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(Revision of ANSI/IEEE C37.96-1976)

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(Revision of ANSI/IEEE C37.96-1976)

An American National Standard

IEEE Guide for AC Motor Protection

Sponsor

IEEE Power System Relaying Committee of the
IEEE Power Engineering Society

Secretariat

Institute of Electrical and Electronics Engineers
National Electrical Manufacturers Association

Approved June 9, 1988

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Foreword

(This Foreword is not a part of ANSI/IEEE C37.96-1988, IEEE Guide for AC Motor Protection.)

Since the original guide was issued in 1976 ANSI/IEEE C37.96-1988 incorporates a number of changes. Some of the more significant changes were made in the sections dealing with phase overcurrent protection, locked rotor protection, and additions to sections on variable speed motor protection and motor protection using solid-state devices. Other changes were made to bring this guide up-to-date and more in line with present-day requirements.

This guide was revised by the AC Motor Protection Guide Working Group, of the Rotating Machinery Subcommittee, of the Power System Relaying Committee, of the IEEE Power Engineering Society. The working group membership at the time of this revision was as follows:

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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 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 variable-speed motors where specifically indicated.

This guide 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, application, and setting philosophy is presented. However, to enable the user to evaluate the need for various forms of protection and to select and properly apply suitable equipment, for most situations

(1) Section 2 presents a brief description of the damaging effect on a motor of abnormal voltage, current, temperature, and incorrect operation 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 specific situation.

(2) Section 3 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 combinations of devices normally applied for the associated protective function. For a complete listing of all device designations (both ANSI and NEMA) used in this guide see Table 7.

(3) Section 4 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 desirability 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 lines, 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 a 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 or wire, and a direct current is circulated through the winding to create alternately north and south magnetic flux poles.

The direct current (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 (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 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 disconnection 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 and protection of certain motors may be secondary. In this case see 2.7.1.1.1 and 2.7.1.1.2.

1.3.1 Alternating Current (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 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 loss of voltage protection. Loss of voltage protection is inherent with magnetic contactors when used with integral control supply and three-wire control circuits. Loss of voltage *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 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 V-4800 V). Standards for these motor controllers are given in ANSI/NEMA ICS 2-1983 [9][1], .324. The ratings are listed in ANSI/NEMA ICS 2-1983 [9], Table 2-324-2. 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, however, fault protection is provided by instantaneous overcurrent relays. Other relaying is added as described in Section 2.

1.3.1.3 NEMA Class E2 High-Voltage Motor Controllers (2200 V-4800 V). These motor controllers are similar to Class E1 controllers described in 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, ANSI C37.16-1980 [2], 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

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[1] The numbers in brackets correspond to those of the references in 1.5.

motors, whereas ANSI C37.16-1980 [2], covers the limitations relating to repetitive duty and normal maintenance. ANSI C37.06-1987 [1] 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 that 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, 2, and 3.

1.4.1 Stator Control Equipment. Protection from extremely low or complete loss of line voltage is an inherent feature of the nonlatched-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% of rated line voltage, according to ANSI/NEMA ICS 2-1983 [9], 110.41 (b) while the dropout point is not defined and may vary from 20% to 70% 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 Loss of Voltage 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 loss of voltage protection. During a condition of low-line voltage, a synchronous motor acts as a generator for a short period of time and therefore tends to maintain its ac terminal voltage for a considerably longer period than an induction motor. See 2.7.1.1 for information on the protection of the motor for this condition.

1.4.1.2 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, the control circuit shown in Fig 2 should be used. This is referred to as three-wire control with time-delay loss of voltage protection, and consists of a

Fig 1
Three-Wire Control Circuit with Loss of Voltage Protection
(Field Control Not Shown)

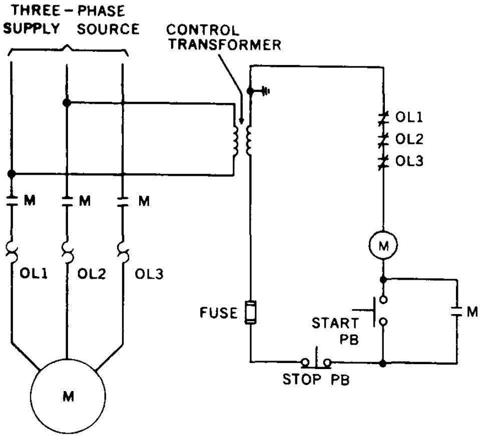
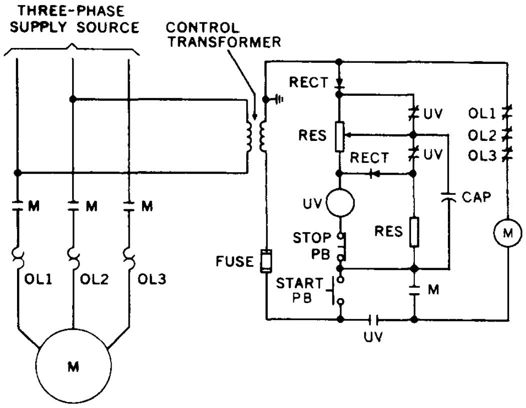


Fig 2
Three-Wire Control Circuit with Time-Delay Loss of Voltage Protection

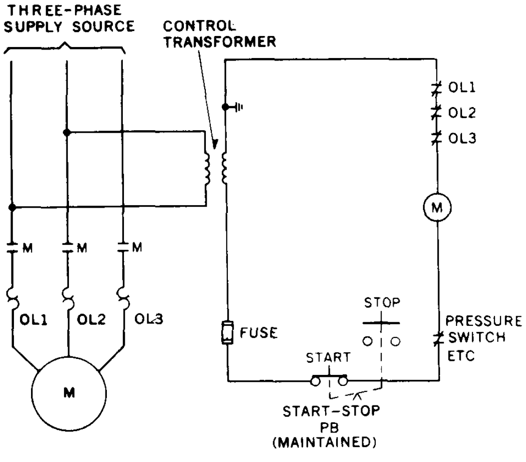


time-delay undervoltage relay that maintains a sealing contact for a definite period after a voltage failure.

1.4.1.3 Two-Wire Control. When the auxiliary control contact M of Fig 1 is omitted, the start-stop pushbutton 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 Fig 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. In addition, unexpected automatic restarting after restoration of voltage may be a safety hazard.

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.

Fig 3
Two-Wire Control Circuit with Loss of Voltage Release



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

1.4.1.4 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 in and must be tripped by operating a specific device or contact.

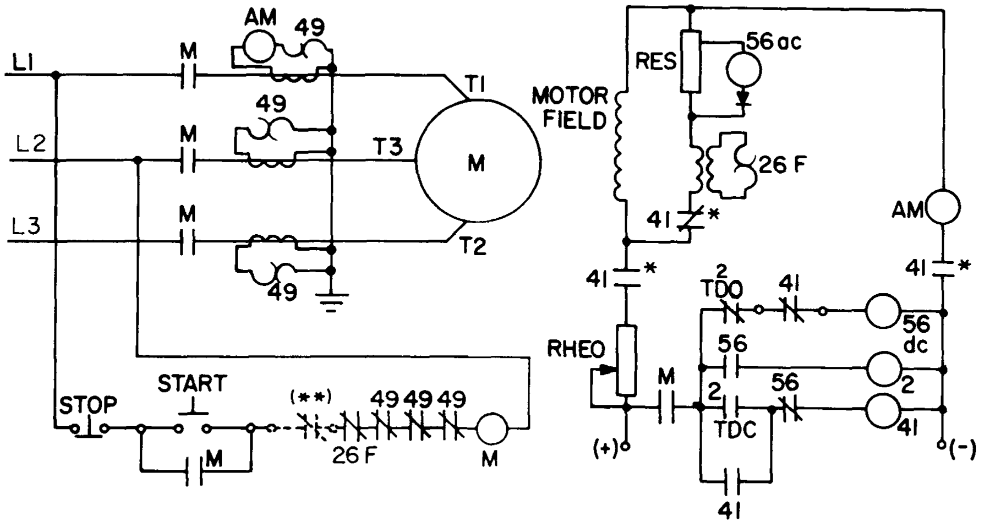
1.4.2 Field-Control Equipment. Switching the field of a synchronous motor is complicated by the fact that the field may be any of

(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
    (a) A shaft-driven dc exciter
    (b) A separate motor-generator set
    (c) A separate static rectifier
(2) A brushless type field that requires
    (a) Direct-current excitation for the field of a rotating ac exciter
    (b) Alternating-current 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 rate (95%-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.

1.4.2.1 Brush-Type. A typical low-voltage brush-type synchronous motor control is shown in Fig 4. The details of operation varies 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 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 2.3. It is fre-



TDC-TIME-DELAY CLOSE
TDO-TIME-DELAY OPEN
*CONTACTS ARE "MAKE-BEFORE-BREAK"
(**)OTHER PROTECTIVE DEVICES

Fig 4
Typical Brush-Type Synchronous-Motor Control

quently 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%-98% 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 sensitive part of the control circuit ensures that the field excitation is applied at the proper pull-in speed for successful synchronizing.

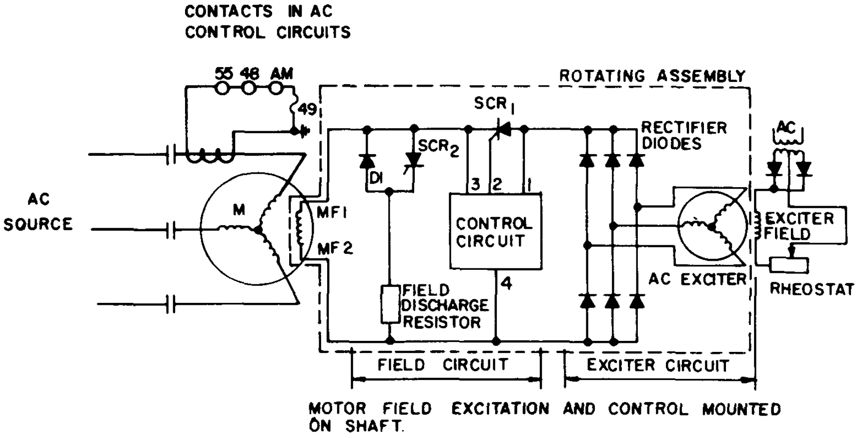


Fig 5
Typical Brushless-Type Synchronous-Motor Control

1.5 References. This guide shall be used in conjunction with the following publications:

[1] ANSI C37.06.1987, American National Standard Preferred Ratings and Related Required Capabilities for AC High-Voltage Circuit Breakers on a Symmetrical Current Basis.[2]

[2] ANSI C37.16-1980, American National Standard Recommendations for Low-Voltage Power Circuit Breakers and AC Power Circuit Protectors, Preferred Ratings, Related Requirements and Application.

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

[4] ANSI/IEEE C37.2-1987, IEEE Standard Electrical Power System Device Function Numbers.[3]

[5] ANSI/IEEE C37.13-1981, IEEE Standard for Low-Voltage AC Power Circuit Breakers Used in Enclosures.

[6] ANSI/IEEE C37.101-1985, IEEE Guide for Generator Ground Protection.

[7] ANSI/IEEE C62.92-1987, IEEE Guide for Application of Neutral Grounding in Electrical Utility Systems, Part I — Introduction.

[8] ANSI/NEMA ICS 1-1983, General Standards for Industrial Control and Systems.[4]

[9] ANSI/NEMA ICS 2-1983, Industrial Control Devices, Controllers, and Assemblies.

[10] ANSI/NFPA 20-1987, Centrifugal Fire Pumps.[5]

[11] ANSI/NFPA 70-1987, National Electrical Code.

[12] 29 CFR, ch XVII, part 1910, OSHA.[6]

[13] NEMA MG1-1987, Motors and Generators.

[14] NEMA MG10-1983, Energy Management Guide for Selection and Use of Polyphase Motors.

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[2] ANSI publications are available from the Sales Department, American National Standards Institute, 1430 Broadway, New York, NY 10018.

[3] ANSI/IEEE publications are available from the IEEE Service Center, 445 Hoes Lane, PO Box 1331, Piscataway, NJ 08855-1331, or from the Sales Department, American National Standards Institute, 1430 Broadway, New York, NY 10018.

[4] ANSI/NEMA publications are available from the National Electrical Manufacturers Association (NEMA), 2101 L. Street, NW, Washington, DC 20037, or from the Sales Department, American National Standards Institute, 1430 Broadway, New York, NY 10018.

[5] ANSI/NFPA publications are available from the Sales Department of the Fire Protection Association, Batterymarch Park, Quincy, MA 02269, or from the Sales Department, American National Standards Institute, 1430 Broadway, New York, NY 10018.

[6] This publication is available from the Superintendent of Documents, US Government Printing Office, Washington, DC 20402.

[15] BOOTHMAN, D. R., ELGAR, E. C., REHDER, R. H, and WOODALL, R. J. Thermal Tracking — A Rational Approach to Motor Protection. *IEEE Transactions on Power Apparatus and Systems*, vol PAS-93, Sep/Oct 1974, pp 1335-1344.

[16] IEEE REPORT. *Transient Response of Current Transformers*. Power System Relaying Committee, July 6, 1973.

[17] RAMSAUR, O. *Performance of Overcurrent Relays on Cold Load Restoration*. 1952 PEA Relay Committee Proceedings.

[18] ROCKEFELLER, G. D. Relaying CT — *A Source of Vital Information and Misinformation*. Georgia Institute of Technology, Atlanta, GA. Conference on Protective Relaying, 1973.

[19] SHULMAN, J. M., ELMORE, W. A., and BAILEY, K. D. Motor Starting Protection by Impedance Sensing. *IEEE Transaction on Power Apparatus and Systems*, vol PAS-97, no 5, Sep/Oct 1978, pp 1689-1695.

[20] WAGNER, C. F. and EVANS, R. D. Symmetrical Components. New York: McGraw Hill.

1.6 Applicable Documents in Preparation[7]

2. Motor Protection Requirements

2.1 Pullout Protection

2.1.1 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 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 out of step. This occurs when the following actions take 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 occuring 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. 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. When 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 a synchronous motor, loss of synchronism is a gradually evolving phenomenon rather than an 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 maching 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 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 alternating 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).

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[7] When the following document is completed, approved and published, it will become a part of this listing: IEEE Standards Project PC62.21 (in preparation) Application Guide for Surge Protective Equipment on AC Rotating Machinery.

Devices used in the 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 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 with a brushless excitation scheme. For such a scheme, a power-factor relay may be used. See 4.2.12.

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 field breaker (or contactor) or loss of field current can be accurately detected by this device (see 4.2.5). 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 or thermal damage.

The physical and dielectric properties of an insulation system deteriorate 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 the life of an insulation system is approximately halved for each 10 °C incremental increase (the range of 7 °C - 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 impulse or switching surge voltage, moisture, penetration or 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 motor industry, see the following sections of NEMA MG1-1987 [13], 12.41, 12.42, and 12.52. For induction motors see NEMA MG1-1987 [13], 20.40. For synchronous motors see NEMA MG1-1987 [13], 21.40.

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 that 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 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 heat storage capacity appears to be small, and thermal limits of the winding insulation may be reached within seconds.

2.2.3 National Electrical Code (NEC) Requirements for Motor Protective Devices and OSHA. ANSI/NFPA 70-1987 [11] 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. ANSI/NFPA 70-1987 [11] 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, 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 ANSI/NFPA 70-1987 [11] and incorporates its requirements for electrical installations. The edition of ANSI/NFPA 70 (NEC) 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 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 70-1987 [11], 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 70-1987 [11], 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 70-1987 [11], Art, 430-32.)

For continuous duty motors, a separate overload device responsive to motor current is specified in ANSI/NFPA 70-1987 [11] Articles 430-32, 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 70-1987 [11], Articles 430-32 specifies that the thermal protector shall be approved for use with the motor that 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% of motor full-load current rating where full-load current is not exceeding 9 A, between 9.1 A to 20 A, and above 20 A, respectively.

Other overload protection recognized by ANSI/NFPA 70-1987 [11], Articles 430-32(a) (4) involves the use of embedded temperature detectors used in conjuction with intermediate devices that 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 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 controls, such as separate overload devices, are ordinarily rated for use in a maximum ambient no higher than 40 °C and, conversely, in areas where the ambient temperature at the motor or the overload device, or both, exceeds or is appreciably lower than this 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. The effect on 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. Loss of life can occur anytime equipment is operated outside its design specifications. For operation under specific abnormal operating conditions special studies should be conducted or information on loss of life should be obtained from the manufacturer.

Illustrative of locations that 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 that have their rotor 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.

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 made. 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 that motors be loaded beyond their rating in lower than normal ambients without careful investigation.

In the case of separate overload devices, such as thermal overload relays, the effective heater rating is reduced when located in an ambient higher than 40 °C and, conversely, increased in lower ambient temperatures. When the temperature at the control is the same as at the motor, the proper relationship is generally 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 are given in 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, considerations 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 that may be used for visual instrumentation, signaling, or shutdown.

2.2.6 High and Low Voltage and Frequency. According to NEMA MG1-1987 [13], 20.45 motors are generally expected to operate successfully under running conditions at rated load with a variation of ± 10% of rated voltage, ± 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 ± 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 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 that sense line current but otherwise are independent of frequency. Direct winding temperature sensing devices also 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% of rated current to prevent nuisance tripping for most motors. The minimum tripping value of the overload protection should factor in this extra current.

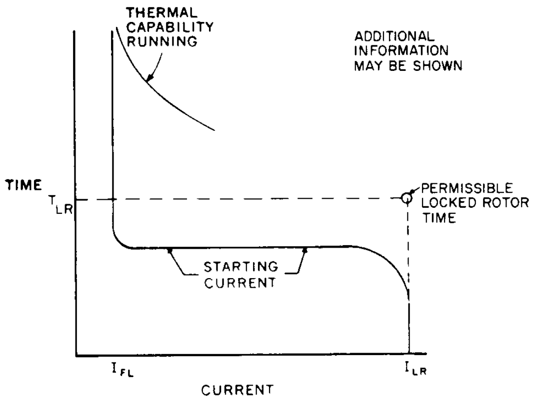
However, if these voltage and frequency variations are expected to occur frequently or to continue for extended periods of time, motor insulation life expectancy is shortened. In such instances motors may be obtained with lower than normal temperature rises at rated condition to compensate for the adverse 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 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.

2.2.7 Locked Rotor or Failure to Accelerate. Failure of a motor to accelerate when its stator is energized may be caused by many things 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 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 impedance. The motor controller must be capable of interrupting locked-rotor current. See Fig 6 for a typical example of starting current and locked-rotor time.

Another factor is that heating in the stator winding is 10 to 50 or more times rated conditions 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 loss 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 tolerate high currents for a short time during acceleration, some time delay must be incorporated in the current-sensing device, or provision must be made in the protective device to sense motor winding temperature and also 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 before the motor stator insulation suffers thermal damage or the rotor conductors melt or suffer damage due to repeated stress and deformation.

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



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 vary from < 2 s to > 20 s 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 starting 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 starting.

Care must be exercised in applying overcurrent relays for locked-rotor conditions. 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 the relay might still operate during starting. Reference [17] 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 of an induction motor nearly equals locked-rotor magnitude but has a lesser heating effect. This occurs because rotor resistance is a function of slip and decreases during acceleration. When at rest the rotor is swept by the rotating field set up by 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. Consquently, for some large induction motors, with low starting voltage or with high inertia drives, the starting time may exceed the allowable locked-rotor time without excessively heating the rotor. This condition is shown in Fig 7 with one method of showing the accelerating time limit for three different starting voltages. The lower ends of the curves are the locked-rotor time points.

For this case an overcurrent relay set to coordinate with the locked-rotor thermal limit trips on starting current.

For these applications four approaches are possible:

(1) Include a motor zero-speed switch that 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. When the design is such that the starting time exceeds the allowable locked-rotor time, a zero-speed switch should be specified with the motor, rather than after the installation of the motor. See Fig 8.

(2) Apply a distance (mho type) relay device, 21 to supervise the time-overcurrent relay device 51, which has been set within the thermal limit of the motor for a locked-rotor condition. For a successful start-up of the motor, the mho relay will pick up when the motor is energized, but will prevent unnecessary tripping by resetting before the time-overcurrent 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 time-overcurrent relay operates (see Figs 8, 9, and 27). Although a single-phase mho relay works, in practice a three-phase relay is used.

A time overvoltage relay device 59 may be used instead of the time overcurrent relay to implement this scheme since voltage and current are proportional under locked-rotor conditions. The use of a time overvoltage relay is dependent on sufficient voltage drop through the source impedance due to the starting current inrush and is therefore limited to relatively high impedance sources (see [18]). It is set similar to the time overcurrent 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 pick-up 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 time overcurrent relay because of the decreasing current characteristic of the motor as it accelerates for normal start-up.

(3) For some applications where the operating time of the time overcurrent relay is approximately the same as the start-up time of the motor, it is possible that an instantaneous overcurrent relay can be used instead of the mho relay (see Fig 10). For most high inertia drive motors, this scheme has limited application. This is because of the difficulty in setting the instantaneous overcurent relay sufficiently low to pick-up reliably on start-up and still reset to prevent tripping before the time overcurrent relay times out. The problem is compounded where starting-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 start-up is approximately the same regardless of the voltage at the motor terminals.

(4) 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 [15]).

