American National Standard

guide for ac motor protection

ANSI C37.96-1975—IEEE Std 588-1976

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(Revision of IEEE Std 288-1969 and IEEE Std 329-1971)

An American National Standard

IEEE Guide for AC Motor Protection

Sponsor
Switchgear Committee of the
IEEE Power Engineering Society

Approved May 29, 1975
IEEE Standards Board

Secretariat
Edison Electric Institute
Institute of Electrical and Electronics Engineers
National Electrical Manufacturers Association

Approved December 30, 1975
American National Standards Institute

Published by
The Institute of Electrical and Electronics Engineers, Inc.

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Foreword

(This foreword is not a part of IEEE Std 588-1976, IEEE Guide for AC Motor Protection.)

This guide was prepared by the Motor Protection Working Group of the Rotating Machinery Subcommittee of the Power System Relaying Committee of the IEEE Power Engineering Society. It is a combination and updated expansion of two previous standards, IEEE Std 288-1969, Guide for Induction Motor Protection (ANSI C37.92-1972) and IEEE Std 329-1971, Guide for Synchronous Motor Protection (ANSI C37.94-1972).

The Institute is indebted to those individuals who gave so freely of their time and contributed so willingly and cooperatively to this document as well as the original guides. Particular credit goes to A. Hauspurg, M. F. Rosol, and S. H. Horowitz, the chairmen, without whose sustained efforts the original guides would not have been possible.

The guide is intended to enable one to determine the protection requirements for a specific application. During the development of this guide, the Working Group had active participation from the following members:

W. A. Elmore, *Chairman*

H. C. Bicknell, Jr
A. R. Gilmour
Ian Harley
D. H. Jackson
R. A. Larkin
J. R. Linders
W. R. Lund
J. F. MacMaster
L. B. McClung
W. K. Morrison
R. C. Moore
J. W. Olson
G. J. Potochney
M. F. Rosol
H. J. Sutton
J. Vosicky

A. P. White

The personnel of the C37 Subcommittee on Protective Relays which reviewed and approved this Guide were:

G. J. Marieni, *Chairman* **H. H. Connelley,** *Secretary*

J. W. Chadwick
R. J. Felton
C. R. Griffin
J. A. Imhof
J. L. Koepfinger
J. R. Linders
J. W. Lipnitz
J. Lockyer
C. A. Mathews
M. B. Purvis
R. J. Sullivan
F. Von Roeschlaub

When this standard was approved on December 20, 1974 the IEEE Standards Board had the following membership:

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The Standards Committee on Power Switchgear, C37, which reviewed and approved this Standard had the following personnel at the time of approval:

C. L. Wagner, *Chairman*
J. E. Beehler, *Executive Vice-Chairman, High-Voltage Switchgear Standards*
W. R. Wilson, *Executive Vice-Chairman, IEC Activities*
W. E. Laubach, *Executive Vice-Chairman, Low-Voltage Switchgear Standards*
H. H. Connelley, *Secretary*

Organizations Represented	*Name of Representative*
Association of Iron and Steel Engineers	J. M. Tillman
Electric Light and Power Group	J. E. Beehler
	H. F. Frus
	K. D. Hendrix
	F. R. Solis
	C. D. Stalnaker
	K. G. Adgate *(Alt)*
	R. W. Hudson *(Alt)*
	R. H. Knight *(Alt)*
Institute of Electrical and Electronics Engineers	M. J. Maier
	H. H. Fahnoe
	R. E. Friedrich
	G. W. Walsh
	H. F. White
	R. N. Bell *(Alt)*
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National Electrical Manufacturers Association	A. P. Colaiaco
	R. W. Dunham
	C. E. Gryctko
	G. A. Wilson
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Tennessee Valley Authority	Robert C. St. Clair
U.S. Department of the Army	R. H. Bruck
U.S. Department of the Interior, Bureau of Reclamation	Edward M. Tomsic
U.S. Department of the Navy, Naval Facilities Engineering Command	D. M. Hannemann
Testing Laboratory Group	Leonard W. Johnson *(Alt)*
	E. J. Huber
	W. G. Pracejus
	W. A. Farquhar *(Alt)*
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IEEE Guide for AC Motor Protection

1. Introduction

1.1 General Format. This application guide for the relay protection of squirrel-cage and wound-rotor induction motors and synchronous motors presents a review of the generally accepted forms of motor protection and summarizes the use of relays and devices, singly and in combination, so the reader may select the necessary equipment to obtain adequate motor protection. The guide is concerned primarily with the protection of three-phase integral horsepower motors and refers to two-phase motors only in special instances where specifically indicated.

