on starting current.

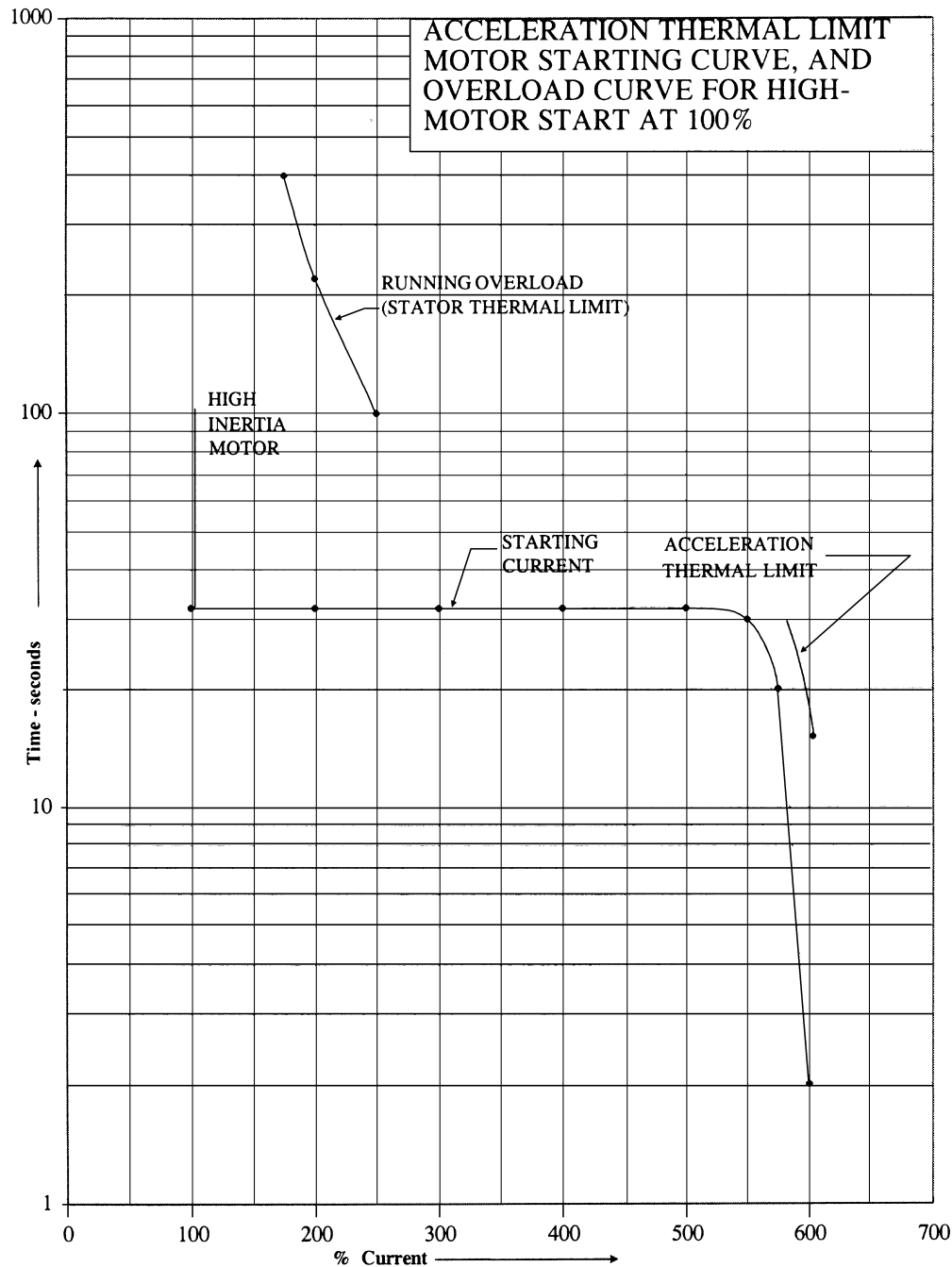


Figure 7—Typical time-current and thermal limit curves for high-inertia motor start

For these applications, the following approaches are possible:

- Include a motor zero-speed switch (12) that supervises an additional overcurrent relay 51 (START) set to protect the motor against a locked-rotor condition. As soon as the motor begins to accelerate, the 51 (START) is disabled, leaving the overcurrent protection to the longer time overcurrent (TOC) relay 51. When the design is such that the accelerating time exceeds the locked-rotor thermal limit, a zero-speed switch needs to be supplied with the motor [see Figure 8(a)].