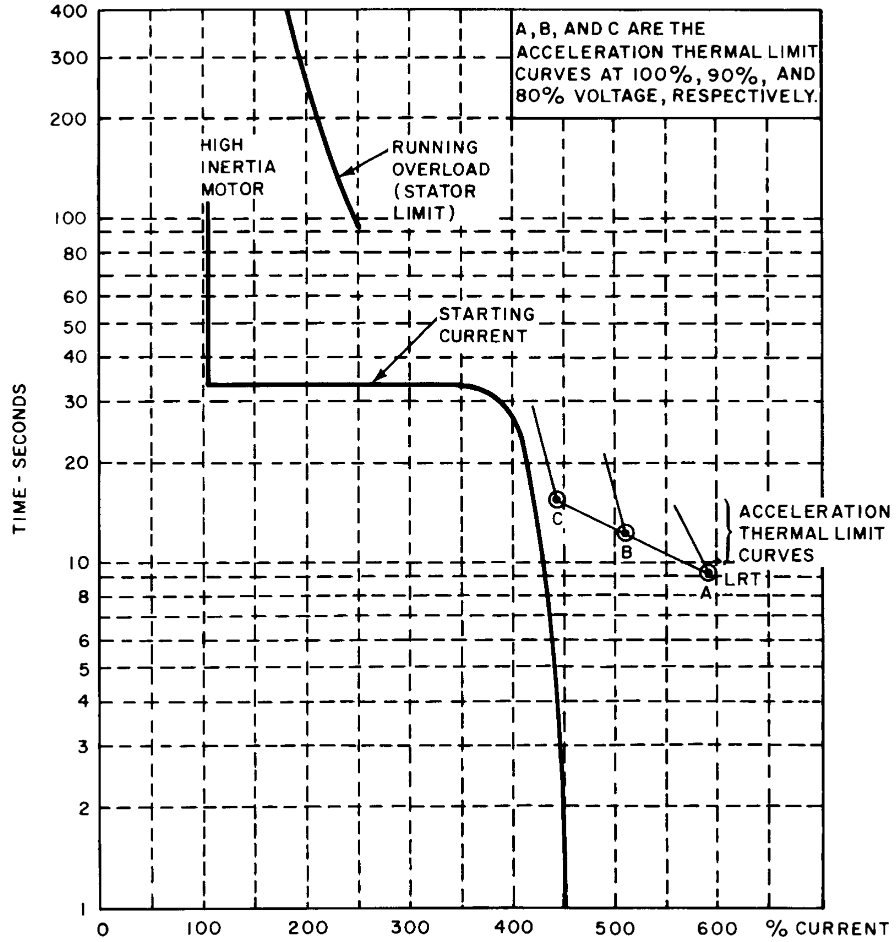


Fig 7
Typical Time-Current and Thermal Limit Curves

For brush-type synchronous motors, one method for locked-rotor protection used is a device 26F, 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 larger 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 start-up, 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 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 enough time is provided to allow the heat to be dissipated.

Induction motors and synchronous motors are usually designed for the starting conditions indicated in NEMA MG1-1987 [13], 12.50, 20.43, and

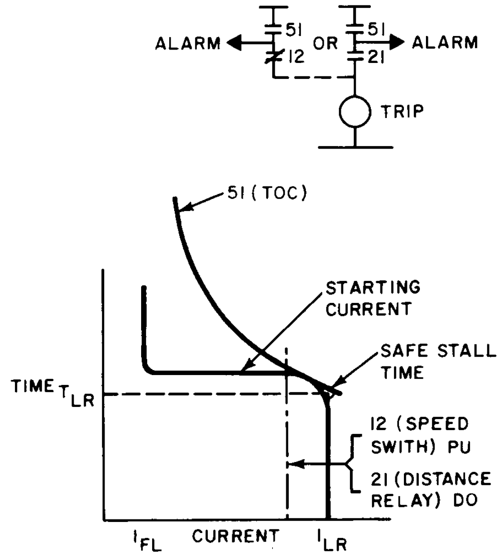


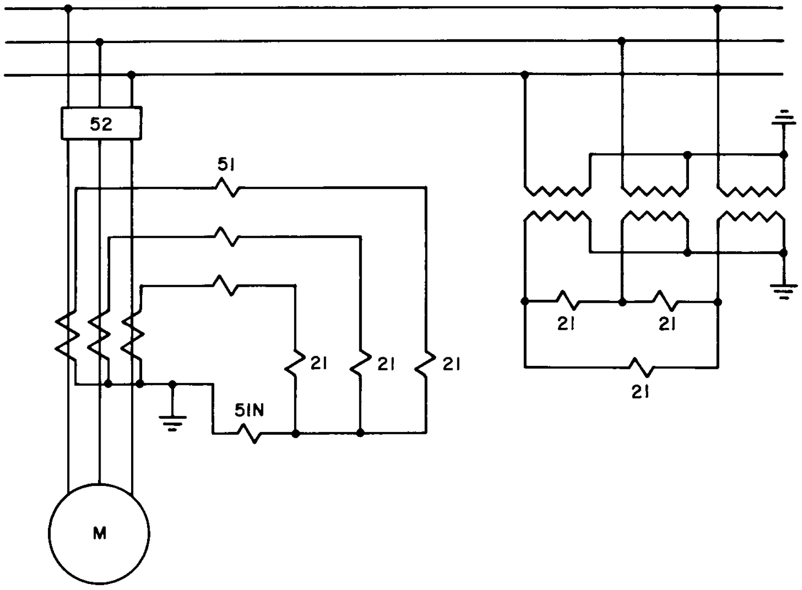
Fig 8
Locked-Rotor Protection with Time-Overcurrent Supervised by a Speed Switch or a Distance Relay

21.43. These standards provide for two starts in succession, coasting to reset between starts with the motor initially at ambient temperature, and for one start when the motor is at a temperature not exceeding its rated load operating temperature. This assumes that the applied voltage, load torque during acceleration, method of starting, and load WK^2 are all within values for which the motor was designed. The application and protection of motors having abnormal starting conditions must be coordinated with the motor manufacturer.

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 MG1-1987 [13], 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.

Information on repetitive start-stop cycling of motors can be found in NEMA MG10-1983 [14].

Fig 9
Distance Relay Used for Locked-Rotor Protection



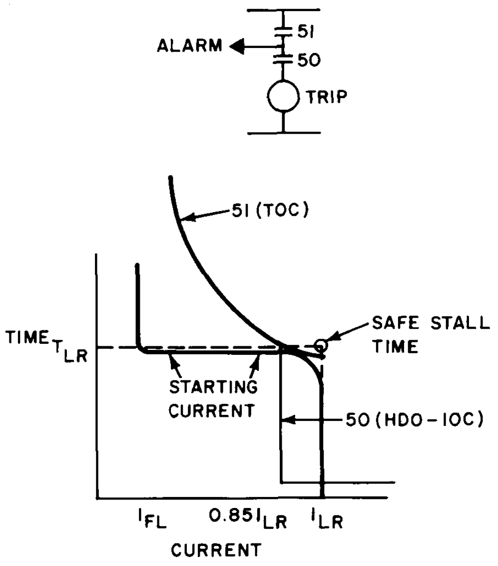


Fig 10
Locked-Rotor Protection with Time-Overcurrent Supervised by a High Dropout Instantaneous Overcurrent

2.2.9 Overtemperture Thermal Protective Devices. There are two main classes of these devices (see 2.2.3). One is a linebreak type, which interrupts load current directly. The second is a control circuit system using detector devices, which interrupt 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 curent 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.

2.2.9.1 Control Circuit Devices Sensing Motor Temperature Only. Devices of this type 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 upon 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 a minimum. Here, thermal element temperture 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, 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 conjuction with supplementary overload devices. With the supplementary overload device and either manual or automatic restarting, the motor cutoff is by the supplemetary overload device detecting the high overcurrent on the first few cycles of a stalled condition and initiating 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 usually 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 but for larger motors 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

(1) Are rotor temperature limited, or
(2) Have stators having an extremely rapid rate of temperature rise.

In the former, 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. In the latter, the mass of the thermal element and its manner of installation determines 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.

2.2.9.2 Linebreak Devices Sensing Motor Temperature and Curent. Devices of this type carry the full motor current through their electrical contacts and interrupt line current directly on operation. They are available, because of physical size limitations, on motors from subfractional horsepower sizes through 5 hp single phase and approximately 10 hp three phase. They consist of a temperature-sensitive element and heater(s) in addition to the contacts and are designed to operate at approximately the same temperature as that established for the maximum limiting insulation temperature for the winding.

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 Underwriters Laboratories 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. Devices responsive to current only may be unable to protect against automatic restarting.

2.2.9.3 Control Circuit Devices Sensing Motor Temperature and Current. In this type of motor protective device, resistance temperature detector (rtd) located between 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. High temperature increases the rtd, which when combined with motor current, provides protection against locked rotor, repeated starts, overload, or inadequate cooling. Other devices allow either quantity to produce operation.

2.2.10 Current-Sensing Type Devices. The recommendations given in ANSI/NFPA 70-1987 [11] for motor overload protection using separate overcurrent (overload) protective devices are referred to in 2.2.3.

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 of a current of sufficient magnitude and duration to cause 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 is dependent on the temperature rise of the windings and 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 ± 10%.

In another type, 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 type 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 that produces an alarm or trip output. Time versus current trip characteristics are similar to those of thermal overload devices. However, there is no overshoot or lag as normally found in a thermal overload type relay.

NEMA T frame motors may require special consideration as described in 2.2.10.3.

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

(1) Thermal overload relays (device 49) incorporating bimetallic elements connected in current transformer secondaries, thus responding to motor current.
(2) Temperature relays operating from search coils or resistance temperature detectors built into the motor.
(3) Resistance capacitance (RC)timing circuits energized by current transformers in the motor leads or combination relays utilizing RC timing circuits and resistance temperature detectors built into the motor (see [15]).

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 plot the relay and motor curves to check the protection obtained. Supplementing the thermal relay (device 49), with other relays, such as a long-time overcurrent relay (device 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 2.2.9.1, 2.2.9.3, and [15].

A time-overcurrent relay can be used to detect an overload by alarming only for moderate overloads.

2.2.10.1 Protection Afforded by Thermal Overload Relays. Most induction motors are protected against damage from unbalanced voltages, running overload, and either a single- or three-phase stalled condition by properly selected thermal overload relays (device 49) in each phase. However, the rotor heating in some larger induction motors and all synchronous motors is more critical. Such machines may warrant the added investment in control to sense single-phasing or voltage unbalance, such as a phase-balance current relay (device 46) or negative-sequence voltage relay (device 47) to provide specific protection against rotor overheating. Additional relaying is described in 2.7.1.3. The NEC requires one thermal element per phase for the protection of all three-phase motors unless protected by other approved means.

After tripping, the relay must cool before it can be reset, and this provides time for the motor winding to cool. Because of its smaller mass, the relay-cooling characteristic is normally somewhat faster than that of the motor. If the overload persists and the relay is reset either normally or automatically at frequent intervals, it is possible for the motor winding to attain an excessive temperature. For this reason, when an overload relay trips, a check should be made to see whether an abnormal condition exists, such as an overload or phase failure of the power supply. The relay should not be reset repeatedly if the overload condition persists.

For the same reason, relays that reset automatically should not be used with two-wire control or with a circuit such that the motor would be restarted automatically after an overload trip. Automatic reset should be used only with three-wire control to prevent restarting until a start button or equivalent device is manually actuated.

Thermal overload relays operated by motor current do not protect motors against overheating due to inadequate ventilation.

2.2.10.2 Ambient Temperature Effects and Ambient-Compensated Types. General and special-purpose motors and industrial control equipment are rated for use in a maximum ambient of 40 °C. When the normal temperatures at the control and motor are different, in general, a heater may be used that differs by one size for each approximate 15 °C difference in temperature, but the control manufacturers' recommendations should be obtained because of the different ambient temperature sensitivities that overload relays exhibit. When the relay ambient is higher than the motor, a higher rated heater is used and vice versa.

The ambient-compensated type of thermal overload relay has essentially the same minimum operating current and time-current characteristics regardless of its ambient temperature. Thus, it allows the motor to carry its rated load regardless of changes in relay ambient temperature. For essential drives, this prevents the motor from being shut down when carrying its normal load, even though the relay ambient temperature may be abnormally high. Solid-state relays are inherently compensated for ambient variations.

The ambient-compensated type of relay prevents nuisance tripping due to high relay ambient temperature. Whether this is achieved without sacrifice of motor insualtion life depends on the motor-winding temperature profile over several years. In an abnormally low motor ambient temperature, the compensated relay allows the motor to carry only the rated current of the relay and therefore protects the motor for inadvertent overload, which might be possible without ambient compensation. With proper considerations of motor and load mechanical characteristics, it may not be necessary to use compensated relays when relay and motor are in the same ambient.

2.2.10.3 Special Application Problems. For certain duty cycles, such as crane applications, it may be difficult to obtain protection at operating overloads and still permit the motor to perform useful work within its thermal capabilities on a short-time basis. In some instances, the difference between the thermal time constants of the motor and the conventional thermal overload relay can result in premature relay operation. Special consideration must be given such applications. Both overcurrent devices and temperature sensors may be necessary. For the type of duty cycles encountered on machine tools however thermal overload relays have been successfully used. For high inertia and other loads requiring a long accelerating time, a thermal overload relay selected to protect the motor at operating overloads may operate during the accelerating cycle or even after the motor has reached rated speed. Again, special consideration must be given such applications.

Generally speaking, directly-heated type thermal overload relays designed for long accelerating time application have proven to be the most suitable protective devices for small motors. Other methods to obtain protection are described in 2.2.7 (see ANSI/NEMA ICS 1-1983 [8]).[4]

ANSI/NEMA ICS2-1983 [9], pt 222 includes both definitions and the recommended nomenclature for expressing the performance characteristics. Overload relays are classified in accordance with the response times at a fixed multiple of the current ratings. For example, a Class 20 overload relay can be expected to operate in not more than 20 s at a current value corresponding to six times its assigned current rating in an ambient temperature of 40 °C while a Class 30 relay can be expected to exhibit an operating time of not more than 30 s at the same overcurrent multiple and ambient temperature. Overload relays with lower response times or for long starting applications are available to meet the protective requirements imposed by the wide variety of motor designs.

In most applications, general and special purpose NEMA T frame motors may be considered to be protected at operating overloads when NEMA Class 20 overload relays are used for this function. Both general purpose and special purpose motors assembled in NEMA U frame sizes can usually be protected by the NEMA Class 30 relay, but Class 20 overload relays should be applied unless individual motor data confirms suitability of Class 30.

Overcurrent devices for the protection of hermetic and other definite purpose motors are usually selected by the manufacturer of the combined equipment rather than by the user, and equipment warranties can be voided by alterations. Some overload relays allow independent locked rotor and running overload protection adjustments.

2.3 Rotor Thermal Protection. Rotor thermal protection for synchronous motors logically includes both the insulated exciting field winding and the uninsulated starting damper or *cage* winding. The field winding is not normally temperature monitored during rotation. However, if desired, the field winding temperature can be determined for brush-type motors by the rise-of-resistance method; an accurate evaluation of the rotor hot-running resistance may be obtained using the brush voltage and field current. An allowance for brush voltage drop may be made for improved accuracy. Another method of obtaining the field winding voltage uses soft metallic points momentarily touched to the slip ring to measure voltage directly and thus avoid measuring brush voltage drop.

The damper winding of a synchronous motor or the cage winding of a squirrel-cage motor performs the function of starting the load and thus must be protected against damage. During stalled conditions, such as locked rotor, dangerously high damper-winding temperatures may be reached in a few seconds. Excessive temperature can damage the damper-winding material, thereby changing its physical characteristics. Repeated excessive thermal stresses can cause the winding bars and short-circuiting end rings or the brazed joints between them to crack (see 2.2.8).

For most synchronous machines, the allowable stall time of the rotor is too short to use a stator-winding temperature-sensing device to provide protection of both rotor and stator. This type machine is typically damper-winding temperature limited.

The methods outlined in 2.2.7 or the use of a long time stator overcurrent relay can provide rotor protection or squirrel-cage thermal protection. There are also other devices available, such as the damper-winding thermal relay (device 26) listed in Table 5.

While running, excessive temperatures in parts of the rotor of either synchronous or induction motors can result from excessive unbalance (negative sequence) currents. There is no allowance for any unbalance in motor starting standards. Negative sequence currents reduce the available starting torque. This lengthens the accelerating time and further contributes to motor overheating (see 2.4.4 and 2.7.1.3).

Operation of synchronous motors drawing reactive power from the system can result in overheating in parts of the rotor that do not normally carry current. Some loss-of-field relays (device 40) can detect this phenomenon.

2.4 Stator Fault Protection

2.4.1 General Consideration. The current flowing to a fault within a motor can vary greatly in magnitude. The main factors that affect the magnitude of fault currents are the source motor feeder and grounding impedances; the type of fault (phase or ground); and the location of the fault in the motor winding.

In the case of high-magnitude short-circuit currents, immediate isolation of the faulted motor is always necessary. However, when the fault current is only a few amperes and the motor is a critical one, an alarm without immediate tripping is sometimes justified.

2.4.2 Effects of System and Motor Characteristics. On systems of low source impedance (high fault current) there is little difficulty for protective relays to distinguish between load, starting, and short-circuit currents. On systems grounded through a resistance or impedance, the ground-fault current is approximately equal to the prefault voltage to ground at the point of fault divided by the grounding or neutral impedance. In a solidly grounded system the maximum ground-fault current is of the same order of magnitude as the three-phase fault current, assuming zero-fault impedance.

Internal faults in motors are usually line to ground, or line to line with or without involving ground. Three-phase faults that do not involve ground are most likely to occur near the line terminals. Faults may also occur from turn to turn in the same phase, or between parallel windings in the same phase of a multiple winding. Certain types of faults are more likely to occur than others due to the motor design and the application.

A short circuit in a wye-connected motor can be

(1) Near the line end

(2) Near the middle

(3) Near the neutral end of the winding

In the first case the voltage across the faulted portion of the winding is the full voltage of the system. With the fault near the neutral end, the voltage across the faulted portion of the winding is quite small. The corresponding short circuit currents are high at the line end and are extremely small or essentially zero for faults near the winding neutral.

In a delta-connected machine on a grounded-neutral system, sensitive ground-fault protection can be obtained for the entire winding, since all portions of the winding are at a minimum of 50% of line-to-neutral voltage above ground potential.

In providing protection over the entire range of fault current, tripping should not be permitted to occur under normal operating conditions. Probably the most important of these conditions is motor starting. Starting current is commonly approximately six times normal full load. However, it may be lower or very much higher for a particular motor design. This initial inrush current contains a direct-current component to which some protective devices are responsive.

Current transformer performance is highly influential in relaying system behavior and can be estimated by methods described in [16], or [18].

2.4.3 Phase-Overcurrent Protection. Motor circuits complying with ANSI/NFPA 70-1987 [11] are required to have one overcurrent unit (series tripping device, protective relay, or fuse) in each phase conductor or other approved means. When fuses are used, the consequences of unbalanced operation and backfeeding of faults following a blown fuse must be considered.

Instantaneous overcurrent relays (IOC) (device 50) are used to detect motor supply cable faults and also severe stator faults. They may be connected to trip directly or through a short time delay to coordinate with the asymmetrical starting current when set just above the locked-rotor current (see Figs 36 and 37). Instantaneous relays can be used for phase protection if the motor kilovoltampere (kVA) is less than half the supply transformer kilovoltampere (kVA) (as a rule of thumb). Where the starting current value approaches the fault current, differential relays should be used.

When a more sensitive setting than allowed by an IOC is required, a time overcurrent (TOC) relay is applied. Time-overcurrent (TOC) relays are available with time-current characteristics suitable for coordination with motor starting characteristics and thermal limits.

A TOC relay can usually be set to provide the desired stator and rotor protection and still permit the rotor to accelerate to running speed without an undesired trip. Normally the TOC relay is connected to trip directly but when desirable it may be supervised by a high dropout (HDO) IOC relay (see Fig 10). The IOC relay allows tripping for severe faults but permits an alarm only for moderate overloads or minor faults. The HDO unit is required to drop out quickly below locked-rotor current, preventing an undesired trip during start-up by the TOC relay. This latter scheme allows a more sensitive setting of the TOC relay without fear of an undesired trip due to a slight overload.

Two time-overcurrent relays, with different time-current characteristics, have occasionally been applied to obtain a better match to the motor thermal limits during start-up and locked rotor.

For wound-rotor induction motors where starting currents are quite low, the use of time-overcurrent relays gives substantially improved protection for short circuits in the ranges immediately above the starting current.

2.4.4 Negative-Sequence Protection. Negative-sequence current is contributed by the motor or system during an unbalanced voltage condition (for example, open-phase, single-phase faults, or unbalanced load) or when there are shorted turns in the stator winding. These negative-sequence currents induce double line-frequency currents that flow in the damper or rotor parts. The magnitude of the double line-frequency current depends upon the location of the fault, number of turns shorted, mutual induction, and system and motor impedance. The danger to the rotor parts is a function of the unbalance in the stator current (see 2.7.1.3).

2.4.5 Ground-Fault Protection. On solidly grounded systems, phase overcurrent relays, direct-acting trip devices, and fuses afford a certain measure of ground-fault protection. For motors where greater sensitivity to ground faults is required, ground relays should be used. Ground relays can be connected residually or to a ground sensor by using a toroidal current transformer that encircles all three-phase conductors.

2.4.5.1 Residually Connected Ground Relay. Figure 31 (b) shows a residually connected ground time overcurrent relay (device 51N). Theoretically the device 51N relay only operates on the zero-sequence current due to ground faults. In practice, however, current may flow through this residual circuit due to the unequal outputs of the phase current transformers. This may be due to the unequal burdens on the current transformers, difference in the current transformer characteristics caused by variations in manufacturing, or current transformer saturation caused by high motor starting currents. Because these unbalanced currents are present, it often becomes necessary to use time-delay residual relays so that undesired tripping on starting does not occur with sensitive current settings on the relay. If instantaneous residually connected relays (device 50N) are used, they may trip due to the false residual that may occur during motor starting or from feedback for an external fault unless they are set fairly high. Where a large ground-fault current exists, this presents no problem but where high-impedance grounding is used, they may be of little value. False residual current can be decreased markedly by increasing residual burden through the use of a lower tap value or by adding a series resistance. However, the former also increases sensitivity to ground-fault currents. Lower phase burden, as for example, through the use of solid-state *phase* relays, also reduces the false residual current.

The combination of three-phase relays and one residually connected ground relay connected to three current transformers is often used to provide phase- and ground-fault protection shown in Fig 31(b).