This guide is not a standard and does not purport to detail the protective requirements of all motors in every situation. Its recommendations are of a general nature, designed to cover the usual or typical motor installations. Sufficient background material on objectives, applications, and setting philosophy is presented, however, to enable the reader to evaluate the need for various forms of protection and to select and properly apply suitable equipment for most situations.

Section 2, Motor Protection Requirements, presents 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 reader in evaluating the need for, and the means of, obtaining adequate motor protection in any specific situation.

Section 3, Motor Protection Specifications, presents detailed recommendations in a series of tables and diagrams showing good engineering practice. The tables and diagrams are classified according to type of switching, normal source voltage, and motor and circuit ratings; they show the combination of devices normally applied for the associated protective function. An index of all ANSI (American National Standards Institute) or NEMA (National Electrical Manufacturers Association) device designations used in this guide is shown in Table 7.

Section 4, Settings and Adjustments of Protective Devices, presents a discussion of the various factors that must be considered in determining the setting of each relay or device. Whenever it is applicable, a discussion is given on the desireability of using a device to actuate an alarm or a trip.

1.2 Motor Description

1.2.1 ***Induction Motors.*** The primary (stator) winding of an induction motor is connected to the power line. The winding in the secondary (rotor) slots is not connected to any power line, but receives its current by means of induction. Energy is transferred to the rotor by means of the magnetic field. Depending upon the type of power supply, the stator winding is a polyphase winding (usually three-phase, seldom two-phase) or a single-phase winding. The rotor winding is designed as either a polyphase 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 ring at each end.

1.2.2 ***Synchronous Motors.*** Polyphase 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 cir-

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culated 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 through an appropriate starting and field discharge resistor during starting.

The differences between control and motor protection of the synchronous motor as compared to the induction motor are related to the rotor construction. Since the dc excitation is usually a necessity for synchronous operation and synchronous operation is fundamental to the synchronous motor, protection against 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 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 the induction motor, protection schemes for these parts are basically the same.

1.3 Switching and Control. All motors require the following functions to be incorporated in their control and switching equipment.

(1) Stator disconnecting means
(2) Stator fault-interrupting devices
(3) Stator switching means

In addition, a synchronous motor must have some means of field switching.

In this section 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 to the user. In this case see Sections 2.7.1.1.1 and 2.7.1.1.2.

1.3.1 ***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 over-all protective package. Although a detailed review of such devices is beyond the scope of this guide, a summary of their application and limitations is essential.

1.3.1.1 *Low-Voltage Magnetic Contactor With Circuit Breaker or Fuses (up to 600 V).* These controllers consist of a magnetic contactor used for starting or stopping the motor. The controller is equipped with thermal overload and undervoltage protection. Undervoltage protection is inherent with magnetic contactors when used with integral control supply and three-wire control circuits. Undervoltage "protection" in this context connotes 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 completely 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 in fused starters a separate disconnecting means is required.

1.3.1.2 *NEMA Class-E1 High-Voltage Motor Controllers (2200 to 4800 V).* Standards for these motor controllers are given in American National Standard,Industrial Control Apparatus — Controllers and Controller Assemblies (partial revision of C19.1-1959) C19.7-1973, Section 7-14; the ratings are listed in Table 20 of the same publication. These controllers consist of a medium-voltage magnetic contractor used for starting and stopping the motor with thermal overload and under voltage protection similar to that listed for the low-voltage units. In addition, however, fault protection is provided by instantaneous overcurrent relays. Other relaying is added as described in Section 2.

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1.3.1.3 *NEMA Class-E2 High-Voltage Motor Controllers (2200 to 4800 V).* These motor controllers are similar to the Class E1 controllers described in Section 1.3.1.2 except that the short-circuit protective relays are omitted and fault interrupting fuses are added.

1.3.2 ***Switchgear-Type Motor Controllers.*** In switchgear-type motor controllers all stator-disconnecting, fault-interrupting, and switching functions are done by the power circuit breaker. Standards are available covering the application and limitations of ac power circuit breakers for these functions. For example, Table 6 of American National Standard, Preferred Ratings and Related Requirements for Low-Voltage Power Circuit Breakers, C37.16-1970, 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 Table 5 of the same standard covers the limitations relating to repetitive duty and normal maintenance. Table 6 of American National Standard, Schedules of Preferred Ratings and Related Required Capabilities for AC High-Voltage Circuit Breakers Rated on a Symmetrical Current Basis, C37.06-1971, shows the number of operations for various operating conditions that can be performed before maintenance is required.