- b) Apply a distance (mho type) relay, Device 21, to supervise the time-overcurrent (TOC) relay Device 51 (START), which has been set within the locked-rotor thermal limit. For a successful startup of the motor, the mho relay will pick up when the motor is energized, but will prevent unnecessary tripping by resetting before the TOC relay operates. If, upon energization, the motor fails to accelerate, the mho relay will remain picked up, and the motor will be tripped when the TOC relay operates (see Figure 8(b), Figure 9, and Figure 36). Although a single-phase mho relay works, in practice a three-phase relay is used.

The distance relay provides a reliable detection of rotor motion, but is sometimes difficult to set and calibrate to the required accuracy. The relay must drop out fast enough to open the starting overcurrent tripping path as the motor begins to turn. In many cases, the relay is operating very near pickup and must be set very accurately to operate correctly. Usually, in-service startup tests are required because of poor accuracy of the locked-rotor impedance data. Maintaining the high-accuracy set points requires more frequent calibration of the distance relays to correct for normal relay calibration changes.

- c) A time-overvoltage relay device (59) may be used instead of the TOC relay Device (51 START) in schemes 1 and 2, since voltage and current are proportional under locked-rotor conditions, as shown in Figure 8(a) and Figure 8(b). The use of a time-overvoltage relay depends on sufficient voltage drop through the source impedance due to the starting current inrush and is, therefore, limited to relatively high-impedance sources (see IEEE Std 620-1996). It is set similar to the TOC relay to obtain thermal protection of the motor for a locked-rotor condition. For some applications, however, the time margin between the reset of the mho relay and pickup of the time-overvoltage relay may be inadequate to permit the use of this relay. Adequate margin is more apt to be obtained using a TOC relay (51 START) because of the decreasing current characteristic of the motor as it accelerates for normal startup.
- d) For some applications where the operating time of the TOC relay (51 START) is approximately the same as the startup time of the motor, it is possible that an IOC relay (50) can be used instead of the mho relay (21) [see Figure 10 (a)]. For most high-inertia drive motors, this scheme has limited application. This is because of the difficulty in setting the IOC relay (50) sufficiently low to pick up reliably on motor acceleration, and still resetting it to prevent tripping before the TOC relay (51) times out. The problem is compounded where the accelerating current characteristic of the motor varies with the system operating voltage for abnormal operating conditions. This does not pose a problem, however, with the mho relay application because the impedance characteristic on acceleration is approximately the same, regardless of the voltage at the motor terminals.
- e) Use a relay that uses motor voltage and current to calculate the impedance, separating the speed-dependent rotor resistance from the real part of the impedance, and uses it in an I^2R calculation of the watts in the thermal model. The relay will trip in locked-rotor time for a stall condition, but will calculate the slip-dependent heat and allow the start in the high-inertia case (see Zocholl [B114] and Zocholl [B115]).
- f) For brush-type synchronous motors, one method for locked-rotor protection uses a device (26F) shown in Figure 4. The effective ratio of the coupling transformer varies with the frequency of the discharge current, so that the tripping time is short for a locked-rotor condition but much larger for a normal acceleration.