2.4.5.2 Ground Sensor Relay. Figure 32 illustrates a method of obtaining sensitive ground-fault protection with instantaneous overcurrent relays (device 50G). The toroidal current transformer encircles all three-phase conductors. This arrangement allows all positive- and negative-sequence currents, including their dc components, to be cancelled out, so that only ground-fault current appears in the relay. Figure 11 shows the proper method of grounding the cable sheath when using a toroidal current transformer.

Selection of the optimum toroidal current transformer ratio and quality is important. For minimum primary current pick-up, the current transformer exciting impedance (as indicated by the excitation or saturation curve) and relay impedance should be matched. Therefore, the lowest primary current pick-up value may not occur at the lowest current transformer ratio for a given relay burden. Primary current pick-up values in the range of 4 A - 12 A are practical, utilizing a plunger or induction-disk relay; approximately 1 A primary current pick-up can be achieved with sensitive relays. The latter may have to be time delayed to prevent operation due to zero-sequence cable capacitance current flow during external ground faults.

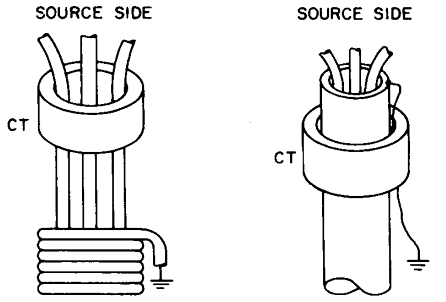


Fig 11
Toroidal (CT) Current Transformer; Cable Sheath Grounding

When surge-protection or lighting arresters are connected at the motor terminals, the sensitivity of the toroidal current-transformer ground-protective scheme should be considered. The relay must be made insensitive to the capacitor inrush current or to the arrester power follow current. The relay must not pick up on these transient currents, or alternatively a short-time delay must be used.

2.4.6 System-Ground Protection. Where a group of motors is supplied from a transformer having a grounded neutral connection, ground-fault currents may be detected in the ground-to-neutral connection of the transformer.

A current transformer with time-delay overcurrent relay, (device 51G), is inserted in the neutral conductor for direct- and resistance-grounded systems. This relay must coordinate with the ground relays in each feeder to avoid tripping the entire bus for a fault in one feeder (see Fig 12).

A distribution transformer with a secondary loading resistor and an overvoltage relay (device 59G) is employed between the supply transformer neutral and ground to provide sensitive high-resistance ground protection (see Fig 13).

Since the loading resistance reflected into the neutral is multiplied by the square of the transformer ratio, fault currents are limited to a very few amperes. Hence, the relay may be used for alarm or tripping. However, tripping is usually recommended to avoid the possibility of a second

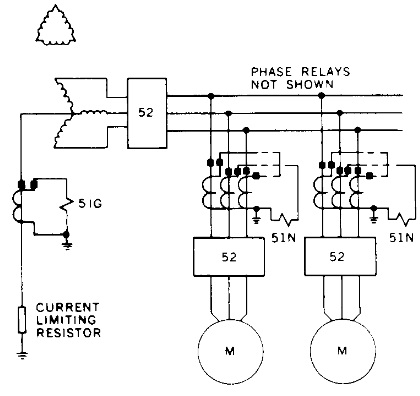


Fig 12
Bus Ground Protection by Current Transformer and Overcurrent

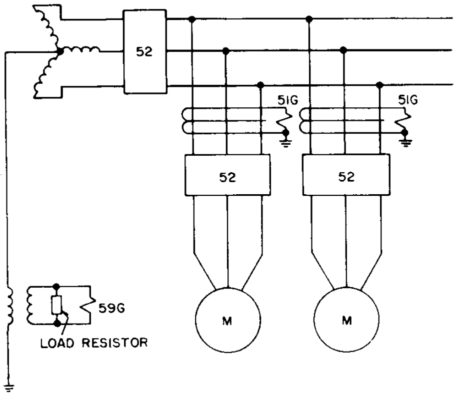


Fig 13
Bus Ground Protection by Distribution Transformer and Overvoltage Relay

ground causing an interphase fault. When high-resistance neutral grounding is used, the sensitivity of the system ground relaying must be commensurate.

Ungrounded or delta-connected systems should have line-to-line voltage-rated voltage transformers, with primaries wye-connected and grounded (see Fig 14). The secondaries are connected-broken-delta across which a loading resistor is connected in parallel with a voltage relay (device 59G). Single-point grounding of the secondary should be used.

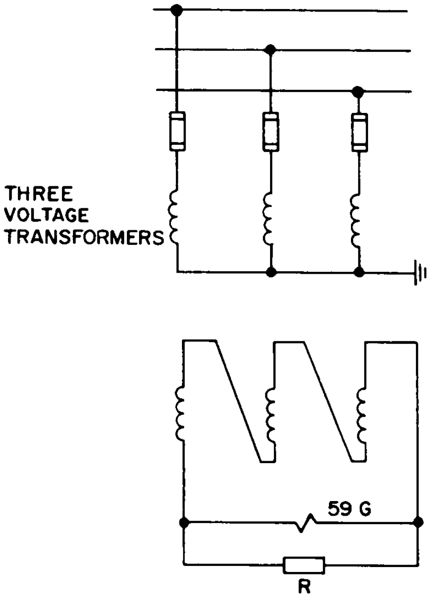


Fig 14
Ground-Detection Relaying for Ungrounded System or High Resistance Grounded System

Care should be exercised in sizing the resistor in accordance with established grounding practice (see ANSI/IEEE C37.101-1985 [6] and ANSI/IEEE C62.92-1987 [7], and in selecting a voltage relay that is insensitive to third harmonics.

2.4.7 Differential Protection. Differential relay protection is a scheme in which the current entering a winding is matched against that coming out of the winding. These relays detect low-magnitude fault currents during normal loads and do not trip falsely during high-magnitude external faults, or during starting periods. Differential relays cannot detect turn-to-turn faults in the same winding.

Connections for differential protection of a wye-connected motor are shown in Fig 15(a). The relay responds to the percentage difference between the incoming and outgoing current values. Current transformers should have matched characteristics and should not be used for any other purpose without a careful check of the effect of current transformer performance. Three current transformers are located within the switchgear so as to include the motor cables within the protection zone. The other three current transformers are located in the neutral connection of the motor. Six leads must be brought

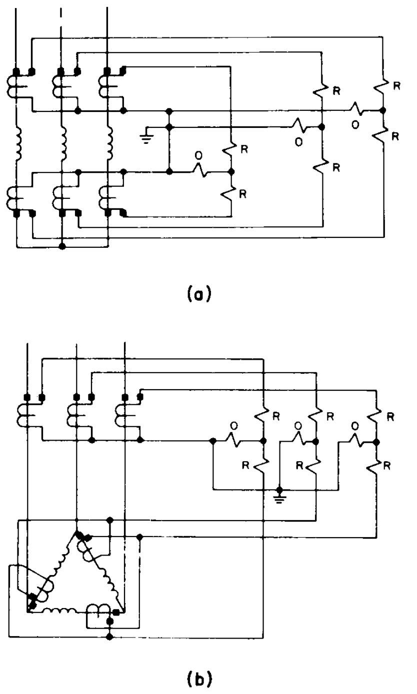


Fig 15
Differential Protection of Motors
(a) Wye-Connected Motor
(b) Delta-Connected Motor

out of the motor. This must be specified when the motor is purchased.

Figure 15 shows common connections for differential protection of a wye- and a delta-connected motor. The motor feeder cables and the breaker, where possible, are also included within the protected zone.

Figure 16 illustrates the flux-balancing primary-current differential protective scheme. Both ends of each motor winding serve as the primary winding of the current transformers. This scheme can be used for both wye- and delta-connected motors. The differential relay (device 87) sees the difference or internal fault current. Extremely sensitive phase and ground protection can be obtained by using only an overcurrent relay. Where the through-type current transformer is located at the motor, as is the usual case, this scheme requires that other devices be applied for the protection of the motor feeder cable. The cables from the switchgear to the motor cannot be included in the differential zone unless the current transformers are

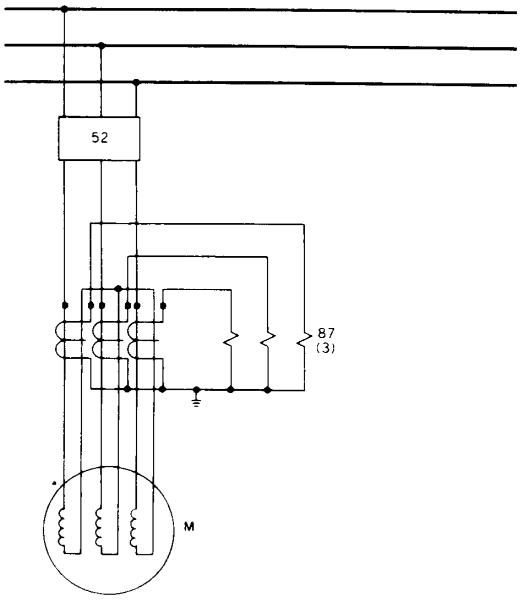


Fig 16
Flux-Balancing Current Differential Scheme

located in the switchgear, which, in turn, requires that neutral leads also be routed to the switchgear.

One method of providing differential protection for a split-winding motor and its feeder cable using line-current transformers of twice the ratio of the neutral current transformers is shown in Fig 17.

An alternative method is shown in Fig 18. This arrangement includes a differential relay (device 87) connected as shown in Fig 15, and a second set of time overcurrent relays (device 51) connected as shown. This scheme requires a total of twelve transformers and six relays, but provides approximately twice the sensitivity of that shown in Fig 17.

Figure 19 illustrates an extra-sensitive differential ground-fault protection scheme. The product-type relay (device 87N) receives its polarizing signal from a current transformer connected in the system neutral. Voltage polarization is also possible by using a set of wye-broken-delta voltage transformers. The product type relay (device 87N) can be used when the available ground-fault current is limited to a very low value and is used as an alternative to the toroidal current transformer with relay (device 50G) scheme when the toroidal current transformer does not accomodate the

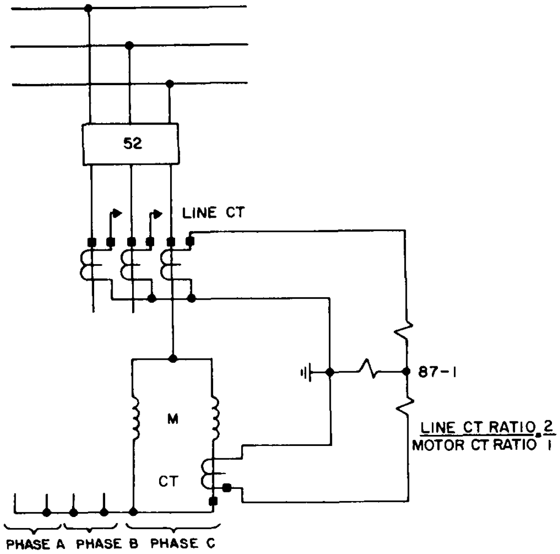


Fig 17
Differential Protection of Split-Phase Wye-Connected Motor

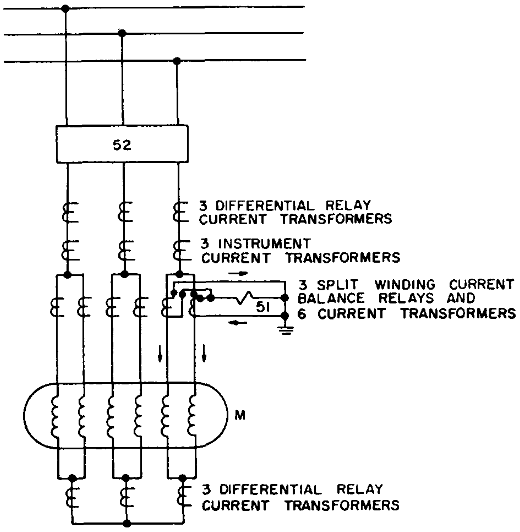


Fig 18
Alternate Method for Split-Phase Differential Protection

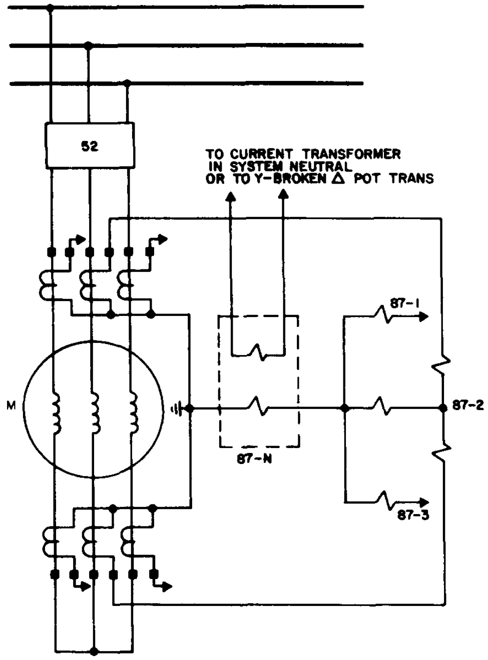


Fig 19
Sensitive Differential Protection with Directional Ground Relay

cable space requirements. The product-type relay is directional, and this must be considered in the connection of the relay. It is chosen because of its sensitivity, not because of its directional characteristic.

2.5 Rotor-Fault Protection (see 2.7.1.3)

2.5.1 Induction-Motor Protection. Because of the construction of squirrel-cage induction motors, protection of the rotor circuit is not considered a necessity. Wound rotor motors may be protected for slip-ring and rotor flashover to ground by the circuit in Fig 20. This protection is not effective at or near synchronous speed since the rotor induced potential is greatly reduced. Many wound-rotor installations depend on the stator instantaneous overcurrent device to provide rotor flashover protection. The reliability depends on system impedance and motor parameters.

2.5.2 Synchronous-Motor Protection. When the field supply and rotor circuit operate above ground, one rotor ground does not require immediate tripping, and indication-only is permissible as in Fig 21. Two common methods of ground

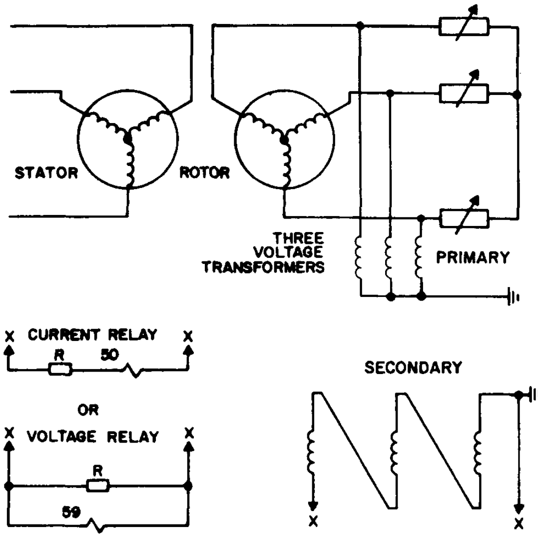


Fig 20
Wound-Rotor Motor Rotor Ground Protection

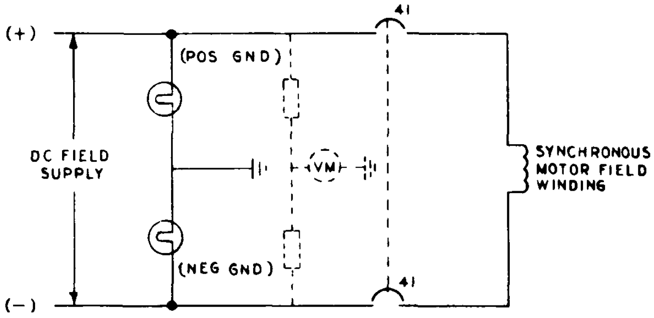


Fig 21
Ground-Detection Lamps

protection are shown in Figs 22 and 23. The sensitivity of these circuits is reduced when a ground connection appears near the center of the rotor winding or the supply source.

One method for overcoming this is shown in Fig 23. Without the varistor, a ground fault at the center of the field winding still results in a zero voltage at the device 64F relay. With the varistor in the circuit there is still a point in the field winding that results in zero voltage to device 64F relay. However, any change in the field voltage moves the zero point because of the varistor's nonlinear characteristic so the voltage at device 64F relay is no longer at zero and it could operate. While starting, high alternating-current rotor-winding potential exists, making it desirable to connect the detection circuit across the dc field supply rather than the rotor winding. This will also ensure that the source is free of ground connections prior to synchronization.

A second ground results in a short circuit in part of the rotor winding. This unbalances the air gap fluxes and magnetic fields causing local heating of the rotor and excessive vibration, and possibly disastrous rubbing between the stator and rotor.

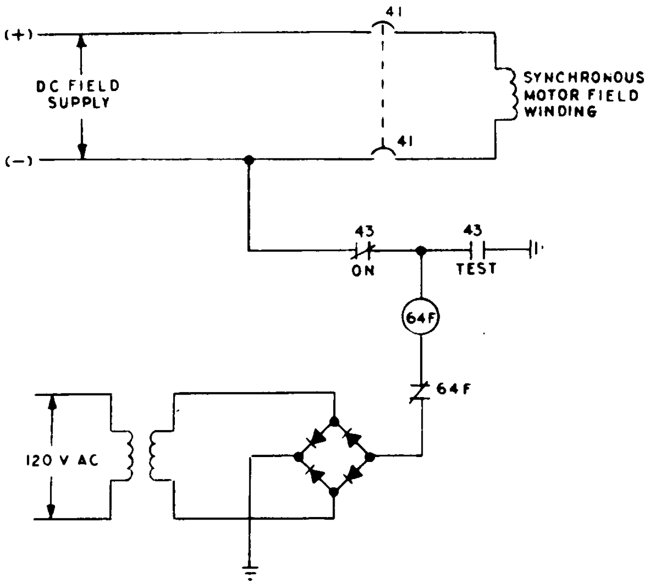


Fig 22
AC Ground Detection

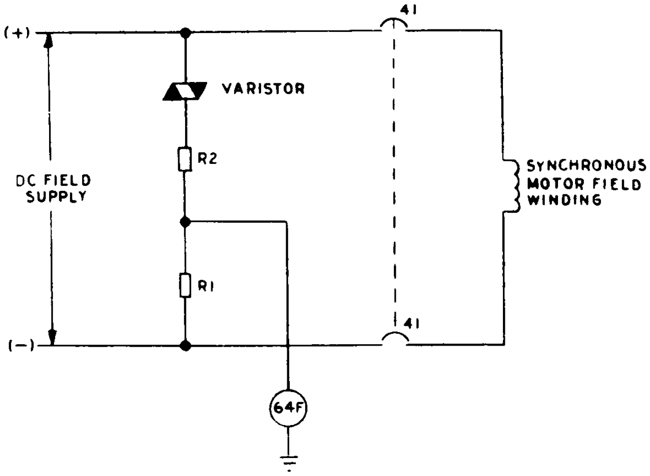


Fig 23
DC Ground Detection

Short-circuit protective devices located in the rotor circuit are generally not used. When a short-circuit occurs at the slip rings, the stator power-factor relay or the loss-of-field relay is expected to trip the motor. Low magnitude faults in the exciter power supply system are often cleared by its own overload protection.

2.6 Bearing Protection

2.6.1 General. Bearings are designed to minimize friction between stationary and moving parts, and may be of journal or thrust types for radial or axial loads, respectively. In general, antifriction bearings are used on smaller motors, and fluid-film bearings are used on larger motors, particularly at high speeds.

2.6.2 Antifriction (Ball, Roller) Bearings. Ball and roller bearings transmit the rotor weight by direct contact with rolling action, and have low starting friction. Failure of this type of bearing usually takes the form of fatigue cracks on the surfaces of the races and rolling parts, leading to spalling or peeling; destruction of the bearing follows relatively quickly. Vibration detection may be applicable, although regular audio and visual inspection forestalls serious conditions.

Temperature sensing similar to that described in 2.2.9.1 can also be applied to bearings to protect against catastrophic damage even though the bearing itself may not be protected.

Overheating may be caused by overlubrication or underlubrication and overloading, but thermal protection is not practicable due to the difficulty of locating heat-sensing devices in the proper places.

2.6.3 Fluid-Film (Sleeve) Bearings. Sleeve bearings transmit the rotor weight by a thin film of lubricant that reduces the coefficient of friction. The shaft diameter is smaller than the inside of the bearing so that the shaft tends to lie eccentrically. Lubricant is supplied at the point of greatest clearance and is literally pumped into the wedge-shaped space between shaft and bearing by the rotation of the shaft, thereby establishing a hydrodynamic pressure that supports the shaft.

When the film of lubricant is destroyed, friction losses rise rapidly, and metal-to-metal contact is likely to occur. Conditions leading to film failure are reduced lubricant viscosity, falling speed, increased loading, or particles in the lubricant larger than the minimum film thickness. Since an increase in temperature reduces viscosity, these conditions tend to be cumulative and bearing failure is accelerated. The rate of temperature rise depends on the severity of the fault condition and thermal capacity of the bearing.

2.6.4 Bearing Failure. Bearing failure may be due to one or more of the following causes:

2.6.4.1 Lubricant Problems

(1) Incorrect grade or viscosity of lubricant
(2) Inadequate cooling of bearing or lubricant, or both
(3) Deterioration, saponification, or frothing of oil
(4) Abrasive particles in lubrication system

2.6.4.2 Mechanical Problems

(1) Failure of oil supply due to
    (a) Stuck oil rings
    (b) Lubricant pump failure
    (c) Low lubricant reservoir level
    (d) Fractured oil pipe
(2) Excessive radial loading due to
    (a) Misalignment of shaft and bearings of motor
    (b) Misalignment of coupling between motor and load
    (c) Improper fit of bearing
    (d) Bent motor shaft
    (e) Unbalanced rotor
    (f) Tight belt or chain drive
(3) Excessive axial or thrust loading due to
    (a) Improper leveling
    (b) Improper axial alignment with respect to magnetic center
    (c) Improper axial alignment of driven equipment reflected through double helical gear drive
(4) Rough bearing surfaces due to
    (a) Fatigue cracks
    (b) Abrasive particles
    (c) Shaft currents
(5) Loose bolts in the bearing cap
(6) Phase current unbalance and harmonics causing
    (a) Vibration
    (b) Heating of rotor structure

2.6.5 Protection. To minimize damage caused by bearing failure, protective devices should be used to sound an alarm or de-energize the motor. Bearing protective devices responsive to one or more of the following conditions may be included:

(1) Low oil level in reservoir: (device 71) level switch
(2) Low oil pressure: (device 63) pressure switch
(3) Reduced oil flow: (device 80) flow switch
(4) High temperature: (device 38) thermocouples or resistance temperature detector
(5) Rate of temperature rise
(6) Vibration (used on motors with antifriction bearings in place of thermal devices)

The low-oil-level, low-pressure, and reduced-oil flow devices should indicate the extent of the reduction in level, pressure, or flow, sounding an alarm for relatively minor reductions and causing motor shutdown for large reductions.