1.3.3 ***Field Switching Equipment.*** All synchronous motors are equipped with some form of field application equipment. For brushless synchronous motors, an ac power supply to a rotating transformer or a dc supply to the ac exciter is used. The control of this power supply must be integrated with the stator control. The equipment which rectifies ac power to the field is contained on the rotating element. For the smaller motors, contactors are used to switch the power supply to the field. For the larger ratings, field circuit breakers may be needed.

1.4 Effect of AC and DC Control Equipment. Since the supply of electrical energy to the stator of either a synchronous or induction motor and the field of a synchronous motor can use any one of a variety of ac or dc circuits and devices, there are too many variations to cover each in detail. Some examples of stator control schematics are shown in the simplified circuits of Figs 1-3.

1.4.1 ***Stator Control Equipment.*** Protection from extremely low or complete loss of line voltage is an inherent feature of the non-latched-in type of alternating current 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 transformer. The line contactors must close at 85 percent of rated line voltage, according to NEMA Publ ICS-1970, Section ICS2-110.41.2, and American National Standard, Industrial Control Apparatus — Switching or Controlling Devices (partial revision of C19.1-1959), C19.5-1973, Section 5.2.3.7.2, while the dropout point is not defined and may vary from 20 to 70 percent of rated voltage. If a severe voltage dip or complete loss of line voltage should occur while a motor is running, the line contactor will drop open.

1.4.1.1 *Three-Wire Control With Undervoltage Protection.* When the circuit shown in Fig 1 is used, the contactor 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 undervoltage protection. During a condition of low line voltage, a synchronous motor will act as a generator for a short period of time and will therefore tend to maintain its ac terminal voltage for a considerably longer period than will an induction motor. The protection of the motor for this condition is covered further in Section 2.7.1.1.

1.4.1.2 *Three-Wire Control With Time Delay Undervoltage Protection.* If it is desired to ensure that the motor will continue to operate during voltage dips or outages of short duration, the control circuit shown in Fig 2 should be used. This is referred to as three-wire control with time-delay undervoltage protection, and consists of a time-delay relay UV that maintains a sealing contact for a definite period after a voltage failure.

1.4.1.3 *Two-Wire Control.* If the auxiliary control contact *M* of Fig 1 is omitted, and the start-stop pushbutton replaced with a

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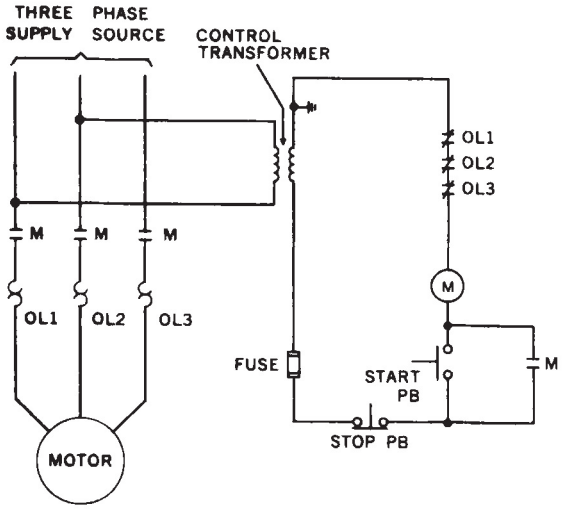


Fig 1
Three-Wire Control Circuit With Undervoltage Protection
(Field Control Not Shown)