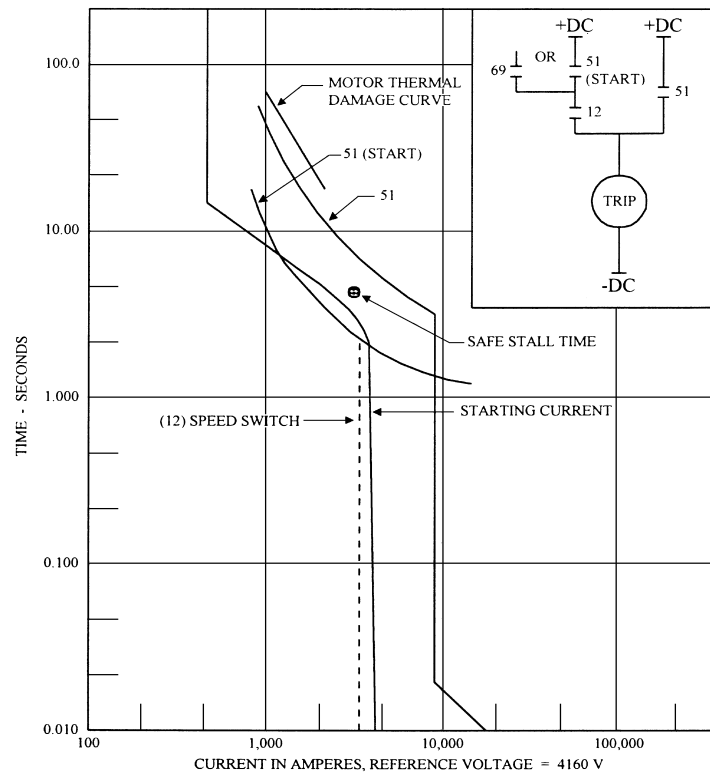


Figure 8 (a)—Starting characteristics using a speed switch (12) supervising the 51 (START) relay

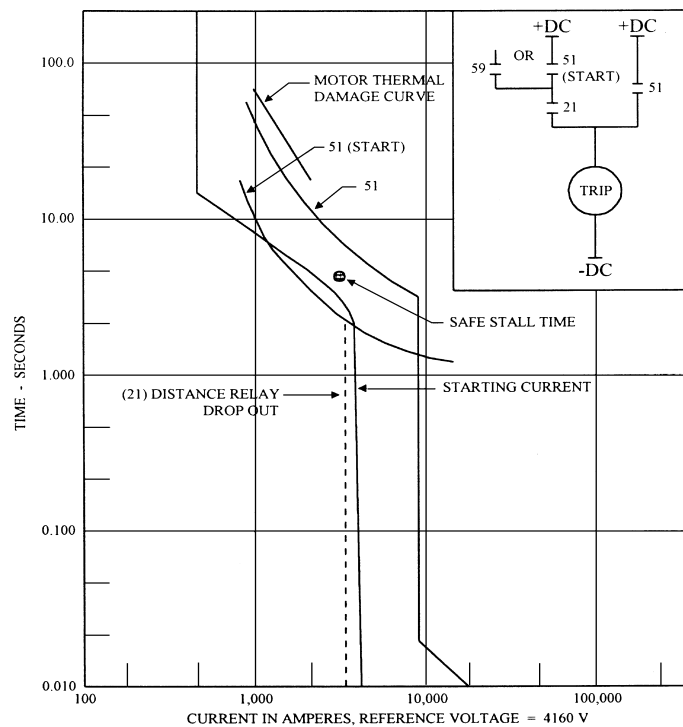


Figure 8 (b)—Starting characteristics using a distance relay (21) supervising the 51 (START) relay



Repetitive intermittent operation of the motor types mentioned also can cause mechanical stressing of the stator winding coil ends and of the damper or rotor winding end connections. NEMA MG1-1998, Article 12.50, recommends minimizing the number of starts to maximize the life of the motor. For automatic operation (and in some cases, manual operation) with a remote control device, it may be necessary to provide a fixed-time interval between starts, or limit the number or starts within a period of time to ensure safe operation. A microprocessor-based motor protection system may include this feature.

Information on repetitive start-stop cycling can be found in NEMA MG10-1990.