Prelubricating and postlubricating periods may be employed in the start sequence of larger motors, with a monitoring timer to check that satisfactory lubricating conditions have been established before starting the motor.

High-bearing-temperature protection is the most difficult to apply effectively. A tip-sensitive temperature-responsive device, either in the bearing babbitt or in the lubricating oil flowing from the bearing, is generally utilized. Large motor bearings are usually monitored by either a resistance temperature detector or thermocouple device used in conjuction with a complete multiunit monitoring system for automatic high-temperature detection and direct reading of all bearing temperatures.

The choice of alarm versus trip function as the response to temperature rise depends on the availability of personnel attending the motor and the service requirement. The rate of temperature rise of bearings indicates the extent and type of bearing malfunction. A slow rise in temperature indicates a less serious malfunction than a fast rise. When a high-temperature rise is slow, sounding an alarm only may be satisfactory. When a high-temperature rise is rapid, the motor should be shut down immediately. One type of device provides an alarm at a lower temperature followed by a shutdown of the motor at a higher temperature. An alarm or shutdown based on a rate-of-temperature-rise device is the best protection for the high-temperature conditions.

A word of caution: the bearing may be destroyed before the high-temperature relays can operate to shut down the motor. However, operation of the protective device will save the journal, and prevent the rotor from rubbing on the stator laminations.

Vibration detectors that react to displacement, acceleration, or impulse, if used, should be mounted with the sensitive axis to coincide with the direction of displacement. Such devices are usually deactivated during start-up or shutdown.

2.7 Abnormal Power Supply Conditions

2.7.1 Abnormal Voltage. Operating voltages that deviate from rated voltages more than the tolerance given in ANSI and NEMA induction and sychronous motor standards (see NEMA MG1-1987 [13]) will subject the motors to hazards for which special forms of protection may be required. In the present context, abnormal voltage encompasses

(1) Undervoltage
(2) Overvoltage
(3) Unbalanced voltage and phase failure

2.7.1.1 Undervoltage Protection. A large induction motor rotating at essentially rated speed or a large synchronous motor with fixed excitation may be approximated at steady-state conditions as a constant kilovoltampere device for a given shaft load, and therefore current variations follow voltage variations inversely. Balanced three-phase undervoltage is accompanied by balanced three-phase overcurrent. The protection described in 2.2 and 2.3 may adequately protect against this source of damage.

When selecting undervoltage protection for large induction and synchronous motors, the selection should differentiate between undervoltage of long-time duration entailing possible thermal damage and undervoltage of short-time duration (0 cycles to 15 cycles). The latter condition should, therefore, be evaluated in regard to mechanical or stability effects.

2.7.1.1.1 Undervoltage of Long Time Duration. Too low a voltage at the terminals of a motor while the motor is being started may prevent it from reaching its rated speed, resulting in excessive heating of the rotor and stator windings. In the case of a synchronous motor, the motor may not reach sufficient speed to enable it to pull into synchronism when the field in applied.

Low voltage encountered while the motor is running results in higher than normal operating currents, and in the case of induction motors results in increased heating of the stator winding and rotor. In the case of synchronous motors, low voltage results in higher stator currents with increased heating of the stator with the possibility of the motor pulling out of synchronism.

In the case of some synchronous motors, the dc field supply is obtained by rectifying the ac voltage from the same source as the stator supply. When the ac supply voltage is low, that means the dc voltage is also low or the field is weaker, tending to make the synchronous motor less stable.

In the case of low voltage during starting or during running conditions, some means of undervoltage protection should be used if the overheating caused by undervoltage is not adequately protected against by other relays or devices.

The action of the undervoltage device depends upon the service that the protected motor is providing. Some motors are classified as essential and should not be removed from service by relays that do not protect the system from the effect of a fault on the motor or its associated circuit. Quite often the undervoltage condition is caused by some abnormality in the power-supply system that requires the continued operation of the motor so the system may recover even though the motor may be forced to operate at an overtemperature or at reduced capability.

Power-plant station service is a major area where this condition may exist. During a system disturbance that reduces voltage, the system may separate and completely collapse upon additional loss of generation capacity, which can happen if motors drop out on undervoltage. The successful recovery of the system depends upon maintaining each unit at maximum possible capability. In this case, the fans, pumps, etc, that serve the unit must remain in operation even though the voltage is reduced below a normally designated safe value. Recovery can then be accomplished by suitable operator action.

2.7.1.1.2 Undervoltage of Short Duration (Voltage Dips). Often voltage dips last for only 5 to 15 cycles (60 Hz base), and in most cases no harm is done to induction motors if they are allowed to stay on the line. If motors are automatically disconnected during these dips, expensive shutdowns can be experienced. In applying protection for such installations, the relaying should be no faster nor more sensitive than needed.

In the case of large synchronous motors supplying critical process loads, it is usually desirable to run stability studies, taking into account the total inertia of motor and driven load, the duration of the voltage dip, and the characteristics of the motor. Such a study is most helpful in selecting the protective equipment that will permit holding the motor on the line, and for determining the limiting voltage dip conditions.

Consideration must also be given to the condition in which the supply voltage is removed by a breaker or switch remote from a motor. Such a condition might involve the reclosure of the normal supply or a transfer from normal supply to an alternate supply.

Safe transfer of a motor to an alternate power supply can be accomplished if such a transfer is done very quickly (on synchronous motors, this time is approximtely six cycles and assuming there is little initial phase displacement between the two power supplies), or after a specific time delay. Transfer can be dangerous in the intermediate time. Either of the following criteria will provide safe transfer:

(1) The transfer must be fast enough so that the generated voltage due to the magnetic flux trapped is sufficiently close in phase relationship to the voltage of the alternate supply voltage, that the disturbance created by out-of-phase connection is within tolerance limits with respect to transient shaft torque, and transient current flow. Undervoltage relays cannot be relied upon in this instance since the motor may generate sufficient voltage to prevent the relay from dropping out. Underfrequency relaying (device 81) may be used in this application, depending upon the system configuration. In the case of synchronous motors, reverse power relays (device 32) might also be used to detect this condition. Studies should be performed to determine the maximum safe transfer time and minimum load shed requirements.

(2) The transfer must be slow enough so that the generated voltage due to the magnetic flux trapped by the rotor will have decayed to a low value. Ordinarily, if one open-circuit time constant on induction motors and two open-circuit time constants on synchronous motors has elapsed, safe transfer may be accomplished. Alternatively, a transfer can normally be safely made if motor residual voltage is less or approximately 25% of rated. The transfer voltage should be determined by studies.

Automatic transfer switches can be provided with in-phase monitors that prevent retransfer to the normal source until both sources are synchronized. Automatic transfer switches can also be provided with accessory controls that disconnect motors prior to transfer and reconnect them after transfer when the residual voltage has been substantially reduced. Motor loads above 50 hp with relatively low-load inertia in relation to torque requirements, such as pumps and compressors, may require special controls.

If safe transfer cannot be accomplished, some provision must be made to trip the local breaker and restart the motor when the supply voltage is normal (see 2.8.2 for further information).

2.7.1.1.3 General Comments. When a motor is not considered essential, the undervoltage device may be connected to trip the appropriate contactor or breaker where tripping is allowed. A time delay should be included to allow faults or system disturbances to clear before tripping the breaker. The time delay depends upon and should coordinate with the time to clear or isolate system faults by backup relay operations.

The type of undervoltage device used depends upon the type of motor control. High-voltage power circuit breakers require an undervoltage relay and potential transformer for the sensing and tripping signal. These are applied on circuits with voltages of 2.4 kV-13.8 kV.

Low-voltage air circuit breakers up to 600 V alternating current can be equipped with time-delay undervoltage tripping attachments if used alone.

In switchgear assemblies, an undervoltage relay and a shunt trip device with dc or capacitor trip can be provided to protect for undervoltage.

Motor contactors do not provide adequate undervoltage protection because of the low value of voltage at which dropout occurs. A more complete discussion of the effect of the motor controller is included in 1.4.

2.7.1.2 Overvoltage Protection. Operation of induction and synchronous motors on moderate overvoltage within the tolerance of motor standards is not generally considered to be injurious. Overvoltage causes an increase in iron losses in the machine. Since iron losses, and also copper losses, contribute to the temperature rise of the stator winding, then operation at any given current, but at higher voltage, causes an increase in winding temperature. Therefore, overcurrent devices with their distinct current pickup level permit a higher winding temperature to occur on overvoltage than at rated voltage. Only a device that senses winding temperature can adequately protect against such an abnormal operating condition.

When starting with overvoltage, the locked-rotor current is higher than rated starting current in somewhat greater than direct proportion to the increase in voltage. The locked-rotor relay protects the motor against thermal damage when the voltage is not more than 10% above rated voltage at the time of start.

2.7.1.3 Unbalance Protection and Phase Failure. Unbalanced voltage and phase failure are similar phenomena, differing only in degree of unbalance. While unbalanced phase voltages or currents are readily identified, it is the negative sequence component (see [20]) that actually jeopardizes the motor. Hence simple unbalance measurements may not provide the degree of motor protection required.

When the voltages supplied to an operating motor become unbalanced, the positive-sequence current remains substantially unchanged, and a negative sequence current flows due to the unbalance. If for example, the nature of the unbalance is an open circuit in any phase, a negative-sequence current flows that is equal and opposite to the previous load current in that phase. The combination of positive- and negative-sequence currents produces theoretical phase currents of approximately 1.7 times the previous load in each sound phase and zero current in the open phase. This is illustrated in Figs 24, 25, and 26. Due to additional motor losses, the actual value of motor phase current in each sound phase is closer to twice the previous load current.

Three-phase voltages will still be observed at the motor terminals with one supply phase open.

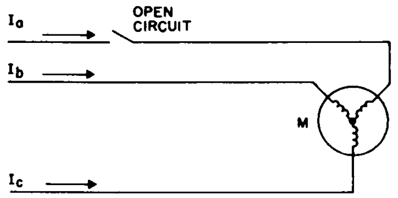


Fig 24
Current in Motor Windings with One Phase Open Circuited; Wye-Connected Motor

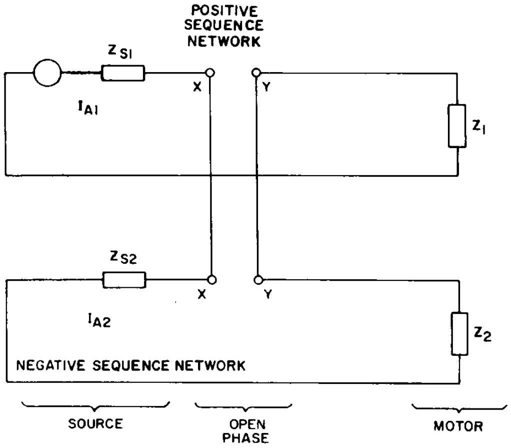
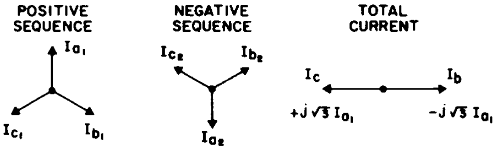


Fig 25
Connection of Sequence Networks for Open-Phase Condition



$$I_a = I_{a_0} + I_{a_1} + I_{a_2} = 0 \text{(OPEN CIRCUIT IN a-PHASE)}$$

$$I_b = I_{a_0} + a^2 I_{a_1} + a I_{a_2} = -j\sqrt{3}\, I_{a_1}$$

$$I_c = I_{a_0} + a I_{a_1} + a^2 I_{a_2} = +j\sqrt{3}\, I_{a_1}$$

Fig 26
Sequence Currents for Open-Phase Supply to Motor

The actual magnitudes depend on the motor shaft load and on whether any other loads or capacitors are connected in parallel.

When a synchronous motor is running at rated load and then one supply phase is lost, the motor will probably pull out of step and must be removed from service. However, if the motor is lightly loaded and continues running synchronously, there will be extra losses as a result of the asymmetry in line current, and destruction of the damper winding may result.

When an induction motor loses one phase, its slip increases, but it usually does not stall unless the resulting single-phase supply voltage is below normal or the shaft load is more than 80% of full load. The losses increase significantly when loaded near or above its rating. With either type motor, single phasing is a hazardous condition, and steps should be taken (preferably by relay action) to de-energize the motor.

A small-voltage unbalance produces a large negative-sequence current flow in either a synchronous or induction motor. The per-unit negative-sequence impedance of either is approximately equal to the reciprocal of the rated voltage per-unit locked-rotor current. When, for example, a motor has a locked-rotor current of six times rated, it has a negative-sequence impedance of approximately 0.167 on the motor rated input kilovoltampere base. When voltages having 0.05 per-unit negative-sequence component are applied to the motor, negative-sequence currents of 0.30 per unit flow in the windings. Thus, a 5% voltage unbalance produces a stator negative-sequence current of 30% of full-load current. The severity of this condition is indicated by the fact that with this extra current, the motor may experiance a 40%-50% increase in temperature rise.

The increase in loss is largely in the rotor. Negative-sequence phase currents produce a flux that rotates in a direction opposite to the rotor rotation. This flux cuts the rotor bars at a very high speed and generates a pronounced voltage resulting in a large rotor current. In addition, the 120 Hz nature of the induced current produces a marked skin effect in the rotor bars, greatly increasing rotor resistance. Rotor heating is substantial for minor voltage unbalance. Excessive heating may occur with phase current less than the rated current of the motor.

When a three-phase induction or synchronous motor is energized and one supply phase is open, the motor will not start. Under these conditions, it overheats rapidly and is destroyed unless corrective action is taken to de-energize it. The heating under these circumstances is similar to that in a three-phase failure to start, except that the line current is slightly lower (approximately 0.9 times the normal three-phase locked-rotor current).

Unbalance protection must sense damaging conditions without responding to conditions for which the protective equipment is not intended to operate. Several classes of relays are used to provide unbalance protection.

Phase-balance relays (device 46) compare the relative magnitudes of the phase currents. When the magnitudes differ by a given amount, the relay operates. When an open circuit occurs on the load or source side of the current transformer supplying the relay, sufficient unbalance should exist to make it operate. Phase balance relays are available with 1.0 A sensitivity and operate if one phase of the supply to the motor opens with the load on the motor prior to the open in excess of approximately 0.6 A in the relay. Caution must be exercised in current transformer selection to ascertain with older phase-balance relays that the thermal capability of the relay is not exceeded at maximum load.

Phase-balance relays without additional time delay beyond what the available relays inherently provide may cause unnecessary tripping of large motors during phase-to-ground or phase-to-phase disturbances remotely located on the power system. In as much as the clearing time of the relays on a power system are generally quite short in comparison with the required clearing time of phase-balance relays on the motor, a timing relay can be used without degrading the protection of the motor. Relay coordination is usually easier to attain with inverse-time relay characteristics than with separate fixed time delays.

Negative-sequence current relays (device 46) respond to the negative-sequence component of the phase currents. The instantaneous version of this relay provides excellent sensitivity. Because of this, it will operate undesirably on the motor contribution to unbalanced faults on the supply system and therefore must trip through a timer or be directionally supervised.

The application of phase-balance and negative-sequence overcurrent relays (and neutral overcurrent relays (device 51N)) should consider current-transformer characteristics under high-current conditions. Excessive current-transformer burdens result in current transformers saturating during fault conditions. Heavy motor starting currents can also cause current-transformer saturation, especially when the starting current has a large asymmetrical dc component. This dc resulting from motor inrush may last for a significant period of time compared to an asymmetrical fault current condition. This is because of the much greater inductance/resistance *L*/*R* of the total circuit when starting a motor.

Phase current-transformer saturation usually is not the same between phases and result in false negative- or zero-sequence currents. Hence, this needs to be considered when applying these types of relays. Unequal saturation is also encouraged by unequal burdens on the three-current transformers. Phase unbalance relays usually have considerable variation in the burden between the three phases, and any unsymmetrical conditions such as single-phase ammeters and ammeter selector switches can cause relay misoperation due to unequal saturation.

Current-transformer saturation is minimized by keeping burdens low (especially the dc resistive component), by using high-ratio current transformers, and by selecting current transformers with a high knee point (saturation) voltage. Even these may be insufficient for the sustained dc in some motor inrush currents. In such cases desensitizing the relay with respect to current or increasing operating time, or both, may be necessary.

Negative-sequence voltge or reverse-phase relays respond to single phasing, to unbalanced voltage, or to reversed phase sequence. For motor protection these relays must sense the same voltage supplying the motor. They are particularly applicable to a bus with substantial static load along with the motor load. For an all-motor load, the negative-sequence voltage relay may not, depending on the motor characteristics, operate for single phasing at light load. Where motors constitute only a small proportion of the total load, single phasing of the total load is recognized by this relay even with no shaft load irrespective of motor characteristics. In general, only the motor loads should be tripped when source single phasing or excessive unbalance is recognized.

2.7.2 Abnormal Frequency. Frequency in excess of rated frequency but not in excess of 5% over the rated frequency without a corresponding voltage rise is not considered to be a hazardous condition for synchronous or induction motors, provided the driven equipment does not overload the motors at the higher frequency.

At decreased frequency without a corresponding voltage reduction, the flux requirements of a motor are increased, thus increasing the hysteresis and eddy-current losses and heating. Sustained operation at reduced frequency and rated or overvoltage is not permissible if the effect of the voltage and frequency exceeds the standard tolerances (see 2.2.6). Protection against this type of operation is usually allocated to the thermal protective equipment, but more refined protection is possible using a frequency-sensitive relay or a volt per hertz relay, which measures the actual abnormality.

2.8 Abnormal Operating Conditions

2.8.1 Incomplete-Starting-Sequence Protection. An incomplete-sequence relay (device 48) is a relay that returns the equipment to the normal or off position and locks it out if the normal starting, operating, or stopping sequence is not properly completed within a predetermined time.

Incomplete-starting-sequence protection can be provided by an adjustable definite-time relay furnished on electrically operated reduced-voltage, and some full-voltage, motor starters to protect the machine and starting reactor, autotransformer, or resistance against prolonged operation at subnormal speed. The stator overload relays do not provide such protection.

2.8.2 Out-of-Phase Re-Energization Protection. Induction motors designed for across-the-line starting have the ability to withstand the mechanical forces developed by normal currents during starting at rated voltage. Abnormally high inrush currents can be produced in a motor when it is re-energized soon after a power interruption, and the possibility of damage should be assessed.

Inrush currents under such conditions can be as much as 2.5 times the magnitude of the normal locked-rotor currents for which the motor is designed, depending on the degree of saturation of the motor magnetic paths, the system impedance, and the resultant voltage at the instant of re-energization.

High-speed automatic reclosure of a single feeder to an industrial plant can produce abnormally high inrush currents and transient shaft torques in the motors served by the feeder due to the high resultant voltage impressed on the motors by out-of-phase re-energization. The currents and torques are a function of the number, size, and type of motors and loads on the industrial system and the elapsed time before the motors are re-energized. For the latter conditon, the time can vary widely depending upon the types of relays and breakers used and the reclosing scheme. If a single feeder must trip and reclose, this time will vary from approximately 15 cycles to 60 cycles (60 Hz base). In the case of a transfer to an alternate source, simultaneous signals can be given to trip one breaker and close another. The dead time would, therefore, be the difference between the tripping and closing times and could vary between 5 cycles and 10 cycles. Reclosure following dead times in the broader range of 5 cycles to 90 cycles, or when the alternate power source may not be essentially in phase with the primary power source should be considered only after careful investigation. See 2.7.1.1.2 and ANSI C50.41-1982 [3], Section 15. Studies must be made for specific cases to determine if the motor breaker must be tripped or if the motor can be re-energized with the feeder. As a general rule, if the dead time exceeds six cycles on a synchronous motor, a study should be made.

2.9 Surge Protection. Rotating machines present special problems in surge protection. The insulation of the stator winding of ac rotating machines has a relatively low impulse strength. The highest test voltage it must withstand is simply the crest of the 1 min high-potential test, which has a root-mean-square (rms) value of twice the rated (line-to-line) voltage plus 1000 V. Also, the steep-front characteristic of lightning or switching-produced surges may damage the turn insulation even though the magnitude of the surge is limited to a value that can be safely withstood by the major (conductor-to-ground) insulation.

The relatively low impulse strength of motors indicates their need for surge-protective equipment even though they may be connected to exposed overhead line(s) through apparatus (transformers, regulators, reactors, or cables) whose line side is adequately protected by a surge-protective device.

Surge protection cannot be adequately covered in this guide.[8]

In 5.8, [B124] through [B133] give considerable insight into the problem.

2.10 Motors or Motor Controls Used in Class 1E Nuclear Exposure. When necessary to apply motors and their controls in Class 1 nuclear exposure in nuclear plants, reference should be made to IEEE guides, ANSI guides, and Nuclear Regulatory Commision rules pertaining to this subject.

3. Motor-Protection Specifications

3.1 General Considerations. The complete protection scheme must be chosen to achieve optimum service reliability, safety, and protection of equipment at a reasonable cost. It is essential that the operating characteristics of the chosen motor-protection system be coordinated with those of the supply and, if necessary, the process or load involved if selective operation of the protective and control devices is to be achieved.

In large motor installations it may be necessary to consult the motor manufacturer to establish clearly such requirements as service factor, duty cycle, frequency of starts, WK^2 of rotating parts, acceleration time, cooling, bearing lubrication supply, mechanical stress and vibration limits, and rotor and stator heating rates, and the effects of surge protectors and power-factor-correction capacitors, if used.