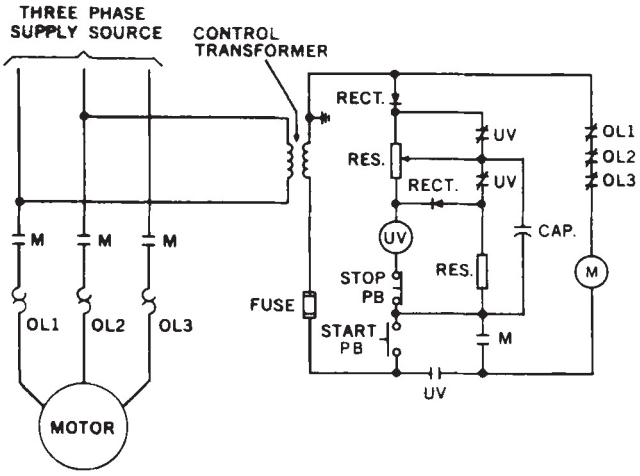


Fig 2
Three-Wire Control Circuit With Time-Delay Undervoltage Protection

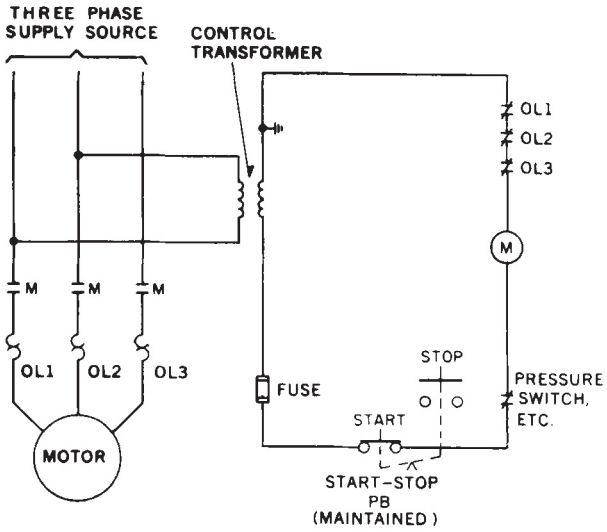


Fig 3
Two-Wire Control Circuit With Undervoltage Release

knife switch, pressure switch, or other type of maintained contact device the two-wire control of Fig 3 results. With this scheme, the line contactor will open on any low voltage which is below the dropout value to disconnect the motor. The motor will automatically restart when sufficient voltage is restored to close the line contactor. This arrangement is referred to as two-wire control with undervoltage release. This two-wire control arrangement has the disadvantage that several motors on the same power system would attempt to restart simultaneously when voltage was restored. Such a strain on a system may drag the voltage down to the point where the motors would never be able to accelerate to full speed. In ad-

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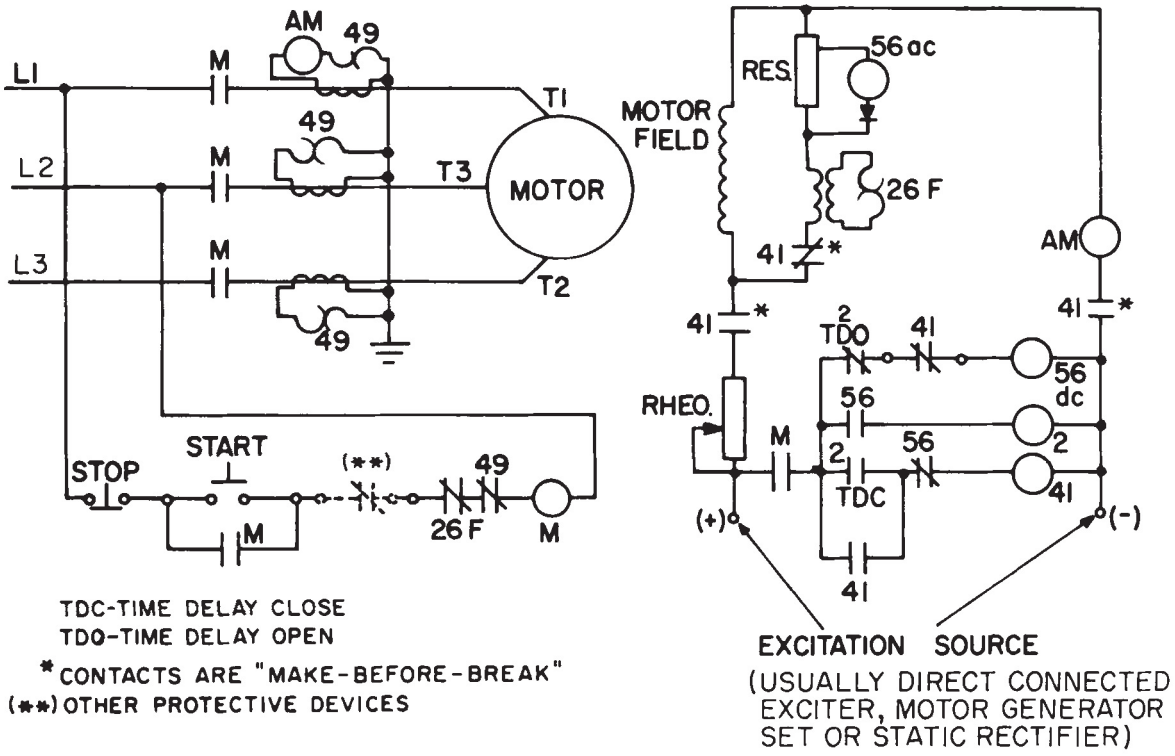


Fig 4
Typical Brush-Type Synchronous Motor-Control

dition, unexpected automatic restarting after restoration of voltage may be a safety hazard.

When two-wire control is used, overload relays with automatic reset should not be applied. If the automatic reset overload relays are installed in this arrangement, an overload would cause the motor to shutdown, but the motor would be restarted when the relays reset. The cycle could continue until the motor is damaged.