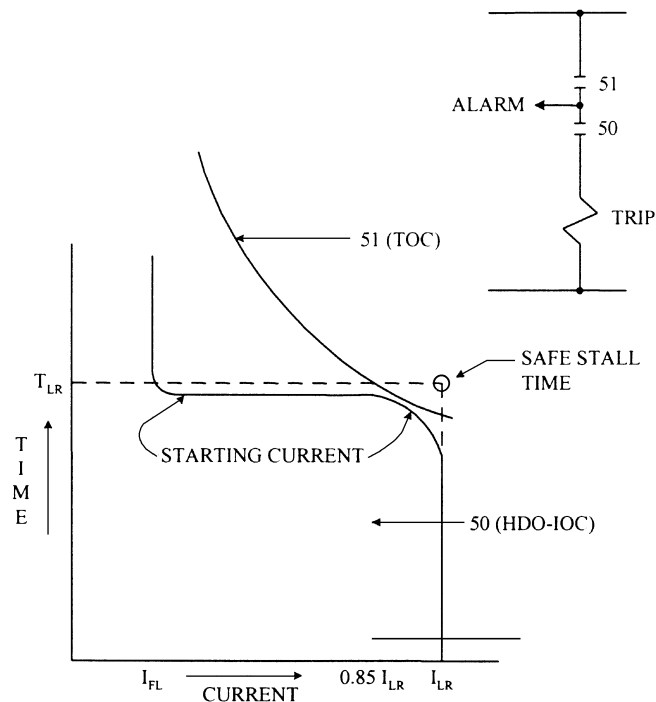


Figure 10 (a)—Locked-rotor protection with TOC element supervised by a high-dropout IOC element

5.2.9 Overtemperature thermal protective devices (49)

There are two main classes of overtemperature thermal protective devices (see 5.2.3). One is a line break type, which interrupts load current directly. The second is a control circuit system using detector devices, which interrupts the motor current through its controller.

Thermal protectors are intended to limit motor-winding temperature and motor current to predetermined values during abnormal motor operating conditions. This prevents premature motor insulation failure.

Abnormal conditions that can result in overheating include overload, stalling, failure to start, high ambient temperature, restricted motor ventilation, reduced speed operation, frequent starting or jogging, high or low line voltage or frequency, mechanical failure of the driven load, improper installation, and unbalanced line voltage or single phasing. Current sensing alone cannot detect some of these conditions, such as restricted ventilation. Temperature sensing alone may be inadequate, for example, with frequent starting or jogging. For some conditions, a coordinated arrangement of current and temperature sensing may be required.

The temperature sensing capability of thermal protectors depends on their location with respect to the motor windings. The protectors should be installed within or on the motor frame in such a manner that the temperature at the device changes in proportion to the winding temperature, and they should be matched to the motor's insulation class.

The advent of microprocessor-based protection systems has made it possible to provide a more refined thermal protection than was possible with electromechanical relays. Since no attempt is made with electromechanical relays to match the thermal time constant of the motor, thermal coordination is achieved under limited operating conditions. Conversely, microprocessor-based protection systems make it possible to

match thermal properties identified by motor data and, as a result, tracks the motor temperature more accurately over a wider range of operating conditions (Zocholl [B115]). Microprocessor systems can also monitor resistance temperature detectors (RTDs) embedded in the motor stator windings to detect temperature rise caused by impaired or lost ventilation not indicated by current. In addition, these systems can monitor temperature detection devices for motor bearings.

5.2.9.1 Control circuit devices sensing motor temperature only

Devices used in this type of control circuit consist of a thermal element and circuit interrupting means. In some forms, the element is calibrated to trip at a fixed temperature value and, in other forms, the trip temperature decreases as the rate of temperature rise increases. The device may automatically reset upon cooling after operating to shut down the motor. These devices are usually connected electrically in the control circuit of the magnetic motor controller that interrupts the motor line current.

Various thermal elements are used, including bimetal snap-acting elements, thermocouples, resistance coils, semiconductor materials (such as thermistors with either negative or positive temperature coefficients), and liquid or gas-filled assemblies.

Operation of the various types depends on the transfer of heat from the motor winding to the thermal element. Since heat flow is involved, the temperature difference between the thermal element and the winding, for a given element mass and installation, is related to the rate of temperature change and increases with the winding heating rate.