In the event of motor failure, subsequent repair, and reinstallation the existing motor protection should be reviewed in light of any shop modifications (inferior or superior) to the design of the machine. Such modifications may affect heating and winding insulation characteristics and include added protection devices such as rtd. When considering replacement of older design machines with ones of newer design, closer manufacturing tolerances due to tighter design margins resulting from computer-aided motor design may require review of existing protection schemes.

Selection of the specific protection schemes should be based on the following factors:

(1) Motor horsepower rating and type
(2) Supply characteristics-voltage, phases, method of grounding, and available short-circuit current
(3) Type of motor controller employed
(4) Operating characteristic and settings of protective devices between the motor starter and source supply
(5) Protective devices monitoring the driven machinery or load process-vibration, torque, and other mechanical limits
(6) Function and nature of the process that determines the importance of the drive
(7) Environment of motor, associated switching device, and protective devices
(8) Cost of protection scheme relative to that of the associated equipment
(9) Hot and cold permissible locked-rotor time and permissible accelerating time
(10) Time versus current curve during starting

3.2 Motor-Protection Tables. The purpose of this section is to summarize the devices available for the protection of induction and synchronous motors employed in general applications. The

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[8] See footnote 7.

motor-starting equipment and associated protective devices illustrated herein are not to be regarded as a design specification or standard, but rather as a guide for the selection of adequate protection for any general induction or synchronous motor application.

Alternative protective devices are tabulated, the use of which may be justifiable or preferable depending upon the particular application considered and the philosophy of opertion. Tables 1 through 5 and Figs 27 through 33 cover devices

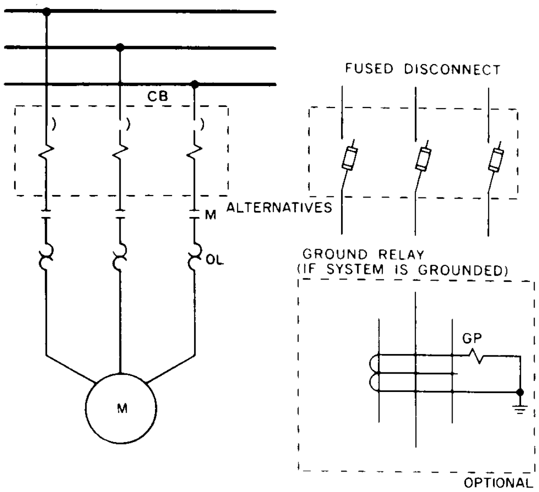


Fig 27
Low-Voltage Motor Controller
(See Table 1)

Table 1
Low-Voltage Combination Starter Comprised of Either a Molded-Case Air Circuit Breaker or Fused Disconnect and a Magnetic Contactor with an Overload Relay
(See Fig 27)

Ratings	Range of Ratings
Continuous amperes	9 - 2250
Utilization voltage	200 - 575
Horsepower	1.5 - 1600
Starter size	00 - 9

Types of protection	Quantity	NEMA Designation
Overload		
Overload relay elements	3	OL
Short circuit		
Circuit-breaker current trip elements	3	CB
Fuses	3	FU
Undervoltage		
Inherent with integral control supply and three-wire control circuit		
Ground fault (when specified)		
Ground relay with toroidal current transformer	1	GP

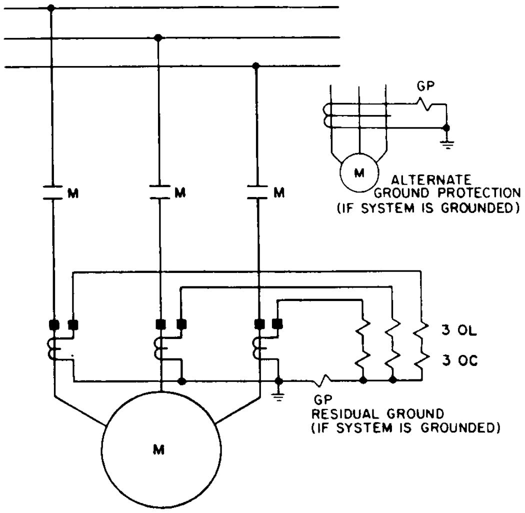


Fig 28
Class E1 High-Voltage Motor Controller
(See Table 2)

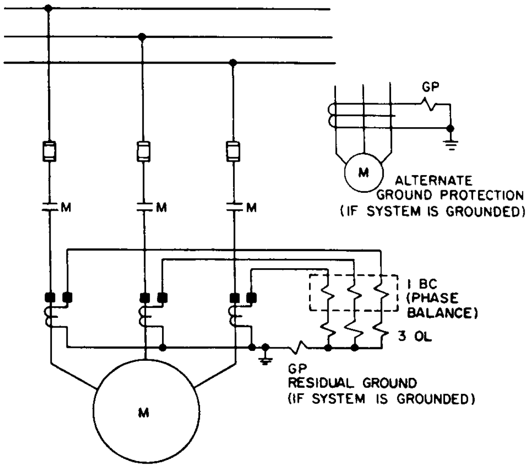


Fig 29
Class E2 High-Voltage Motor Controller
(See Table 2)

Table 2
High-Voltage Class E Motor Controller
(See Figs 28 and 29)

Ratings	Class E1 (Without Fuses)	Class E2 (With Fuses)
Utilization voltage	2300 - 6600	2300 - 6600
Horsepower	0 - 4500	0 - 4500
*Symmetrical MVA interrupting capacity at normal utilization voltage	25 - 75	160 - 570
Type of protection device	Quantity	NEMA Designation
Overload or locked rotor, or both		
Thermal overload relay	3	OL
Time overcurrent relay	1	OC
Instantaneous overcurrent relay plus time delay	1	TR/OC
Short circuit		
Fuses, Class E2	3	FU
Instantaneous overcurrent relay Class E1	3	OC
Ground fault		
Time-overcurrent residual relay	1	GP
Overcurrent relay with toroidal current transformer	1	GP
Phase balance		
Current balance relay (per motor) or	1	BC
Negative-sequence voltage relay (per bus), or both	1	
Undervoltage		
Inherent with integral control supply and three-wire control circuit when voltage falls sufficiently to permit the contactor to open and break the seal-in circuit		UV
Temperature		
Temperature relay, operating from resistance sensor or thermocouple in stator winding		OL

*ANSI/NEMA ICS 2 (1983) [9], 324.

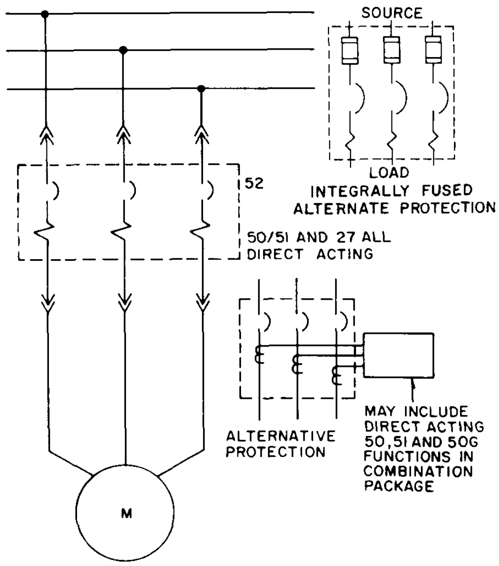
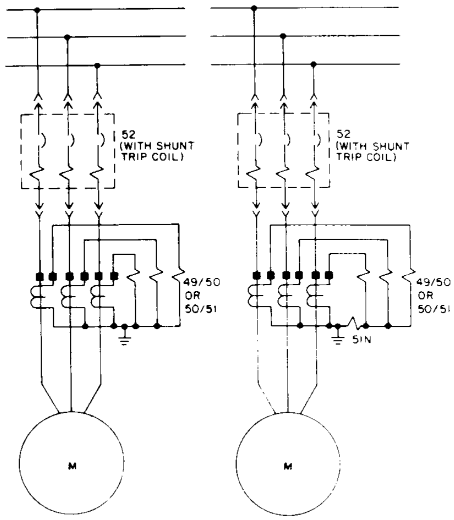


Fig 30
Low-Voltage Power Circuit-Breaker with Series Trip Device
(See Table 3)

Table 3
Low-Voltage Power Circuit Breaker, Manual or Electrically Operated, with Series Trip Device
(See Fig 30)

Ratings		Range of Ratings	
Continuous amperes		0 - 4000	
Nominal voltage		240 - 600	
*Symmetrical amperes interrupting capacity at maximum rated voltage		14 000 - 130 000	
Manual operation not recommended where interrupting duty exceeds 22 000 A symmetrical			
Type of stator protective device (all direct acting)	Quantity	Standard Device Function Number	NEMA Designation
Overload			
Static trip devices	3	51	
Short circuit			
Fuses	3		FU
Static trip devices	3	50	
Undervoltage			
Time-delay undervoltage relay	1	27	
Ground fault			
Overcurent relay with toroidal current transformer	1	50G (or 51G)	

*See ANSI/IEEE C37.13-1981 [5] for application of integrally fused devices.



(a) (b)

Fig 31
Low-Voltage Power Circuit-Breaker with Protective Relays
(See Table 4)

Table 4
Low-Voltage Power Circuit Breaker, with Protective Relays and Electrical Tripping in Addition to or in Place of Series Overcurrent Devices
(See Fig 31)

Ratings	Range of Ratings
Continuous amperes	0 - 4000
Nominal voltage	240 - 600
*Symmetrical amperes interrupting capacity at maximum rated voltage	14 000 - 85 000

Type of stator protective device	Quantity	Standard Device Function Number	NEMA Designation
Overload			
Static trip devices	3	51	
Thermal-overcurrent relay	3	49	
Time-overcurrent relay	3	51	
Short circuit			
Fuses	3		FU
Static trip devices	3	50	
Instantaneous overcurrent relay	2 or 3	50	
Ground fault			
Time-overcurrent relay, residual connection	1	51N	
Time-overcurrent relay with toroidal current transformer	1		GP
Undervoltage			
Direct-acting time delay undervoltage relay	1	27	

*See ANSI/IEEE C37.13-1981 [5] for application of integrally fused devices.

NOTE: Select at least one device under each category for which protection is desired.

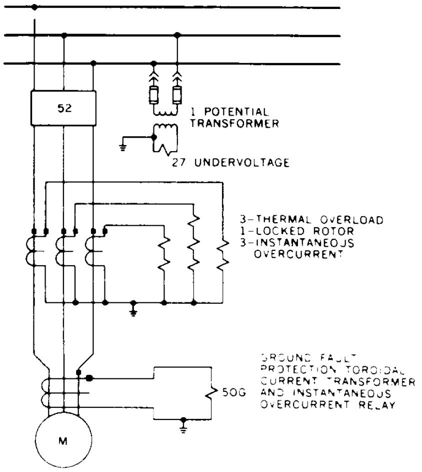


Fig 32
Power Circuit-Breaker Motor Controller, Typical Protection
(See Table 5)

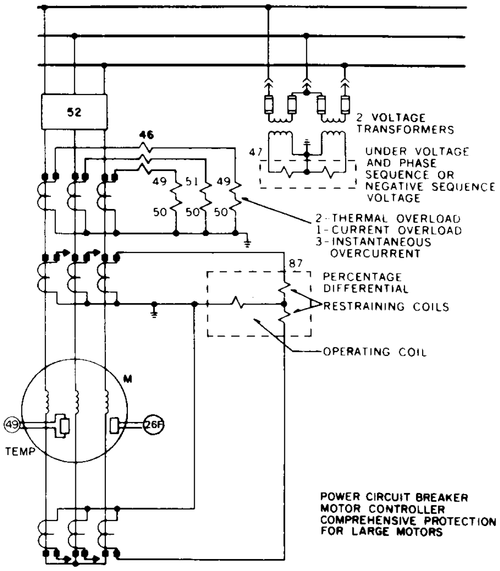


Fig 33
Power Circuit-Breaker Motor Controller Starter, Comprehensive Protection for Large Motors
(See Table 5)

Table 5
Power Circuit Breaker
(See Figs 32 and 33)

Ratings	Range of Ratings
Continuous amperes	0 - 3000
Nominal voltage	4160 - 13 800
Symmetrical amperes interrupting capacity at maximum rated voltage	3500 - 41 000

Type of relay for stator protection	Quantity	Standard Device Function Number
Overload		
Thermal-overcurrent relay	2 or 3	49
Time-overcurrent relay	2 or 3	51
Temperature relay, operated from resistance sensor or thermocouple in stator winding	1	49
Locked rotor		
Damper winding thermal relay	1	26
Time-overcurrent relay with instantaneous attachment	1	50/51R
Short circuit		
Time-overcurrent relay with instantaneous attachment	2 or 3	50/51
Instantaneous overcurrent relay	3	50
Percentage differential relay	3	87
Self-balancing primary current, differential relay	3	87
Ground fault		
Time-overcurrent residual relay	1	51N
Instantaneous or time-overcurrent relay with ring current transformer	1	50G or 51G
Phase balance		
Current phase-balance relay	1	46
Negative sequence voltage relay	1	47
Undervoltage		
Instantaneous undervoltage relay	1	27
Time undervoltage relay	1	27
Undervoltage and phase-sequence relay	1	27/47
Undervoltage supervised by phase-sequence relay	1	27/47
Underfrequency relay (where required)	1	81
Ancillary protection		
Vibration limit relay	1	39
Bearing overtemperature/wear device	1 or 2	38
Ambient temperature control device	1	23
Atmospheric condition monitoring device	1	45
Zero speed/overspeed device	1	12/14

NOTE: Select at least one device under each category for which protection is desired.

Table 6
Field-Excitation Protection for All Synchronous Motor Controllers

Function	Standard Device Function Number	NEMA Designation
Synchronous speed device	13	—
Field contactor or circuit breaker	41	FC
Field discharge resistor	—	—
Field-application relay	56	—
Power-factor relay (out-of-step)	55	PF
Field-failure relay	40	FL
Excitation-check relay	53	—
Incomplete-sequence relay	48	—

NOTE: More than one function can be combined in a single device for large or special applications. Additional devices are sometimes required (see Table 7 for complete listing).

Table 7
Device Designations and Functions

Protective Function	Standard Device Function Number*	NEMA Designation**
Time-delay relay	2	TR
Overspeed device	12	—
Synchronous speed check (centrifugal switch) or ac field current	13	FR
Underspeed device	14	—
Impedance relay	21	—
Temperature control device	23	—
Apparatus overheating detection device	26	—
Undervoltage, instantaneous, or inverse time relay	27	UV
Directional power relay	32	—
Bearing protecting device for overtemperature or wear	38	—
Mechanical condition monitor, vibration	39	—
Loss of field protection for synchronous motors	40	FL
Field contactor or circuit breaker	41	FC
Atmospheric condition monitor	45	—
Phase-balance current relay	46	—
Phase-sequence relay	47	—
Negative-sequence voltage relay	—	—
Incomplete-sequence relay	48	—
Thermal relay operated by motor current (replica), winding temperature or both (also embedded detectors)	49	OL
Overcurrent relay	—	OC
Instantaneous ocvercurrent relay	50	—
Instantaneous overcurrent relay, ground	50G	—
Time-overcurrent relay	51	—
Time-overcurrent relay, ground	51G	—
Extreme overload protection for unloaded start of large synchronous motors (usually 1000 hp) set just below pull-out torque	51R	—
Residually connected ground time-overcurrent relay	51N	—
Circuit breaker	52	CB
Main-line contactor	—	M
Excitation-check relay for synchronous motors	53	—
Power-factor relay	55	—
Field application relay	56	—
Overvoltage relay, instantaneous or time delay	59	OV
Voltage or current-balance relay	60	—
Liquid or gas-pressure relay or vacuum relay	63	—
Ground-fault detection for current flowing from machine casing or structure to ground	64	—
Ground-fault protective relay	—	GP
Liquid or gas level relay	71	—
Phase angle measuring or out-of-step protective relay	78	—
Liquid or gas flow relay	80	—
Frequency relay, operated by above or below normal, or rate of change of supply frequency	81	—
Lockout relay, manually or electrically reset	86	—
Differential protective relay, operated by phasor difference between compared electrical quantities	87	—
Differential ground-fault protection extra sensitive detection relay	87N	—
Tripping or trip-free relay, operates to trip a circuit breaker, contactor, or equipment and prevent immediate reclosure	94	—

*ANSI/IEEE C37.2-1987 [4].
**ANSI/NEMA ICS 1-1983 [8].

used for stator and ancillary protection. Table 6 covers motor field-excitation protection. Table 7 lists selected device designations and functions.

In [8] Tables 6 and 7 note that NEMA designation uses the terminology of ANSI/NEMA ICS 2-1983 [9] and the device designations of ANSI/NEMA ICS 1-1983 [8] refers to ANSI/IEEE C37.2-1987 [4].

In all of the tables, functions may not be in discrete relays but in combination packages.

3.3 Variable-Speed Motor-Protection Table. The purpose of this section is to summarize the protection of multiple and variable-speed motors. Table 8 in this section is not to be regarded as a standard or design specification, but should provide a guide to the selection of adequate protection for multiple and variable-speed motors and their associated drive equipment.

Table 8 outlines the general protection philosophies as related to the type of motor drive. Most variable frequency drives employ transformer isolated frequency conversion circuitry to drive synchronous and induction motors and therefore appear as transformer loads on the electrical system to which they are connected. Multiple speed motors contain multiple or tapped windings and rely on contactors to accomplish speed change by way of alteration of the winding configurations. Figure 34 details two alternatives of a two-speed motor protection. Wound-rotor slip recovery systems utilize the rotating transformer properties of a wound-rotor machine to provide regenerative energy recovery while controlling speed. The wound-rotor variable-speed motor appears as an induction machine and should be protected as such.

Table 9 and accompanying Fig 35 provide basic variable-speed motor-protection guidelines on a subsystem basis. Protection is divided into three logical areas or zones of protection that are inherent to variable frequency and regenerative feedback motor drives.

Fig 34
Two-Speed Motor Protection
(See Table 8)

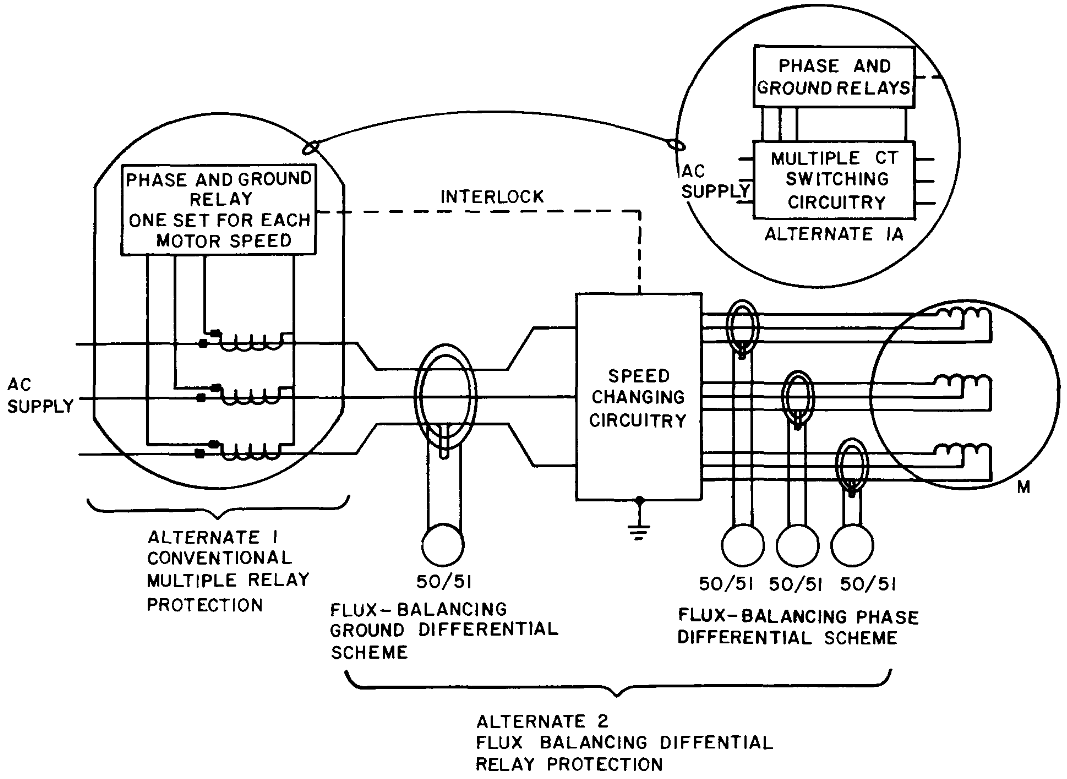


Table 8
Variable Speed Motor Protection
(See Fig 34)

Motor Type	Protection Philosophy
Variable Frequency Motor Drives (Synchronous or Induction Machines)	Relay protection similar to transformer protection. See the appropriate ANSI specifications for transformer phase and ground fault protection philosophies. Motor and electronic drive protection should be generic to the drive package as recommended by the motor manufacturer.* In many cases, full-speed across-the-line starting or run circuitry, or both, is employed that bypasses the Isolation Supply Transformer or Converter Circuitry, or both. While operating in this mode, the motor should be protected as a typical Synchronous Machine (SM) or Induction Machine (IM).
Multiple Speed Winding (Synchronous or Induction Machines)	Multiple relay/CT protection or flux-balancing differential schemes (see Fig 39).
Wound Rotor Slip	Relay protection identical to induction motor Recovery Drives protection. Supplemental motor and electronic drive (Induction Machines) protection should be generic to the drive package as recommended by the motor manufacturer.*

*The motor/drive manufacturer should be consulted for the protection interface requirements between the motor/drive and the electrical power supply.