1.4.1.4 *Circuit Breaker Control.* If circuit breakers are used for motor control, no inherent tripping will occur for low (or zero) line voltage. These devices are latched in and must be tripped by operating a specific device or contact.

1.4.2 ***Field Control Equipment.*** Switching the field of a synchronous motor is complicated by the fact that the field may be any of the following:

(1) A brush-type field (that is, one supplied power through slip rings on the shaft and associated brushes) that derives its direct current from the following:

(a) A shaft driven dc exciter
(b) A separate motor-generator set
(c) A separate static rectifier

(2) A brushless type field that requires the following:

(a) DC excitation for the field of a rotating ac exciter
(b) AC excitation for the primary of a rotating transformer

Generally, the field application circuit must do the following:

(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 percent) 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.

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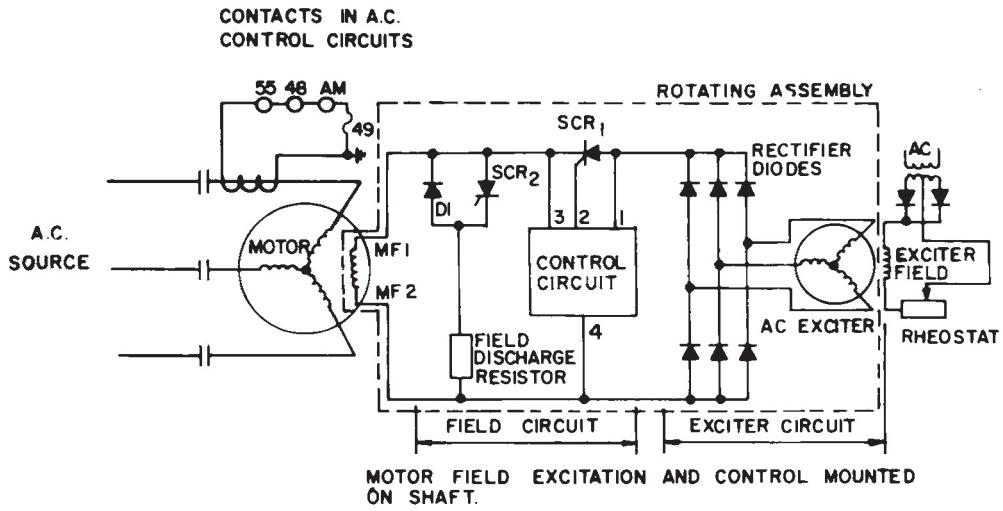


Fig 5
Typical Brushless-Type Synchronous-Motor Control

1.4.2.1 *Brush-Type.* A typical low-voltage brush-type synchronous motor control is shown in Fig 4. The details of operation will 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. The motor accelerates as an induction motor with its field connected across its starting (and discharging) resistor. A thermal relay 26*F* for damper winding protection is in series with this resistor. Should the motor fail to start and accelerate, the relay will operate to open the line-contactor coil circuit. This protection is discussed in Section 2.3. 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 56 ac, an auxiliary timing relay 2, and the field contactor 41. The field application relay has two coils, a dc closing coil 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 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 will occur at 94 to 98 percent of synchronous speed, at which time its contacts will close, energizing the field contactor 41.

1.4.2.2 *Brushless Type.* In the brushless-type synchronous-motor control, the motor field and the field application circuit are mounted on the motor rotor. Alternating current is still required for the line contactor and for 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 Fig. 5 and operates as follows: The purpose of the control circuit is to keep the rectifier SCR1 from firing until the induced field-current frequency is very low, representing a close approach to synchronous speed, then to fire the rectifier SCR1 at the proper time, and thus apply excitation to the synchronous-motor field. At the same time, the field-discharge resistor is removed from the circuit. This is done by the firing characteristic of rectifier SCR2. This frequency sensi-

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tive part of the control circuit assures that the field excitation is applied at the proper pull-in speed for successful synchronizing.

2. Motor Protection Requirements

2.1 Pullout Protection

2.1.1 ***Induction Motor Stalling.*** An induction motor is said to stall 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 produces motor current equal to or approaching locked rotor current.

2.1.2 ***Synchronous Motor Pullout.*** When a synchronous motor loses synchronism with the system to which it is connected, it is said to be out of step. This occurs when the following takes place singly or in combination:

(1) Excessive load is applied to the shaft

(2) The supply voltage is reduced excessively

(3) 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 will favor stability. Three-phase, double line-to-ground, line-to-line, and line-to-ground faults have a decreasing effect on stability in the order listed.