For running overload conditions, the rate of temperature change of the winding is generally slow, and the temperature difference between the winding and thermal element is at a minimum. Here, thermal element temperature varies directly with, and easily tracks, winding temperature. When the winding raises the element to its operating temperature, the motor is shut down. For locked-rotor conditions, the rate of increase in winding temperature depends on the motor design. Bimetallic temperature sensors usually are not capable of adequately following winding temperature on locked rotor, and so are used in conjunction with supplementary overload devices. With the supplementary overload device and either manual or automatic restarting, the motor cutoff is initiated by the supplementary overload device detecting the high overcurrent on the first few cycles of a stalled condition; this starts a timing action, which will cut off the motor if the overcurrent exists for a time sufficient to endanger the motor. The winding temperature at cutoff increases on successive restarts until the thermostat operating temperature is reached. At this point, the thermostat trips and assumes control, keeping the motor de-energized until the windings have cooled to the reset temperature of the thermostat and the cycling process can be repeated. The form of bimetallic temperature sensors that also respond to rate of temperature rise may provide effective locked-rotor protection when properly coordinated with the motor thermal characteristic. Either system is capable of providing safe winding protection for manual and automatic restarting on both running overloads and locked rotor.

Sensors such as thermistors, which undergo a change in resistance with temperature, can be small in size and installed directly on, or buried in, the stator winding. These devices can track the winding temperature on locked rotor as well as running overload for some motors; however, for larger motors, they may be inadequate on locked rotor. The resistance change provides a signal to circuitry whose output is in series with the control circuit of a magnetic motor contactor used to interrupt the motor current. The output may be a thyristor, or it may actuate an electromechanical relay. The resistance sensors may be one of three types.

One type of sensor uses a positive temperature coefficient thermistor, which exhibits a large abrupt increase in resistance at a particular design temperature. This change in resistance, occurring at what is known as an anomaly point, is inherent in the material and remains constant once the sensor is manufactured. Sensors are produced with anomaly points at different temperatures to meet application requirements. Another sensor type uses a resistor, which has an approximately linear increase in resistance with temperature. The sensor assumes a specific value of resistance corresponding to each desired value of response or operating temperature. It is used in a circuit that is calibrated to a specific resistance. A third type is a negative temperature

coefficient of resistance sensor, which is used with circuitry similar in concept to that used with the linear resistor sensor. Temperature sensors do not provide locked-rotor protection for motors that

- a) Are thermally limited by the rotor, or
- b) Have stators having an extremely rapid rate of temperature rise.

In item (a), the rotor reaches its limiting temperature value before the stator reaches its allowable limit. In these motors, sensors responsive to stator winding temperature do not limit the higher rotor temperature to a safe value, and additional means (such as thermal overload relays sensing stator current) are recommended (see 5.2.7). In item (b), the mass of the thermal element and its manner of installation determine the temperature lag between the element and the winding. Carefully installed thermal elements of small mass that reduce this temperature lag, and designs that respond to rate of temperature rise, increase the range of rate of heating of the stator winding over which protection may be obtained.

5.2.9.2 Line break devices sensing motor temperature and current

Devices of this type carry the full motor current through their electrical contacts and interrupt line current directly on operation. Because of physical size limitations, they are available on motors from fractional horsepower sizes through 5 hp single-phase and approximately 10 hp three-phase. Linebreak devices consist of a temperature-sensitive element with a heater(s) and contacts that can interrupt motor current. The elements are designed to simulate the maximum limiting insulation temperature for the winding and open the contacts.

Motor current flow through the heater raises the temperature of the thermal element to approximately the winding temperature. When the winding reaches its maximum allowable temperature, the thermal element reaches its operating temperature and opens its electric circuit to shut down the motor. Locating the protector adjacent to or in the stator winding minimizes the heating required by current in the protector, and further provides optimum correlation of protector and winding temperatures. Approval by the Nationally Recognized Testing Laboratory (NRTL) is related to their use with specific motors for which thermal protectors are designed, based on tests of the motor and protector combination. These motors are designated thermally protected. Both manual-reset and automatic-reset types are available, with the latter designed to provide motor protection even when continuously cycling with the motor stalled or running. Protective devices that do not account for motor operating temperature may not protect the motor during automatic restarting.