Fig 35
Variable Speed Motor Protection
(See Table 9)

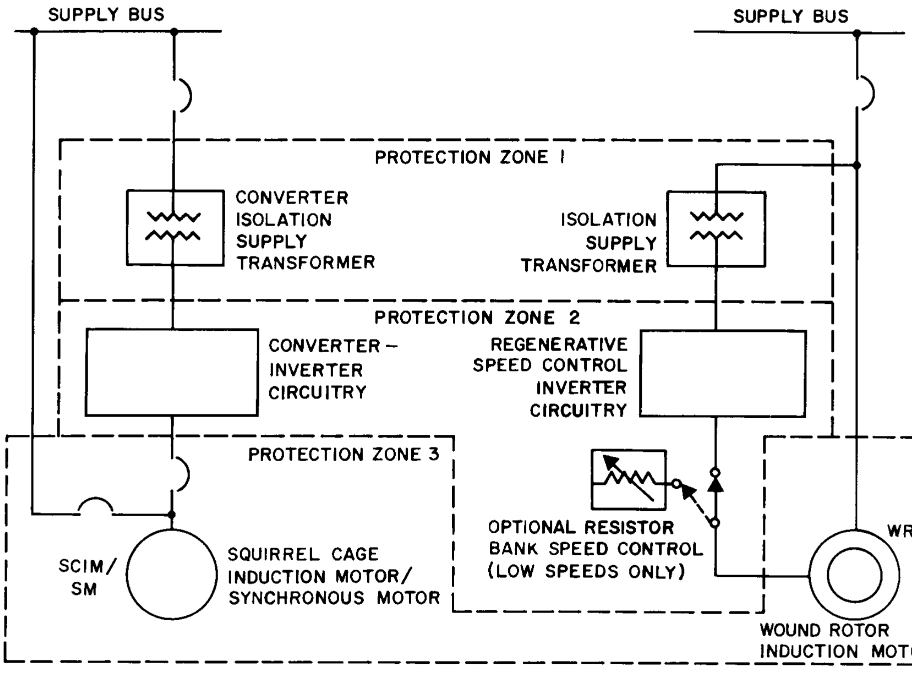


Table 9
Variable Speed Motor Protection
(See Fig 35)

Protection Zone 1	Protection Zone 3	Protection Zone 3
Apply typical transformer protection. Such protection will include:	Apply generic electronic drive protection. Such protection will include:	Apply typical motor protection. Such protection will include:
a. Differential relays b. Phase and ground time-overcurrent relays c. Phase and ground instantaneous current relays d. Transformer neutral relays e. Sudden pressure relays f. Thermal overload sensors	a. Differential relays b. Phase and ground time-overcurrent relays c. Phase and ground instantaneous current relays d. Transformer neutral relays (if employed in converter circuitry) e. Thermal overload relays f. DC overcurrent relays g. Voltage controlled overcurrent relays h. Motor speed protective circuitry or devices, or both i. Undervoltage/overvoltage relays j. Thyristor and thyristor gate protective circutry or devices, or both k. Microprocessor or control system protective circuitry or devices, or both	a. Differential relays b. Phase and ground time-overcurrent relays c. Phase and ground instantaneous current relays d. V/Hz relaying e. Thermal overload relays f. Negative sequence voltage/current relays g. Overspeed protection relays h. Speed switch or impedance relay supervision of time-overcurrent relays

NOTES: (1) Sensing and relay circuitry must respond to the variable frequency of voltages and currents inherent in converter and speed control inverter circuitry.
(2) Overall differential relaying can be employed to cover more than one zone of protection.

4. Setting and Adjustment of Protective Devices

4.1 General Discussion. The purpose of a protective relay setting is to provide optimal protection of the equipment being protected. The setting or adjustment, or both, of a protective relay determines the magnitude of the significant quantity at which it operates.

Many different types of protective relays are available, and some relays protect for more than one circuit abnormality. The methods of selecting protective relay settings are detailed for the protective relay functions as covered in Tables 1 through 6.

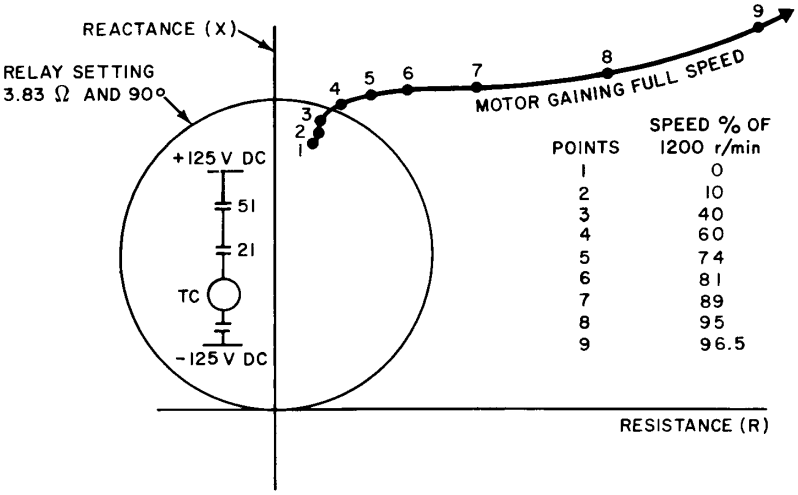
4.2 Protective Device Settings. The device numbers and definitions in this section are taken from ANSI IEEE C37.2-1987 [4][3].

4.2.1 Device 13 — Synchronous-Speed Device. A device such as a centrifugal-speed switch, a slip-frequency relay, a voltage relay, an undercurrent relay, or any type of device that operates at approximately the synchronous speed of a machine.

They are set to pick up after motor starting conditions or motor current has stabilized. Current and centrifugal relays are set to conditions equivalent to 95% rated speed. Slip-frequency relays are set at 1%-5% slip depending on motor application.

4.2.2 Device 21 — Distance (Impedance) Relay. A distance relay is responsive to voltage, current, and the phase angle between them. It can have several characteristics on an R-X diagram. Figure 36 shows an example using a mho characteristic, but others can also be used. There is a separate circle for each setting of the relay and the relay can be used to detect a change in impedance to verify rotor rotation. The circle is the relay balance point and determines its reach. By plotting the motor impedance curve on the R-X coordinates, a relay settting can be found which crosses the motor impedance at any desired point.

The size of the impedance circle can be adjusted in very small steps, so it is possible to set the relay at any desired value of starting current corresponding with any desired value of time during the starting period and consequently at any speed.



POINTS	SPEED % OF 1200 r/min
1	0
2	10
3	40
4	60
5	74
6	81
7	89
8	95
9	96.5

NOTE: Allowable locked rotor time lies between point 6 and point 7 which is 14 s for 100% voltage and 26 s at 80% voltage. Long time-overcurrent relay will trip within these times.

Fig 36
Locked-Rotor Protection with Impedance Relay

The distance relay is set to pick up each time the motor is started and resets as the motor accelerates as shown in Fig 36.

When the motor fails to accelerate, the distance relay stays picked up and allows a timing (time overcurrent or time overvoltage) relay to trip the motor. The timing relay is set to trip the motor within the locked-rotor thermal limit, which is less than the acceleration time for a motor that requires the use of an impedance relay (see 2.2.7). On the other hand, the distance relay resets for successful starts before a trip can be initiated by the timing relay.

4.2.3 Device 26F — Field Thermal Device. This device detects a thermal overload in the field, usually by measuring the current in the field either directly or by way of the voltage across a shunt. It is normally connected to an alarm. The thermal time-constant of the device should be selected to be as close to the thermal time-constant of the protected equipment as possible.

4.2.4 Device 27 — Undervoltage Relay. A relay that operates when its input voltage is less than a predetermined value.

This device provides an adjustable time delay so that momentary voltage dips can be prevented from interrupting the supply source, as, for example, the induction-type relays, which have a time delay that is inversely proportional to the degree of undervoltage.

When the relay is of an instantaneous type, an auxiliary relay is often used so that the time delay is a fixed period after the relay contacts have reached the drop-out position. Instantaneous relays with timers set for very short time settings are often useful to enable motors to stay in operation during voltage dips without degrading the motor protection.

The drop-out of the undervoltage relay is normally set at approximately 80% of normal voltage. For cases where voltage drop during starting is very great, it may be necessary to adjust the relay drop-out to a lower value to prevent operation during the starting period or activate the relay by a timer after completion of the starting period.

The timer setting, when used with an instantaneous type undervoltage device, is normally 2 s-3 s. For cases where the clearing time of faults on the source circuits is exceptionally long, it may be necessary to increase this setting accordingly. In the case of high-speed tripping the undervoltage auxiliary timer might be set to as low as 0.1 s.

For induction-type relays, where the time delay is proportional to the degree of undervoltage, a time delay of 1.25 s-2.0 s for a reduction from normal to zero voltage is usually satisfactory. The relay automatically gives a longer time for a change in voltage from normal to some intermediate voltage value.

Where synchronous motors are located on supply circuits capable of automatic high-speed reclosure, device 27 should be set to trip the motor-control circuit before the circuit is reenergized. If the rate of voltage decay is not fast enough to allow the device-27 relay to respond while the motors are disconnected, a high-speed underfrequency relay set for 58.5 Hz will usually suffice.

4.2.5 Device 40 — Field Relay. A relay that functions on a given or abnormally low value or failure of machine field current, or on an excessive value of the reactive component of armature current in an ac machine indicating abnormally low field excitation.

To protect unloaded-start synchronous motors, a dc undercurrent relay can be connected in series with the field and set below normal operating field current. In some applications a time-delay undercurrent relay can be used to ride through momentary changes in the flow of field current that can occur during system disturbances.

On brushless-excited-field, unity, and leading-power-factor synchronous motors, a power relay connected to measure vars into the motor may be applied. This device should be set to operate when the var flow into the motor exceeds approximately 10% of rated kilovoltampere of the motor. It should remove the field and trip the motor breaker when it operates.

On large synchronous motors, a relay is used that is also commonly used on synchronous generators. This is an impedance relay that operates on an excessive value of var flow into an ac machine, indicating abnormally low field excitation. Where an undervoltage unit is part of this relay, its contacts should be shorted because loss of motor field may produce little voltage drop.

4.2.6 Device 46 — Reverse-Phase or Phase-Balance Current Relay. A relay that functions when the polyphase currents are of reverse-phase sequence, or when the polyphase currents are unbalanced, or contain negative phase-sequence components above a given amount.

4.2.6.1 Phase-Balance Relay. This device trips the motor-control equipment if the phase currents become more unbalanced than the design unbalance of the relay. This is approximately 15%. It has a minimum operating current below which the relay will not close its contacts regardless of the magnitude of the unbalanced currents. Some relays provide a fixed operating current value while others use current taps to vary the minimum operating current. The minimum current tap is the most sensitive and is usually selected except when the continuous current rating of the tap is less than the motor continuous current rating. Additional time delay may be required to avoid unnecessary tripping during starting caused by unbalanced currents resulting from unbalanced current-transformer burdens. A device 46 relay applied to an individual motor is a suitable substitute for the third overcurrent unit as prescribed in ANSI/NFPA 70-1987 [11], Table 430-37.

4.2.6.2 Negative-Sequence Current Relay. These relays respond to the negative-sequence component of the phase currents and are available in the instantaneous type and the inverse-time type. When negative-sequence relays are used for the device 46 function, an inverse-time overcurrent characteristic is usually used. These relays generally have an $I^2t=k$ type of characteristic. That is, their time of operation is inversely proportional to the square of the negative-sequence component in the three-phase current. This type of relay inherently lends itself to proper coordination, even with many identical motors on one bus. Motor standards have not established values for k, however, a value of k = 40 has been used. A negative sequence pick-up setting equal to 15% of motor full-load current ensures reasonable motor protection. This will just trip at a 3% negative-sequence bus voltage for a motor with a typical 20% negative-sequence impedance. This threshold condition will result in an increase in motor losses approximately 10%-25% of normal full-load losses of the motor (but are not related to motor load).

4.2.7 Device 47 — Phase-Sequence or Phase-Balance Voltage Relay. A relay that functions upon a predetermined value of polyphase voltage in the desired phase sequence, or when the polyphase voltages are unbalanced, or when the negative phase-sequence voltage exceeds a given amount.

This device is similar in its function to that of device 27 or 59, the single-phase voltage relays. However, being a three-phase device it responds to the three-phase quantities of the supply system. A relay responsive to the positive- or negative-sequence component of the applied voltage satisfies this definition and most of the needs in this area. However, electromechanical positive- or negative-sequence relays are sensitive to line frequency, and hence the setting should make allowance for the specific relay in question. This is not a significant problem when the relay is used mainly to prevent attempting to start the motor with one phase missing or with reverse-phase sequence. A 90% setting is typical for a positive-sequence voltage realy. For a negative-sequence voltage relay, 5% is a common setting. However, it should not be assumed that any 47 device will prevent insulation deterioration during all possible unbalanced conditions (see 2.7.1.3 and 4.2.6.2).

A more common type of relay used for the 47 device function is built on the principle of a three-phase induction motor. Such a relay has a torque proportional to the area within the voltage triangle. With balanced voltages this is proportional to the positive-sequence voltage squared. As such, the relay is usually set to close its high-voltage contact to permit starting a motor at 90%-95% of rated value. The undervoltage contacts are usually set to close at 80% of normal voltage. The control action that is initiated by the undervoltage contacts depends on the application.

When the three-phase voltages are not balanced, the area of the voltage triangle is no longer proportional to the positive-sequence voltage squared. The torque is now proportional to the difference between the positive-sequence and the negative-sequence values squared. Thus a condition with 90% positive sequence and 10% negative sequence would result in an effective voltage of 89% of normal.

Usually an operating time setting of 2 s upon complete loss of voltage is adequate for annunciation or to initiate the desired shutdown procedure.

4.2.8 Device 48 — Incomplete Sequence Relay. A relay that generally returns the equipment to the normal, or off position, and locks it out when the normal starting, operating, or stopping sequence is not properly completed within a predetermined time.

When the device is used for alarm purposes only, it should preferably be designated as device 48A (alarm). The time of this device should be set for the normal starting time of the motor plus a safe time margin to ensure against unnecessary tripping caused by electrical and mechanical variables.

4.2.9 Device 49 — Machine or Transformer Thermal Relay. A relay that functions when the temperature of a machine armature winding or other load-carrying winding or element of a machine or power transformer exceeds a predetermined value.

4.2.9.1 Connected for Tripping. In setting thermal overload relays, it is desirable to allow the motor to carry overloads of an amount and duration that will not damage it. For this reason, a nominal pick-up (minimum tripping current at ultimate tripping time) of 115%-125% of motor full-load current should be multiplied by the correction factor listed in Table 10, and then this adjusted motor full-load current may be used to choose the heater or coil from the relay manufacturer's table.

The manufacturers' recommendations for selection of a given continuous or short-time rating may differ from Table 10 and should be given due consideration.

Most thermal overload relays provided in the smaller size motor contactors have no adjustable element. The relay heaters or coils are listed to provide protection for motors having rated currents within a specified current range.

Frequently, these ranges are specified so that the relay will operate (ultimate trip point) at 125% of the minimum current and at 115% of the maximum current of the indicated range of the relay. When the actual motor full-load current is near the maximum of the listed range and an operating point of at least 125% is desired, then the next higher rated coil or heater is required. In such a case, the actual operating point may be somewhat above the 125% of full-load current desired. Where the overload is adjustable (commonly 10%) a trip setting can be obtained at any desired value.

For relays available for large contactors or purchased separately for circuit-breaker controlled motors, the coils or heaters will be provided in steps similar to those discussed above. However, they generally have a specified nominal value and an arrangement that changes the nominal value over a range from 80% to 90% to a range of 110%-120% of the nominal value. In this way, a continuous range of operating values is obtainable.

When a minimum relay trip value has been selected (fixed, in the case of nonadjustable relays, or set in the case of adjustable relay), it is usually desirable to check a point on the relay curve to determine if the applied setting is reasonably close to the desired value. To accomplish this, the relay is tested at two values of current,

Table 10
Correction Factors for Motor Full Load Currents

Time Rating of Motor*	Correction Factor
Continuous, 1.15 service factor	1.0
Continuous, 1.0 service factor	0.9
Short time, 60 min	0.8
Short time, 30 min	0.75
Short time, 15 min	0.7
Short time, 5 min	0.6

*See NEMA MG1-1987 [13], 10.35.

measuring the time to trip from a cold (ambient temperature) start for each current. When tested at 200% of its current rating in a 40 °C ambient, the relay shall trip in not more than 8 min. When tested at 600% of its current rating in a 40 °C ambient, a Class 20 relay shall trip in not more than 20 s and 30 s for a Class 30 relay. At lower ambient temperatures, the tripping times will be longer.

4.2.9.2 Connected for Alarm. The method of setting relays connected to provide an alarm is similar in all respects to that used for relay connected to trip. However, it is important to note that when relays are connected to give an alarm, the fact that an alarm is given can only be effective in preventing damage if the alarm is obtained in time to take corrective action. The setting should not be greater than 110%-115% of motor full-load current. Some users set alarm relays at the full-load current rating of the motor, on the premise that the normal load may be as low as 75% of the rated load, and a load increase to the rated value indicates some sort of trouble that should be investigated.

4.2.9.3 Relay Operated from Embedded Detectors. Relays that measure the actual winding temperature by means of embedded detectors are preferred by some users for large motors. The temperature at which they should be set to operate depends upon the class of motor insulation and whether the relays are to trip or give an alarm. The motor manufacturer should be consulted for his recommendation regarding settings. They are frequently set for tripping at 5° below the allowable continuous temperature for the type of insulation used.

Embedded temperature detectors are frequently used where motors must operate under adverse conditions such as widely varying load, ambient temperature, frequent starting, plugging, reversing, or inadequate ventilation. Usually the embedded temperature detectors supplement the protection provided by a thermal relay. Positive- or negative-temperature coefficient thermistors or thermal switches are also available that can be mounted on or attached to the stator winding for temperature measurement. Such devices so mounted are necessarily less responsive to winding temperature changes than are embedded resistance detectors.

Relays utilizing both embedded detectors and motor current in combination are available to users desiring this type of protection. The manufacturer should be consulted regarding their application and setting.

4.2.10 Device 50/51 — Fuses and Overcurrent Devices

(1) Device 50 — *Instantaneous Overcurrent or Rate-of-Rise Relay.* A relay that functions instantaneously on an excessive value of current or on an excessive rate of current rise.

This function indicates a fault in the apparatus or circuit being protected.

(2) Device 51 — *AC Time Overcurrent Relay.* A relay that functions when the ac input current exceeds a predetermined value and in which the input current and operating time are inversely related through a substantial portion of the performance range.

4.2.10.1 Fuses. Fuses for *motor branch circuit overcurrent protection* must have adequate interrupting abilities and also current ratings and performance characteristics that will allow the motor to start and still provide, for all values of overcurrent, as much protection as possible for the motor, the motor branch circuit conductors, the disconnecting means, and the motor controller. These fault-current protective devices are in addition to the separate overcurrent devices included for *motor running overcurrent (overload) protection.*

Nontime-delay fuses with current ratings of 250%-300% of the motor full-load current value are usually required to allow the motor to start and permit normal protective device operation at operating overloads. The fusing ratio range may be reduced from 250% to 300%, to 200% to 250% of motor full-load current, thus providing improved fault-current protection, when reduced voltage starting is used. For fuse ratings of 600 A or less, the fuse rating may be increased to 400% if required by motor starting current. The time-current characteristics of the fuses must be properly correlated with the time-current characteristics of the overload relays so that the overload relays operate before the fuse in the range of operating overloads of the motor. Also, the fuse must operate before the overload relay trips and the contactor opens for values of fault current exceeding the interrupting ability of the contactor. In the case of thermal overload relays, the fuse clearing time characteristic should intersect the overload relay time characteristic at currents not much greater than ten times the heater rating to protect the heaters and overload relay from permanent damage from fault currents exceeding this range.

Time-delay (dual element) fuses with current ratings of 165%-180% of the motor full-load current are usually required to allow the motor to start and permit normal protective device operation at operating overloads. The maximum fusing ratio should not exceed 225% of the motor full-load current. The time-current characteristics of these fuses should also be properly coordinated with the time-current characteristics of the overload relays to obtain the same type performance as described in the previous paragraph. The current ratings of nontime-delay and time-delay fuses should be approximately equal to the motor full-load current value when used as the sole overcurrent device for protection against operating overloads and high-fault currents. Time-delay fuses may be considered more acceptable for this function over a wider range of ambient temperatures due to their ambient-temperature sensitivities and the increased response times of operating overloads.

For current-limiting fuses, their current limiting capability should also be considered in making a selection for circuits having high available short-circuit current. The interrupting ratings of all fuses must be equal to or greater than the available short-circuit current at location.

Current limiting fuses are sometimes applied with a circuit breaker in a fused breaker combination. This allows the circuit breaker to be applied to a system with fault capability greater than the breakers interrupting capability.

4.2.10.2 Characteristics of Fuses. With inverse characteristics used it may be difficult to coordinate time-delay fuses with overload relays in the low fault-current range. The amount of damage on high fault currents, which may occur to motor branch-circuit components, is dependent on the let-through energy of the fuse. The smaller the rating of the fuse the more current limiting is the fuse, and the lower the expected damage.

4.2.10.3 Device 50 — Instantaneous Overcurrent (IOC) or Rate-of-Rise Relay. When the phase-fault current at the terminals of a motor is considerably larger than the starting current or the motor contribution to a fault, a high-set instantaneous trip unit can be set at 165%-187% of locked-rotor current to trip directly (see Fig 37). The general requirement for using this instantaneous unit or separate instantaneous relay is that the setting be as low as possible yet never operate during the starting period. Since this type of relay may be susceptible to operation on dc offset, the inrush current value is multiplied by a factor as high as 1.5 to account for the asymmetrical current value that may be obtained.