Underexcitation of the machine is a distinct cause of out-of-step operation. This may be caused by incorrect tripping of the field breaker (or contactor) or by opening or short circuiting of the field circuit. If loss of synchronism (pullout) of a synchronous motor occurs and the condition is not detected 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.

2.1.3 ***Electrical Quantities Available for Detection.*** For s synchronous motor, loss of synchronism is a gradually evolving phenomenon rather than instantaneous occurrence. 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. If resistance is significant, this reversal occurs prior to the 180° point. The reactive flow for virtually the full slip cycle is into the motor, but may be out of the motor for a small part of the slip cycle, depending upon the machine excitation.

2.1.4 ***Protective Devices.*** Out-of-step detection devices for synchronous motors usually operate on the stator power-factor angle or ac current in the field. 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).

Devices used in the field circuit usually consist of a current transformer with an ac relay on its secondary. When the machine is operating synchronously, there is no ac component of 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, either this relay must be blocked or the current transformer must be so located that no current flows in it at that time. This scheme is not adaptable to motors having a brushless excitation scheme. For such a scheme, a power-factor relay may be used. Refer to Section 4.2.10.

For very large synchronous motors or synchronous condensers, a loss-of-field relay, with an impedance-measuring element (and in one type also with a directional element), is

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often used to detect var flow into the machine. Accidental tripping of the field breaker (or contactor) or loss of field current can be accurately detected by this device. See Section 4.2.3. There have also been successful applications of field current devices operating from a field current shunt and of notching relays that count pole slips based upon power reversals.

2.2 Stator Winding Protection

2.2.1 ***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 and thermal damage.

The physical and dielectric properties of an insulation system deteriorates with age, and like other chemical activity, the process is accelerated by an elevation in temperature. A rule of thumb has been developed from tests and experience to indicate that life of an insulation system is approximately halved for each 10° C incremental increase (the range of 7-12° C is indicated for modern insulation systems) of winding temperature and approximately doubled for each 10° C decrease. 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 electrical surge, moisture, penetration of conducting contaminants, or mechanical stress such as vibration or distortion forces which occur during starting. 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 judgement and applicable standards. [For limits established by the motor industry, see the following sections of NEMA MG 1-1972 (American National Standard, Motors and Generators, C52.1-1973) (See Section 5.10, Ref [11]); MG1-12.41-1972, MG1-12.42-1972, and MG1-12.52-1972 and MG1-20.40-1973 for induction motors and MG1-21.40-1973 for synchronous motors.]

It should be kept in mind 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 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 which would result from a service interruption or a potential motor burnout.

2.2.2 ***Motor Overloading.*** Overloads can produce stator temperature rises in excess of planned thermal limits of the winding insulation system. However, in all cases of operation which 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 will 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 will be very rapid due to the large currents. Since very little heat is transmitted in the short time interval from the conductors to the more massive parts of the motor, the heat storage capacity will appear to be small, and thermal limits of the winding insulation may be reached within seconds.

2.2.3 ***NEC (National Electrical Code) Requirements for Motor Protective Devices and OSHA.*** The American National Standard, National Electrical Code (NFPA No 70-1971), C1-1971, 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, mobile homes, etc. It does not cover installations under the exclusive use of electric utilities, mines, and certain other exceptions. The

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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 approval authority.

OSHA (Occupational Safety and Health Act, Code of Federal Regulations, Title 29, 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 1971 edition of the NEC and incorporates its requirements for electrical installations. The edition of the Code adopted by OSHA is not generally the same as that enforced by local authority.

With 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, the NEC essentially represents requirements for practically all residential, commercial, and industrial installations. For this reason, NEC requirements as applying to motors and motor circuits are included.

The NEC states that the device(s) selected for "motor running overcurrent (overload) protection" must "protect the motor, the motor control apparatus, and branch-circuit conductors against excessive heating due to motor overload and failure to start." By NEC definition, "overload in electrical apparatus is an operating overcurrent which, when it persists for a sufficient length of time, would cause damage or dangerous overheating of the apparatus. It does not include short circuits or ground faults" (This requirement is waived in certain installations such as fire pumps where it is considered that the operation of a protective device may introduce additional or increased hazards.) (See Section 5.10, Ref [21], Sections 433 and 514.)

The NEC also states that the devices selected for "motor branch circuit over-current protection" must protect the motor branch circuit conductors, the motor control apparatus, and the motor against overcurrents due to short circuits and grounds in addition to some operating overloads. 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 which is responsive to motor current" and a "thermal protector integral with the motor."

For continuous duty motors, a separate overload device responsive to motor current is specified in the NEC (article 430-32) to be rated or selected to trip at no more than 125 percent 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 percent of full load current rating for all other motors.