5.2.9.3 Control circuit devices sensing motor temperature and current

In this type of motor protective device, RTDs located between the stator coil sides are used in a control circuit responsive to both temperature and motor current. For the unit to operate, both high temperature and overcurrent must exist simultaneously. This device provides protection against locked rotor, repeated starts, overload, or inadequate cooling. Other protective devices will operate on either quantity (i.e., overcurrent, overtemperature)

5.2.10 Current-sensing-type devices

The recommendations given in the NEC for motor overload protection using separate overcurrent (overload) protective devices are referred to in 5.2.3.

The most commonly used device for protection of integral horsepower motors at operating overloads is a thermal overload relay. It simulates the temperature condition in the motor winding by means of current in a heating element, which varies with the motor current. In the event that a current of sufficient magnitude and duration causes excessive heating of the motor winding, the heating element causes a control circuit contact to open the contactor or circuit breaker in the motor circuit. Proper operation depends on the temperature rise of the windings and the heat dissipation of the motor being similar to that of the relay. A heavily overloaded motor should be quickly removed from its power source. A slightly overloaded motor may carry its

load for a considerable length of time before dangerously high temperatures are reached. Overload relays are designed to have characteristics with this inverse current-time relationship.

In one common type of relay, the heating element causes heating and deflection of a bimetallic element to actuate the contact. This type of relay may be arranged for either manual or automatic reset, and may have its trip current adjustable over a limited range, typically $\pm 10\%$.

In another type of relay, the heating element causes the melting of an eutectic solder, which releases a latch to open the control circuit contacts. This type of relay requires manual reset and is not ordinarily adjustable.

A third type, the thermal induction relay, utilizes the flux produced by a coil carrying the motor current to induce a current in a short-circuited secondary that heats an element to trip the unit.

A fourth relay is a capacitor charge type, where motor line current is sensed by separately furnished current transformers and converted into voltage signals by current-to-voltage transducers. These voltage signals are fed into overload logic, which produces an alarm or trip output. The time vs. current trip characteristic is similar to those of thermal overload devices. However, there is no overshoot or lag as normally found in a thermal overload type relay.

The protection derived by the above four devices depends on their ability to replicate the thermal heating of a motor. The suitability of these devices to protect a T-frame motor requires a comparison of the thermal overload's trip characteristics with the motor's thermal damage curve and time-rated locked-rotor current. These special considerations are described in 5.2.10.3.

Thermal protection for larger motors is often provided using switchgear-type protective relays. These relays are of the following general types:

- a) Thermal overload relays (49) incorporating bimetallic elements connected in CT secondaries, thus responding to motor current
- b) Temperature relays operating from RTDs (49/26) built into the motor
- c) Resistance capacitance (RC) timing circuits energized by current transformers in the motor leads, or combination relays utilizing RC timing circuits and RTDs built into the motor (Boothman [B101]).
- d) TOC relays that operate on the induction-disc principle
- e) A microprocessor-based system that replicates the thermal characteristics of the motor and provides appropriate protective functions

Overload relays having the same current ratings are available with different time-current characteristics to approximate the motor heating curves of rotating machines with different thermal limitations. As motor heating curves vary substantially, it is desirable to obtain the motor heating characteristics for large or special motors from the manufacturer, and then plot the relay and motor curves to check the protection obtained. Supplementing the thermal relay (Device 49) with other relays, such as a long-TOC relay (51), may be necessary to obtain complete protection. Relays available with adjustable curve shapes allow the heating curve of the motor to be matched very closely. Temperature sensors are useful in supplementing thermal-overload relays by sensing winding temperatures in larger machines. A description of temperature sensors is included in 5.2.9.1, 5.2.9.3, and Boothman [B101].

The use of microprocessor-based protection systems provides a more accurate means of determining the status and temperature of motors under restart conditions than traditional devices. The temperature-resistance histories stored in the microprocessor enable the system to measure fluctuations in temperature at a much faster rate and to respond to them by either alarming the condition, or tripping the motor if temperature is in excess of what is considered acceptable. (See Clause 8 for more details.)