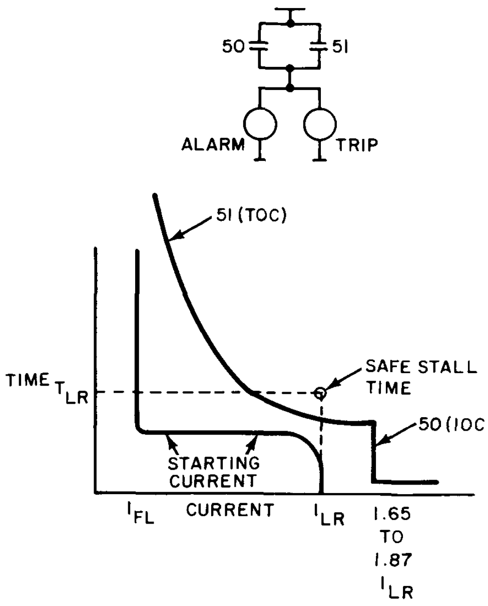


Fig 37
Typical Setting of 50/51 Overcurrent Relays

Since the inrush current is not too accurately known and to allow for the pick-up tolerance of the trip device, an additional 10%-25% is usually added as a safety factor when settings are calculated.

Some users prefer to set this high set instantaneous relay by actual operation test. The usual procedure is to set the relay so that it will trip on start-up and then gradually increase the setting during successive starts until a setting is reached that prevents tripping for three to five starts. When this setting has been established, a 10% margin in pick-up current or plunger calibration is usually added as a safety factor. In using this setting procedure, the number of motor starts within any time period should not exceed the motor manufacturer's recommendation. It should be recognized that this method of establishing a setting may not detect a faulty relay and, as a result, may provide inadequate protection and possible miscoordination with other devices.

Where it is necessary to set a direct tripping instantaneous overcurrent (IOC) lower to provide adequate fault protection, an IOC trip can be delayed with a short time delay, 6 to 15 cycles, to prevent operation on the asymmetrical starting current as shown in Fig 38. Static IOC relays are

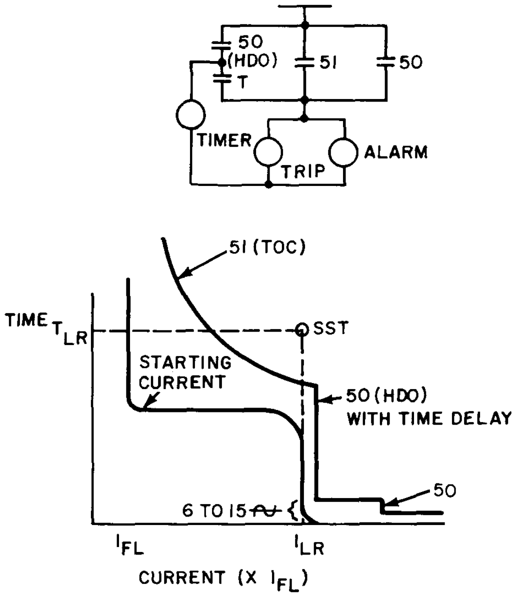


Fig 38
Typical Setting at 50/51 Overcurrent Relays with Separate Time Delayed Instantaneous

available with this inverseness built into the characteristic and thus eliminate the need for the timer described above (see Fig 39).

An IOC relay can also be used to supervise a time-overcurrent relay (see Fig 40). See 4.2.10.7 for setting of the time-overcurrent relay. This scheme is to allow the time-overcurrent relay (TOC) to trip for faults and serious overloads, but to allow the TOC to alarm only for small overloads. Typically, the IOC is a high drop-out-type unit set 175%-200% of full-load current. Whatever the setting, consideration should be given to the drop-out to pick up ratio of the IOC. It must be high enough so that the unit will drop out on decreasing current above the full-load current.

On high inertia drive motors or other motors with low-starting voltage, the motor starting time may be equal to or exceed the allowable locked-rotor time. It is unlikely that a TOC relay can be set to provide start-up protection without tripping during normal start-up. In certain cases, an IOC with a high drop-out to pick up ratio may be employed to supervise the TOC relay. The IOC relay is set at approximately 85% of the motor's locked-rotor current (see Fig 10). The drop-out to pick up ratio must be high enough to ensure that the instantaneous relay will drop out before the TOC relay times out if the motor accelerates and the start current reduces from its LR value. With this scheme the time overcurrent relay performs an alarm function for overloads since the instantaneous unit blocks tripping once the motor is running (see 2.2.7 for additional information on high-enertia drive motor).

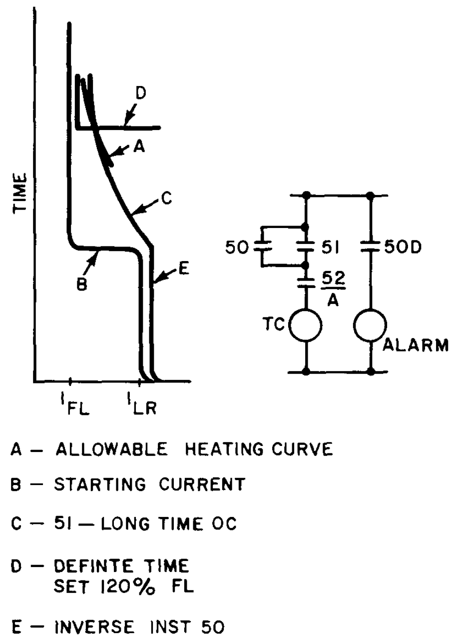


Fig 39
Complete Overcurrent Protection Characteristics

4.2.10.4 Low-Voltage Circuit Breakers

4.2.10.4.1 Low-Voltage Power Circuit Breakers (LVPCB). Where motors are controlled by LVPCB, it is recommended that the circuit-breaker overcurrent trip device long-time pick-up be no less than 115% of the motor rated full-load current, or as recommended in ANSI C37.16-1980 [2], Table 6. With the easily adjustable trip characteristics available on LVPCB, in long-time delay, short-time delay and instantaneous tripping, these circuit breakers provide adequate motor overload protection. The instantaneous trip setting should be set between 10 and 12 times the full-load current rating of the motor since it is usual to assume that the locked-rotor current is 6 to 8 times full-load rating and that the motor inrush current approaches twice the locked-rotor current.

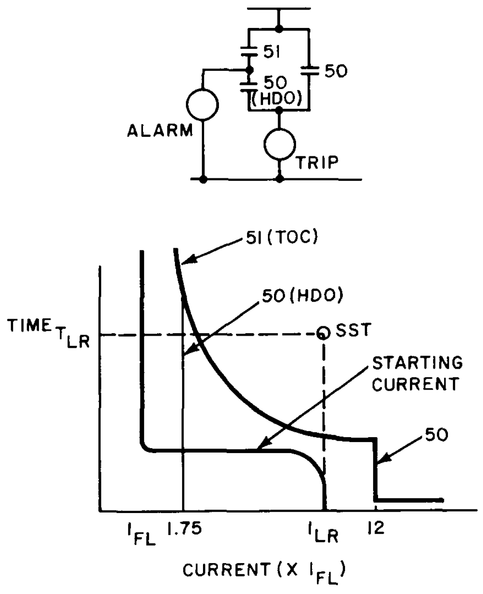


Fig 40
Typical Setting of 50/51 when 50 Supervises 51

4.2.10.4.2 Motor Circuit Protectors. Motor circuit protector (MCP) is an industry name that has been applied to molded case circuit breakers having special instantaneous trips only and designed primarily for motor short-circuit protection. According to ANSI/NFPA 70-1987 [11], Article 430-52, an instantaneous trip circuit breaker should be used only if adjustable, if part of a combination controller having motor running overload and also short-circuit and ground-fault protection in each conductor, and the combination is especially approved for the purpose. ANSI/NFPA 70-1987 [11] further states that the setting of an instantaneous trip circuit breaker shall be permitted to be increased but in no case shall exceed 1300% of the motor full-load current.

4.2.10.5 Motor Short-Circuit Protector (MSCP). ANSI/NFPA 70-1987 [11] permits the use of motor short-circuit protectors. These fuse-like devices with extreme steep characteristics and a very high interrupting capacity, permit extremely small let-through current. They must be rated at not more than 1300% of motor full-load current. The devices are required to be part of a combination controller having both motor-running overload protection and short-circuit and ground-fault protection in each conductor and the combination must be specifically approved for the purpose.

4.2.10.6 Device 50G — Instantaneous Ground-Current Relay

4.2.10.6.1 Ground-Sensor Relay. This relay, which is energized by current from a toroidal or doughnut current-transformer around the three supply conductors to a motor, is intended to provide very sensitive ground-current protection for motors. Since the three-phase currents in the primary of the current transformer add to zero, the relay is responsive only to ground-fault current (see Fig 32).

Minimum primary current pick-up occurs when the current transformer exciting impedance and relay impedance are matched. The current transformer exciting curve and relay instructions provide the information needed to approach this optimum match. The lowest relay tap does not, in general, give the lowest primary current pick-up for electromechanical relays. Low-energy devices such as solid-state relays generally have lowest primary pick-up on the lowest tap.

4.2.10.6.2 Ground-Fault (Flashover) Relay. For the fast tripping of wound-rotor-induction motors when a flashover from slip rings to ground has occurred, device 50 or device 59 is used. The device consists of a low-current instantaneous overcurrent relay, a set of wye-delta voltage transformers, and a resistor. The voltage transformers are selected so that their wye- or high-voltage windings are rated equal to or somewhat greater than the slip-ring voltage. The neutral is solidly grounded and the phase leads are connected to the slip-ring leads. The relay and resistor are connected in series across the open corner of the delta secondaries (see Fig 20). The resistor value is selected so that with the relay impedance it limits the fault current for a solid ground on one slip ring to 25 A to 30 A. The relay pick-up should be set for approximately 2 A.

4.2.10.7 Device 51 — Time-Overcurrent Relays

4.2.10.7.1 Induction-Type Overcurrent Relays. These relays, frequently equipped with one or two instantaneous-overcurrent attachments are commonly applied for protection of motor circuits. For the majority of applications the time-overcurrent (TOC) pick-up is set at 150%-175% of the rated-load current. In cases where a separate thermal overload device is not used, it may be desirable to lower the pick-up setting to approximately 125% of the service factor corrected rated-load current. A time-overcurrent relay with an instantaneous-overcurrent attachment can be set at 115% of full-load current. It alarms for moderate overloads, below the instantaneous-overcurrent setting, and trips for more severe overloads or faults (see Fig 40).

When used for locked-rotor protection, the time-delay setting should be selected to provide 2 s-5 s margin above the starting time at rated voltage. Due consideration should be given the integrating effect of the motor starting current on the relay. When the start time is in a 5 s-10 s range, a 2 s margin is satisfactory. For a start time of 40 s-50 s, a margin of 5 s is more appropriate (see Fig 37).

When the time delay cannot be set to obtain the desired margin above starting current and still protect the motor, that is, trip before the motor thermal limit is exceeded, it may be desirable to supervise the time-overcurrent with another device (see 2.2.7). In such an application it may be necessary to set the TOC pick-up at 175%-250% of motor full-load current. This results from the need to prevent pick-up of the TOC relay before the mho relay resets; thus causing unnecessary tripping of the motor on a successful start.

In some cases it may be possible to obtain a better match to the motor thermal limit by the use of two time-overcurrent relays with different time current characteristics. This could be a more desirable solution if use is made of the motors accelerating thermal limit (see 2.2.7).

Special longtime inverse, very inverse, and extremely inverse characteristics are available and may sometimes provide better coordination for locked-rotor protection on motors with varying starting times (see Fig 39).

Motors that drive large fly wheels, in addition to normal loads, are usually of a special design and have starting currents ranging from somewhat less than normal to over twice the starting current normally expected for the nominal horsepower. Since starting current characteristics of such motors vary so widely, overload protection should be verified against specific motor requirements.

4.2.10.7.2 Plunger-Type Overcurrent Relays. Plunger-type time-delay overcurrent relays are in some cases used in the same manner as induction-type overcurrent relays. The minimum operating current and the time of operation at rated inrush current are selected and set in the same manner as given above for induction-type relays.

4.2.10.7.3 Solid-State Overcurrent Relays. The use of solid-state microprocessor-based digital measuring techniques has expanded the scope of protection to a considerable degree. Solid-state microprocessor-based relays provide improved filtering, tripping criteria, measuring algorithm, setting, and testing features. Accuracy is especially important for parameters such as overload protection. Existing relays often have inacurracy in current measurements, which can vary from 5% to 10%. These inaccuracies can result in significant increases in thermal losses. The solid-state microprocessor-based relays minimize these errors by:

(1) Increasing the flexibility by designing one multifunction and field programmable relay version.
(2) Increasing the reliability and decreasing the maintenance with continuous supervision.
(3) Multifunction features, flexible programmability and accurate display capability of various abnormalities such as current, thermal content, phase unbalance, and starting current.

4.2.10.8 Device 51N—Residually-Connected Ground Overcurrent Relay. Device 51N relay is energized from current in the residual circuit of three wye-connected current transformers, one in each phase. Quite frequently there may be dissimilarities in the burdens in each phase, and unsymmetrical saturation of current transformers during the inrush period may cause incorrect operation of the relay. For this reason, care should be exercised to ensure that the relay tap setting or series impedance, or both, are such as to prevent false tripping. The lowest possible pick-up setting is desirable. A low-burden phase relay, such as a solid-state relay, may be used to advantage here.

In some cases a large individual motor may be supplied from a wye-connected transformer. In such a case, use of transformer-neutral current transformer for an instantaneous relay (which would then be designated 50G) eliminates the possibility of relay operation except for actual ground-current flow.

4.2.10.9 Device 51R—Extreme Overload Protection Relay. This device is used to protect large (1500 hp or larger) unloaded-start synchronous motors against extreme overload that might pull the motor out of step. It is made operative only after the motor is synchronized and set to operate above the maximum acceptable motor overload. The device should open the main ac circuit and remove field voltage.

4.2.10.10 Inverse Time Circuit Breaker. Time limit circuit breakers have inverse time characteristics and function when the current in an ac circuit exceeds a predetermined value. ANSI/NFPA 70-1987 [11] allows their use in combination with running overcurrent protection devices for a motor branch circuit.

4.2.11 Device 53—Exciter or DC Generator Relay. A relay that forces the dc machine field excitation to build up during starting or which functions when the machine voltage has built up to a given value.

This device checks the presence of dc voltage and is used to protect against loss of excitation for synchronous motors when excitation is obtained from a common bus or separately driven exciter. It may also be used to force voltage buildup on a direct-connected exciter at the moment of motor synchronization.

It is a field voltage check relay set at approximately 90% of rated field voltage of the synchronous motor.

4.2.12 Device 55 — Power-Factor Relay. A relay that operates when the power factor in an ac circuit rises above or falls below a predetermined value.

Device 55 detects synchronous motor loss of synchronism, which is caused by increased loading or decreased excitation. Loss of synchronism causes the motor to pull out of step with the supply system, producing high line current pulses and possible physical damage to the motor.

Some of the relays used have an adjustable power-factor angle setting and an adjustable time delay. The relay actuation can be used to remove the synchronous motor from the line (or in rare special cases to operate an alarm). It is usually set or connected for maximum contact closing torque when current into the motor lags its unity power-factor position by 120° - 150°. It will then operate for conditions occuring when the motor loses synchronism (producing watt flow out of the motor and var flow into it), or when the synchronous motor field is lost. The minimum time delay is favored, but the duration of transient effects must be considered when making the time-delay setting.

Most power-factor angle relays are not put into service until after the motor has reached synchronizing speed and the field has been applied. This is accomplished by a timing device in the potential circuit to the relay. The timer allows the potential circuit to be applied to the relay after the allotted time has elasped for the motor to reach synchronous speed.

Some of these relays are not adjustable and operate on line current power factor.

4.2.13 Device 56—Field Application Relay. A relay that automatically controls the application of the field excitation to an ac motor at some predetermined point in the slip cycle.

This is a frequency relay used to determine that motor speed is 1%-5% away from synchronous speed, and, in conjunction with a time-delay relay, to apply field when conditions are proper to close the field breaker. On some motors, where continuity of service is a factor, this same relay is also used to remove the field during an out-of-step condition and then to automatically reapply the field at the proper time and condition.

4.2.14 Device 60 — Voltage or Current Balance Relay. A relay that operates on a given difference in voltage or current input or output, of two circuits.

In the context of this guide, device 60 is an overcurrent relay that is connected to operate on the differential current from current transformers in the split windings of a motor. The relay should be set above the maximum error current caused by winding unbalance. This unbalance can vary with different operating conditions, so it is wise to observe the unbalance under light load, full load, and starting conditons. Ordinarily 10% of full-load pick-up is secure. A delay of approximately 0.3 s for 100% full-load current is recommended.

4.2.15 Device 81 — Frequency Relay. A relay that responds to the frequency of an electrical quantity, operating when the frequency or rate of change of frequency exceeds or is less than a predetermined value.

An underfrequency relay is recommended for the protection of motors from out-of-phase reenergization by automatic reclosing of the supply when the motor is decelerating. The same device can be used for automatic load shedding at abnormally low frequency. The application and setting of this device should be made from a study of the system supply and motor load characteristics as indicated in 2.8.2.

4.2.16 Device 86 — Lockout Relay. A hand or electrically reset auxiliary relay that is operated upon the occurance of abnormal conditions to maintain associated equipment or devices inoperative until it is reset.

It is used for tripping a motor controller or breaker when the tripping is initiated by a differential relay device 87. The hand-reset feature prevents re-energization of the motor after such a trip-out unless the operator resets the lockout relay. The device requires no setting other than an operation check at the minimum control voltage.

4.2.17 Device 87 — Differential Protective Relay. A protective relay that functions on a percentage, or phase angle, or other quantitative difference of two currents or of some other electrical quantities.

The ordinary percentage-differential relay used for motor protection does not require a setting in the same sense that an overcurrent relay does. A 10% slope is generally used, with 25% preferred where substantial current transformer mismatch exists. Care should be exercised to make certain that the current transformer and relay windings are properly connected, and it may be desirable to check the slope of the relay characteristic.

Occasionally, ordinary induction overcurrent relays are connected in a differential circuit to provide differential protection for a motor. In such a case, the pick-up setting of the relay should be selected to give the desired sensitivity. The value should be in the range of 10%-20% of motor full-load current, provided the current-transformer ratio and relay minimum-current tap allow a setting of this range. A typical time-delay setting is 0.1 s. For flux-balancing differential schemes, relays should be set in accordance with instructions for setting device 50G.

5. Bibliography

5.1 Induction Motors, General

[B1] JAIN, G. C. The Effect of Voltage Waveshape on the Performance of a 3-Phase Induction Motor. *IEEE Transactions on Power Apparatus and Systems*, vol 83, Jun 1964, pp 561-566.

[B2] AIEE COMMITTEE REPORT. Survey of Induction Motor Protection. *AIEE Transactions on Power Apparatus and Systems*, vol 79, Jun 1960, pp 188-192.

[B3] PICOZZI, V. J. Factors Influencing Starting Duty of Large Induction Motors. *AIEE Transactions on Power Apparatus and Systems*, vol 78, Jun 1959, pp 401-407.

[B4] MAC MASTER, J. F. *Design Features of an Electrically Driven Gas Compressor Station.* Presented at the PIEA-PESA Annual Conference, Galveston, TX, Apr 1964.

[B5] LAWRENCE, W. H. Large Electric Motors for the Petroleum Industry. *AEI Engineering*, Mar/Apr 1963.

[B6] MOORE, R. C. WK^2 vs Rotor Loss. *Allis-Chalmers Electrical Review*, vol 25, no 3, 1960.

[B7] WOLL, R. F. *Effect of Unbalanced Voltage on the Operation of Polyphase Induction Motors.* Paper PCI 73-35 presented at the 1973 IEEE Petroleum and Chemical Industry Conference, Houston, TX, Sep 10-12.

[B8] CUMMINGS, P. G. *Temperature Rise and Service Factor Standards for AC Motors.* Presented at the Annual American Power Conference, Apr 1971.

[B9] COURTIN, JOHN J. New NEMA Rerating of AC Motors. *AIEE Transactions on Industry and General Applications*, vol IGA-1, Sep/Oct 1965, pp 320-324.

[B10] OOI, B. T. and BARTON, T. H. Starting Transients in Induction Motors with Inertia Loads. *IEEE Transactions on Power Apparatus and Systems*, vol PAS-91, Sep/Oct 1972, pp 1870-1874.

[B11] MOORE, R. C. Fault Contributions of Large Induction Motors. *Allis-Chalmers Electrical Review*, vol 26, no 1, 1961, pp 14-17.

[B12] LA FUZE, D. L. Internal Fault Currents in Multicircuit Induction Machines. *AIEE Transactions on Power Apparatus and Systems*, vol 73, Dec 1954, pp 1428-1433.

[B13] BERNDT, M. W. and SCHMITZ, N. L. Derating of Polyphase Induction Motors Operated with Unbalanced Line Voltages. *AIEE Transactions on Power Apparatus and Systems*, vol 81, Feb 1963, pp 680-686.

[B14] CHIDAMBARA, M. R. and GANAPATHY, S. Transient Torques in 3-Phase Induction Motors During Switching Operations. *AIEE Transactions on Power Apparatus and Systems*, vol 81, Apr 1962, pp 47-55.

[B15] DE MELLO, F. P. and WALSH, G. W. Reclosing Transients in Induction Motors with Terminal Capacitors. *AIEE Transactions on Power Apparatus and Systems*, vol 79, Feb 1961, pp 1206-1213.

[B16] KARR, F. R. Squirrel-Cage Motor Characteristics Useful in Setting Protective Devices. *AIEE Transactions on Power Apparatus and Systems*, vol 78, Jun 1959, pp 248-252.

[B17] OSCARSON, G. L. Applications of Large AC Motors and Controls in Refineries and Pipe Lines. *AIEE Transactions on Applications and Industry*, vol 73, Nov 1954, pp 296-301.

[B18] IEEE COMMITTEE REPORT. Bibliography of Rotating Electric Machinery for 1966-1968. *IEEE Transactions on Power Apparatus and Systems*, vol PAS-89, Jul/Aug 1970, pp 1293-1304.

[B19] IEEE COMMITTEE REPORT. Bibliography of Rotating Electric Machinery for 1962-1965. *IEEE Transactions on Power Apparatus and Systems*, vol PAS-87, Mar 1968, pp 679-689.