For continuous duty motors having a thermal protector integral with the motor, the NEC specifies that the thermal protector shall be approved for use with the motor which it protects on 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 not exceeding 170, 156, and 140 percent of motor full load current rating where full load current is less than 9, between 9.1 and 20, and above 20 A, respectively.

Other NEC recognized overload protection involves the use of embedded temperature detectors used in conjunction with intermediate devices which cause motor current to be interrupted.

2.2.4 ***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

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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.

2.2.5 ***Unusual Ambient Conditions.*** Motors and control such as separate overload devices are ordinarily rated for use in a maximum ambient higher than 40° C and, conversely, in-areas exist where the ambient temperature at the motor or the overload device, or both, exceeds or is appreciably lower than this and may require special consideration as described in the following.

Considering the effect on the motor, when its ventilating medium increases in temperature, the motor winding temperature increases by an equal amount. This means that a motor operating in a higher than rated ambient temperature, even though within rated load, can subject the windings to overtemperature similar to that resulting when the motor is overloaded in a normal ambient. The motor rating may have to be appropriately reduced for operation in such high ambients. However, the life of the motor insulation is a function of its temperature over a period of years. A fully loaded motor which reaches an abnormally high temperature for a short time only on hot summer days but runs at normal or subnormal temperature the rest of the year will not have its insulation life seriously shortened.

Illustrative of locations which may involve higher than normal ambient temperature are motors in direct sunlight during a hot summer day or in boiler rooms. Additionally, excessive motor temperature may result if the discharge air is misdirected so as to reenter the inlet ports. This can be caused by installing motors too close to a wall or to each other.

Motors installed at high altitudes operate in an atmosphere of lower than normal air density with reduced ventilation effectiveness, again resulting in a higher than normal temperature rise unless the motor rating is reduced.

Motors designed for special applications, such as sealed motors on submersible pumps which have their rotor in the path of the fluid being pumped, involve unusual ambient conditions which require special consideration in selecting and setting thermal devices and should be evaluated on an individual basis.

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, however, since other considerations besides the thermal limitations of motor components must be made. Mechanical parts such as shafts and bearings will have to be suited for increased loading. Margins on pull-out torque or breakdown torque may be cut dangerously close. Thus it is not recommended that motors be loaded beyond their rating in lower than normal ambients without careful investigation.

In case of separate overload devices such as thermal overload relays, the effective heater rating will be reduced when located in an ambient higher than 40° C and, conversely, increased in lower ambient temperatures. If the temperature at the control is the same as at the motor, the proper relationship will generally be obtained. Should the temperature at the control and motor be different, special consideration must be given when selecting the protective relay setting or by specifying ambient compensated types. Further details will be discussed in Section 2.2.10.2.

In motors of the totally enclosed, heat-exchanger type, which are cooled by internal recirculation of water-cooled air, overheating of the motor can occur 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 a failure of some other component such as a separately driven fan, which may remain undetected, must be monitored in addition to the water. Various types of detectors are available which may be used for visual instrumentation, signaling, or shutdown.

2.2.6 ***High and Low Voltage and Frequency.*** Motors are generally expected to operate successfully under running conditions at rated load with a variation of plus or minus 10 percent of rated voltage, or plus or minus 5 per-

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cent of rated frequency or a combination of the two provided the sum of the absolute values of the deviations does not exceed 10 percent and the frequency variation does not exceed plus or minus 5 percent. 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 since it is characteristically of short duration and thus is considered as not damaging to the insulation.

The motor can be protected against such overloads by devices which sense line current but otherwise are independent of frequency. Direct winding temperature sensing devices also will give protection from overheating due to the abnormal voltage and 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 percent 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 will be shortened. In such instances motors may be obtained 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, or both, power supplies for adjustable-speed drive applications. For these applications, the motors should have been 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.

2.2.7 ***Locked Rotor or Failure to Accelerate.*** Failure of a motor to accelerate when the stator windings are energized may be caused by many things including mechanical failure of motor or load bearings, by low supply voltage, or by an open circuit in one phase of a three-phase supply voltage. When the motor stator windings are energized with the rotor stationary, a motor performs like a transformer with resistance-loaded secondary windings. Typically, stator winding currents may range from three to seven or more times rated full load value depending on motor design and supply system inpedance. The motor controller must by capable of interrupting locked-rotor current. A representative starting curve with motor thermal capability also shown appears in Fig 6.

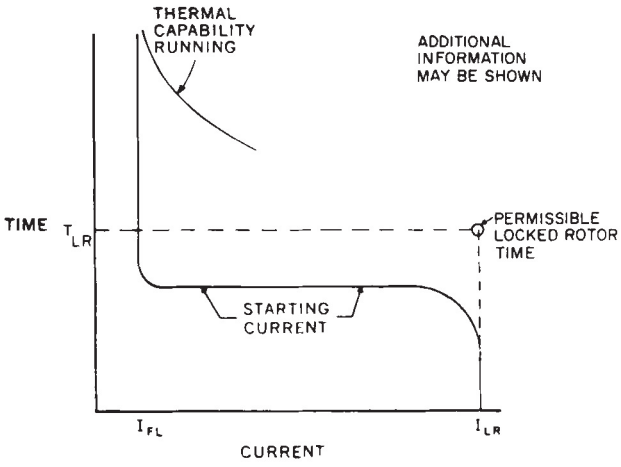


Fig 6
Typical Motor Starting and Capability Curves
(Applies for a Particular Motor Terminal Voltage and for Cold Start)

Another factor is that the heat loss in the stator winding is 10 to 50 or more times normal and the winding is without benefit of the ventilation normally produced by rotation of the rotor. The temperature rise of the windings is proportional to the square of the current multiplied by the time I^2t, neglecting slight heat from the windings. Overtemperature from this cause can be prevented by sensing the line current magnitude and interrupting the power when the current value is excessive. Since motors require and can stand high current for a short time during starting, some time delay must be incorporated in the current-sensing device, or provision

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must be made in the protective device to sense motor winding temperature as well as line current magnitude. Otherwise, the current sensing device must be shunted out during the starting period. To provide protection for locked rotor, the protective devices must be set to disconnect the motor before the stator insulation suffers thermal damage or the rotor conductors melt or suffer damage due to repeated stress and deformation.

Depending on the design, a motor may be stator limited or rotor limited during locked rotor conditions. In high horsepower designs, frequently rotor heating is the limiting factor. The motor manufacturer can furnish the allowable locked rotor time only after the motor design is completed. This is usually given as a time at rated locked rotor current starting from either rated ambient temperature or rated operating temperature. It also can be given as part of the motor time-current curve.

Starting times vary depending on motor design and load torque characteristics. Times may very from less than 2 to more than 20 and must be determined for each application. Overload relays applied to protect against the locked rotor condition must be able to carry full starting current for almost the entire starting period without operating. Although the starting current does drop off near the end of the starting time, this effect is normally neglected providing a slight margin of safety from relay operation during starting.

Care should be exercised in applying overcurrent relays for locked rotor protection. The starting current characteristic, as usually plotted, is a trace of current versus time. The overcurrent relay characteristic, as usually plotted, is a collection of points describing the operating time of the relay with a fixed continuous current applied. If the two characteristic curves are superimposed, the overcurrent characteristic may be at all points above the starting characteristic of the motor and still close its contacts during starting.

Section 5.9, Ref [18], sheds light on the performance of overcurrent relays subject to decreasing current. Proper application of this information allows a satisfactory setting to be chosen.

Some of the larger motors are designed to have a maximum allowable locked rotor current time less than the starting time of the drive. This is permissible since, during a normal start, much of the active power input during starting is utilized as shaft load, while on locked rotor all of the active power input to the motor is dissipated as that loss in the motor. Therefore, an overload relay with time delay sufficient to allow this motor to start would have too much delay to protect the same motor for locked rotor.

For these applications two approaches are possible:

(1) Include motor zero speed switch which supervises an additional overload relay set for locked rotor protection. As soon as the motor begins to rotate, the locked rotor relay is incapacitated leaving the overload protection to the longer time starting duty relay. If the design is such that the starting time exceeds the allowable locked rotor time, a zero speed switch should be supplied with the motor rather than after the motor has been installed.

(2) Use a relay with independent adjustments of locked rotor and running characteristics that tracks temperature rapidly during starting and slower during gradual load increases. (See Section 5.5, Ref [13].)

For brush-type synchronous motors, one method for locked rotor protection used is a 26*F* device shown in Fig 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 start but much longer for a normal start.

The operator can manually monitor the starting operation to provide additional protection during starting.

2.2.8 ***Frequent Starting or Intermittent Operation.*** During startup, the minimum losses or heat energy developed in the rotor winding of induction motors and the damper winding of synchronous motors equals the kinetic energy stored in the rotating parts at synchronous speed. In larger motors, it is likely that rotor winding losses and, therefore, rotor heating exceeds that in the stator.

In repeated starting and intermittent operation such as jogging, inching, or spotting, the running period is short so that very little heat is carried away by the cooling air induced by rotor rotation. Repeated starts can build up temperatures to dangerously high values in either stator or rotor windings, or both, unless

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