[B20] HEIDBREDER, J. F., ROBINSON, R. C., and MERRILL, E. F. Relationship Between High-Temperature Operation and the Performance Guarantees of Induction Motors. *IEEE Transactions on Power Apparatus and Systems*, vol 82, Aug 1963, pp 597-600.

[B21] HEIDBREDER, J. F. Induction Motor Temperature Characteristics. *AIEE Transactions on Power Apparatus and Systems*, vol 77, Oct 1958, pp 800-804.

[B22] HOWELL, J. K. and COURTIN, J. J. Temperature Protection for Induction Motors — Today and Tomorrow. *Westinghouse Engineer*, Nov 1959.

[B23] GAFFORD, B. N., DUESTERHOEFT, Jr, W. C., and MOSHER, III, C. C. Heating of Induction Motors on Unbalanced Voltages. *AIEE Transactions on Power Apparatus and Systems*, vol 78, Jun 1959, pp 282-288.

[B24] MARTINY, R. M., McCOY, R. M., and MARGOLIS, H. B. Thermal Relationships in an Induction Motor Under Normal and Abnormal Operation. *AIEE Transactions on Power Apparatus and Systems*, vol 80, Apr 1961, pp 66-76.

[B25] ELIASEN, A. N. High-Inertia Drive Motors and Their Starting Characteristics. *IEEE Transactions on Power Apparatus and Systems*, Jul/Aug 80, pp 1472-1482.

[B26] STONE, G. C. and SHARMA, D. K. Investigation of Turn Insulation Failure Mechanism in Large AC Motors. *IEEE Transactions on Power Apparatus and Systems*, Sep 1984, pp 2588-2595.

5.2 Synchronous Motors, General

[B27] ROSENBERRY, Jr, G. M. A New Brushless DC Excited Rotating Field Synchronous Motor. *AIEE Transactions on Applications and Industry*, vol 79, Jul 1960, pp 136-139.

[B28] RAMAN, K. S. and GROSS, E. T. B. Rapid Demagnetization of Large Synchronous Machines. *IEEE Transactions on Power Apparatus and Systems*, Special Supplement, 1963, pp 642-653.

[B29] WICHMANN, A. Reliability and Testing High-Voltage Stator Insulation for Large Rotating Machines. *IEEE Transactions on Power Apparatus and Systems*, vol PAS-91, Sep/Oct 1972, pp 2230-2236.

[B30] TREMAINE, R. L. and BLACKBURN, J. L. Loss-of-Field Protection for Synchronous Machines. *AIEE Transactions on Power Apparatus and Systems*, vol 73, Aug 1954, pp 765-777.

[B31] PETERSON, R. S. Use of Synchronous Motor Drives for Maintaining Distribution System Line Voltage and Power Factor. *IEEE Transactions on Industry and General Applications*, vol IGA-7, Nov/Dec 1971, pp 696-707.

[B32] GODWIN, G. A. and MERRILL, E. F. Oscillatory Torques During Synchronous Motor Starting. *IEEE Transactions on Industry and General Applications*, vol IGA-6, May/Jun 1970, pp 258-265.

[B33] ZIMMERMAN, J. A. and RICHARDSON, W. O. Motor Starting with Capacitors. *IEEE Transactions on Industry and General Applications*, vol IGA-5, Nov/Dec 1969, pp 759-765.

[B34] HOFFMAN, A. H. Brushless Synchronous Motors for Large Industrial Drives. *IEEE Transactions on Industry and General Applications*, vol IGA-5, Mar/Apr 1969, pp 158-162.

[B35] ZIMMERMAN, J. A. and HAUCK, T. A. Starting Requirements and Effects of Large Synchronous Motors. *IEEE Transactions on Industry and General Applications*, vol IGA-5, Mar/Apr 1969, pp 169-175.

[B36] PHILLIPS, C. L. and YUEN, M. H. High-Speed Restarting and Protection of Large Synchronous Motors. *AIEE Transactions on Industry and General Applications*, vol 78, Nov 1959, pp 360-368.

[B37] HAMDI-SEPEN, D. Transfer Functions of Loaded Synchronous Machines. *AIEE Transactions on Industry and General Applications*, vol 78, Mar 1959, pp 19-24.

[B38] PETERMAN, M. and WRIGHT, D. *Brushless Synchronous Motors*. Presented at the 1965 IEEE Petroleum Industry Conference, Houston, TX, Sep 13-15, 1965.

[B39] DUNKI-JACOBS, J. R. *A New Technical Approach Related to Starting Large Motors on Weak Power Systems*. Presented at the 1965 IEEE Petroleum Industry Conference, Houston, TX, Sep 13-15, 1965.

[B40] CONCORDIA, C. *Synchronous Machines — Theory and Performance.* New York: Wiley, 1951.

[B41] IEEE COMMITTEE REPORT. Proposed Excitation System Definitions for Synchronous Machines. *IEEE Transactions on Power Apparatus and Systems*, vol PAS-88, Aug 1969, pp 1248-1258.

[B42] IEEE COMMITTEE REPORT. Recommended Phasor Diagram for Synchronous Machines. *IEEE Transactions on Power Apparatus and Systems*, vol PAS-88, Nov 1969, pp 1593-1610.

[B43] WHITE, J. C. Synchronous Motor Starting Performance Calculations. *AIEE Transactions on Power Apparatus and Systems*, vol 75, Aug 1956, pp 772-778.

[B44] HORN, M. E. and CUNNINGHAM, J. C. Transient Voltage and Current Requirements of Main-Field Circuit Breakers for Synchronous Machines. *AIEE Transactions on Power Apparatus and Systems*, vol 73, Aug 1954, pp 894-900.

[B45] THAMES, P. B. and HEARD, T. C. Torsional Vibrations in Synchronous Motor-Geared-Compressor Drives. *AIEE Transactions on Power Apparatus and Systems*, vol 78, Dec 1959, pp 1053-1056.

[B46] HOFFMANN, A. H., RACZKOWSKI, C., and SQUIRES, R. B. Relaying for Synchronous Motor Pullout Protection. *AIEE Transactions on Power Apparatus and Systems*, vol 78, Aug 1959, pp 618-624.

[B47] SUBBA-RAO, V. S. and LANGMAN, R. A. Analysis of Synchronous Machines under Unbalanced Operations. *IEEE Transactions on Power Apparatus and Systems*, vol PAS-89, May/Jun 1970, pp 698-706.

[B48] SANO, K. Pole-Changing of Salient-Pole Synchronous Machines. *AIEE Transactions on Power Apparatus and Systems*, Dec 1960, pp 948-954.

[B49] BARKLE, J. E., STERRETT, C. C., and FOUNTAIN, L. L. Detection of Grounds in Generator Field Windings. *AIEE Transactions on Power Apparatus and Systems*, vol 74, Jun 1955, pp 467-472.

5.3 Variable Speed Applications

[B50] BELLINI, A., DECARLI, A., and MURGO, M. Speed Control of Synchronous Machines. *IEEE Transactions on Industry and General Applications*, vol IGA-7, May/Jun 1971, pp 332-338.

[B51] LAVIS, A. and POLGE, R. J. Induction Motor Speed Control with Static Inverter in Rotor. *IEEE Transactions on Power Apparatus and Systems*, vol PAS-85, Jan 1966, pp 76-84.

[B52] ALGER, P. L. and JALALUDDIN. Stepless Starting of Wound-Rotor Induction Motors. *AIEE Transactions on Industry and General Applications*, vol 81, Nov 1962, pp 262-272.

[B53] ZAGALSKY, N. and SHEPHERD, W. Wide-Range Reversible Voltage Controllers for Polyphase Induction Motors, *AIEE Transactions on Industry and General Applications*, vol 81, Nov 1962, pp 272-277.

[B54] BEDFORD, R. E. and NENE, V. D. Voltage Control of Three-Phase Induction Motor by Thyristor Switching: A Time-Domain Analysis Using the A-B-O Transformation. *IEEE Transactions on Industry and General Applications*, vol IGA-6, Nov/Dec 1970, pp 553-562.

[B55] TSIVITSE, P. J. and KLINGSHIRN, E. A. Optimum Voltage and Frequency for Polyphase Induction Motors Operating with Variable Frequency Power Supplies. *IEEE Transactions on Industry and General Applications*, vol IGA-7, Jul/Aug 1971, pp 480-487.

[B56] BELLINI, A. and CIOFFI, G. Induction Frequency Control: Three-Phase Bridge Inverter Behavior and Performance. *IEEE Transactions on Industry and General Applications*, vol IGA-7, Jul/Aug 1971, pp 488-499.

[B57] ROBERTSON, S. D. T. and HEBBAR, K. M. Torque Pulsations in Induction Motors with Inverter Drives. *IEEE Transactions on Industry and General Applications*, vol IGA-7, Mar/Apr 1971, pp 318-323.

[B58] LONG, W. F. and SCHMITZ, N. L. Cycloconverter Control of Doubly Fed Induction Motor. *IEEE Transactions on Industry and General Applications*, vol IGA-7, Jan/Feb 1971, pp 95-100.

[B59] WURGLER, H. U. The World's First Gearless Mill Drive. *IEEE Transactions on Industry and General Applications*, vol IGA-6, Sep/Oct 1970, pp 524-527.

[B60] WRIGHT, W. F., HAWLEY, R., and DINELY, J. L. Brushless Thyristor Excitation Systems. *IEEE Transactions on Power Apparatus and Systems*, vol PAS-91, Sep/Oct 1972, pp 1848-1854.

5.4 Protection Relays and Settings, General

[B61] MASON, C. R. *The Art and Science of Protective Relaying.* New York: Wiley, 1956, ch 10.

[B62] VAN C. WARRINGTON, A. R. *Protective Relays, Their Theory and Practice.* London: Chapman and Hall, 1962, ch 9.

[B63] *Applied Protective Relaying.* Coral Springs, FL: Westinghouse Electric Corporation, Relay and Telecommunications Division, 1982.

[B64] FAWCETT, D. V. Electric System Design for Continuous Process Plants (Protection), *Power,* vol 107, pt 7, Jul 1963, pp 64-68.

[B65] FAWCETT, D. V. How to Select Overcurrent Relay Characteristics. *IEEE Transactions on Industry and General Applications,* vol 82, May 1963, pp 94-104.

[B66] DESIENO, C. F. and BEAUDOIN, B. J. A Guide to the Application of Capacitors Without Inductors Motor Self-Excitation. *IEEE Transactions on Power Apparatus and Systems,* vol PAS-84, Jan 1965, pp 8-15.

[B67] FAWCETT, D. V. Optimize Protection for 3-Phase AC Motors. *Electrical World,* Sep 9, 1963.

[B68] BRIGHTMAN, F. P., McGee, R. R., and REITSCHNEIDER, P. J. Protecting AC Motors with Low-Voltage Air-Circuit-Breaker Series Trips. *AIEE Transactions on Industry and General Applications,* vol 76, Jul 1957, pp 114-119.

[B69] NEFF, W. F., HOROWITZ, S. H., and SQUIRES, R. B. Relay Protection of Motors in Steam Power Stations with 4 kV Grounded Neutral Systems. *AIEE Transactions on Power Apparatus and Systems,* vol 75, Aug 1956, pp 573-576.

[B70] HOWELL, J. K. *Motor Protection, Electrical and Mechanical.* Presented at the PEIA-PESA Conference, Dallas, TX, Apr/May 1958.

[B71] SLEEMAN, D. B., and BELLINGER, T. F. *Pump Motor Protection Methods.* Paper CPA 62-5018, Presented at the AIEE Petroleum Industry Conference, Cleveland, OH, Sep 1962 (discussion by D. V. Fawcett).

[B72] BARNES, H. C., MURRAY, C. S., and VARRALL, V. E. Relay Protection Practices in Steam Power Stations. *AIEE Transactions on Power Apparatus and Systems,* vol 77, Feb 1959, pp 1360-1367.

[B73] BELLINGER, T. F. and GERG, R. A. Getting Closer Overload Protection for Polyphase Motors. *Allis-Chalmers Electrical Review,* vol 25, no 2, 1960, pp 32-34.

[B74] WHITE, A. P. Service Conditions in Motor Protection Selection. Electrical Manufacturing, Dec 1959.

[B75] BRIGHTMAN, F. P. More About Setting Industrial Relays. *AIEE Transactions on Power Apparatus and Systems,* vol 73, Apr 1954, pp 397-406.

[B76] BRIGHTMAN, F. P. Selecting AC Overcurrent Protective Device Settings for Industrial Plants. *AIEE Transactions on Industry and General Applications,* vol 71, Sep 1952, pp 203-211.

[B77] *Electric Utility Engineering Reference Book, Distribution Systems,* vol 3, 1965. East Pittsburgh, PA, Westinghouse Electic Corporation.

[B78] FAWCETT, D. V. Protection of Large Three-Phase Motors. *IEEE Transactions on Industry and General Applications,* vol IGA-3, Jan/Feb 1967, pp 52-55.

[B79] IEEE COMMITTEE REPORT. Bibliography of Relay Literature, 1965-1966. *IEEE Transactions on Power Apparatus and Systems,* vol PAS-88, Mar 1969, pp 244-250.

[B80] IEEE REPORT on Transient Response of Current Transformers. Power System Relaying Committee, Jul 6, 1973.

[B81] ROCKEFELLER, G. D. *Relaying CTs. A Source of Vital Information and Misinformation.* Presented at the 1973 Conference on Protective Relaying, Georgia Institute of Technology, Atlanta, GA.

[B82] DALASTA, D. and ZOCHOLL, S. E. New Solid-State Protective Devices for Utility Power Plant Applications. *1973 Protective Relaying Conference,* Georgia Institute of Technology, Atlanta, GA.

[B83] SHULMAN, J. M., ELMORE, W. A., and BAILEY, K. D. Motor Starting Protection by Impedance Sensing., *IEEE Transactions on Power Apparatus and Systems,* vol PAS-97, no 5, Sep/Oct 1978, pp 1689-1695.

[B84] KOEPFINGER, J. L. and KHUNKHUN, K. J. S. Protection of Auxiliary Power Systems in a Nuclear Power Plant. *IEEE Transactions on Power Apparatus and Systems,* vol PAS-98, no 1, Jan/Feb 1979, pp 290-299.

[B85] KHUNKHUN, J. K. S. and BUTT, W. H. Protecting Two-Speed Motors. *Electrical World*, vol 189, no 8, Apr 15, 1978, pp 60-62.

[B86] LAZAR, I. Protective Relaying for Motors. *Power Engineering*, vol 82, no 9, Sep 1978, pp 66-69.

[B87] LAZAR, I. Solid-State Motor Controls and Protection. *Power Engineering*, vol 83, no 12, Dec 1979, pp 59-63.

[B88] ELIASEN, A. N. The Protection of High Inertia Drive Motors During Abnormal Starting Conditions. *IEEE Transactions on Power Apparatus and Systems*, Jul/Aug 1980, pp 1483-1492.

[B89] WOODRUF, N. Economical Motor Protection Using Microprocessor Technology. *IEEE Transactions*, vol IA-20, no 5, Sep/Oct 1984, pp 1344-1357.

[B90] ZOCHOLL, S. E. *Abnormal Starting of High Inertia Drive Motors: A Case for Rotor Thermal Protection.* Conference for Protective Relaying Engineers, Apr 14-16, 1986, College Station, TX.

[B91] ELMORE, W. A. and KRAMER, C. A. *Complete Motor Protection by Microprocessor Relay.* Western Protective Relay Conference, Oct 21-23, 1986, Spokane, WA.

[B92] MEISSEL, S. M. and BANDOLINO, J. *Design and Application of a Microprocessor-Based Motor Protection Relay with Historical Analysis for Large Motors.* Presented at the Protective Relaying Conference, Apr 29-May 1, 1987, Georgia Institute of Technology, Atlanta, GA.

[B93] IYER, R., SHAH, N., and ZOCHOLL, S. E. *Techniques for Evaluating Advanced Motor Protection Relays Using Computer Controlled Test Equipment.* Presented at Protective Relaying Conference, Apr 29-May 1, 1987, Georgia Institute of Technology, Atlanta, GA.

5.5 Protection, Thermal

[B94] MOORE, R. C. Protecting Motor Windings with Thermal Detectors. *Allis-Chalmers Engineering Review*, vol 29, no 3, 1964, pp 24-27.

[B95] GAFFORD, B. N. Thermal-Synthesis Relay is Best Replica of Motor Heating. *IEEE Transactions on Power Apparatus and Systems*, vol 78, Jun 1959, pp 288-295.

[B96] VEINOTT, C. G. and SCHAEFER, L. C. Fundamental Theory of Inherent-Overheating Protection under Running Overload Conditions. *AIEE Transactions*, vol 68. pt 1, 1949, pp 266-272.

[B97] WHITE, A. P. Motor Thermal Protection, Machine Design. *The Electric Motor Book*, 1961 ed.

[B98] VAUGHN, V. G. and WHITE, A. P. New Hotter Motors Demand Thermal Protection. *Electrical Manufacturing*, Feb 1959.

[B99] Built-In Overheat Protection for 3-Phase Motors. *Electrical Manufacturing*, Aug 1958.

[B100] STEARNS, F. P. The Case for Inherent Overheat Protection for Motors. *Electrical Manufacturing*, Feb 1952.

[B101] YEAPLE, F. Which Heat Protection, for the Motor. *Product Engineering*, Sep 2, 1960.

[B102] BOOTHMAN, D. R., ELGAR, E. C., REHDER, R. H., and WOODALL, R. J. Thermal Tracking. A Rational Approach to Motor Protection. *IEEE Transactions on Power Apparatus and Systems*, vol PAS-93, Sep/Oct 1974, pp 1335-1344.

[B103] NAILEN, R. L. Safe Locked-Rotor Time: How Safe Is It! *IEEE Transactions on Industry and General Applications*, vol IGA-7, Nov/Dec 1971, pp 708-712.

[B104] BELLINGER, T. F. Running Overload Protection for Motors — Part 1. *Allis-Chalmers Engineering Review*, vol 39, no 2, 1974, pp 27-31. ibid pt 2, vol 40, no 1, 1975, pp 28-31.

[B105] KOLB, A. F. and THOM, H. W. Motor Protection Characteristics of Ambient Insensitive Overload Devices. *IEEE Transactions on Industry Applications*, vol 1A-15, no 3, May/Jun 1979, pp 303-308.

[B106] ZOCHOLL, S. E., SCHWEITZER, III, E. O., and ALIANGA-ZEGARRA, A. Thermal Protection of Induction Motors Enhanced by Interactive Electrical and Thermal Models. *AIEE Transactions on Power Apparatus and Systems*, vol PAS-103, Jul 1984, pp 1749-1755.

5.6 Protection, Fault

[B107] BELL, R. N. Sensitive Ground Relay Protection for 6900 V Motors on a High-Resistance Grounded Chemical Plant Distribution System. *IEEE Transactions on Industry and General Applications*, vol IGA-1, Nov/Dec 1965, pp 435-438.

[B108] MOORE, R. C. Fault Contributions of Large Induction Motors, *Allis-Chalmers Electrical Review*, vol 26, no 1, 1961, pp 14-17.

[B109] SHISHKIN, N. F. Protecting AC Machines from Internal Faults in the Stator Winding, *Electrichestvo* (Russian Language), no 10, 1958, pp 57-59.

[B110] SCHMIDT, R. A. Calculation of Fault Currents for Internal Faults in AC Motors. *AIEE Transactions on Power Apparatus and Systems*, vol 75, Oct 1956, pp 818-824.

[B111] DUNKI-JACOBS, J. R. The Reality of High-Resistance Grounding. *IEEE Transactions on Industry Applications*, vol IA-13, no 5, Sep/Oct 1977, pp 469-475.

5.7 Protection Against Abnormal Conditions

[B112] DALASTA, D. and DURAND, S. High-Speed Breaker Reclosing can put Abnormal Stresses on your Motors. *Power*, Feb 1958, p 90.

[B113] YERKE, R. H. Two Versus Three Running Overcurrent Units for the Protection of Three-Phase Motors. *IEEE Transactions on Power Apparatus and Systems*, Special Supplement, 1963, pp 517-542.

[B114] *Industrial Power Systems Data Book.* Schenectady, NY, General Electric Company.

[B115] ARMSTRONG, H. R. and MULAVEY, J. E. Overvoltage Protection and Maintenance Testing of AC Rotating Machines. *AIEE Transactions on Power Apparatus and Systems*, vol 78, Jun 1959, pp 166-170.

[B116] Protection Against Single-Phase Running of High- and Low-Voltage Motors. *AEG Mitteilungen* (German Language), vol 48, Feb/Mar 1958, pp 101-103.

[B117] GLEASON, L. L. and ELMORE, W. A. Protection of 3-Phase Motors Against Single-Phase Operation. *AIEE Transactions on Power Apparatus and Systems*, vol 77, pt 3, Dec 1959, pp 1112-1120.

[B118] WILLIAMS, J. E. Operation of 3-Phase Induction Motors on Unbalanced Voltage. *AIEE Transactions on Power Apparatus and Systems*, vol 73, Apr 1954, pp 125-133.

[B119] LINDERS, J. R. Effects of Power Supply Variations on AC Motor Characteristics. *IEEE Transactions on Industry Applications*, vol IGA-8, Jul/Aug 1972, pp 383-400.

[B120] WAGNER, C. F. and EVANS, R. D. *Symmetrical Components.* New York: McGraw Hill.

[B121] GRIFFITH, M. S. A Penetrating Gaze at One Open Phase: Analyzing the Polyphase Induction Motor Dilemma. *IEEE Transactions on Industry Applications*, vol IA-13, no 6, Nov/Dec 1977, pp 504-517.

[B122] GILL, J. D. Transfer of Motor Loads Between Out-of-Phase Sources. *IEEE Transactions on Industry Applications*, vol IA-15, no 4, Jul/Aug 1979, pp 376-381.

[B123] CUMMINGS, P. G., DUNKI-JACOBS, J. R., and KERR, R. H. *Protection of Induction Motors Against Unbalanced Voltage Operation.* IEEE Paper no PCI-83-3.

5.8 Protection, Surge

[B124] LEWIS, W. W. *The Protection of Transmission Systems Against Lightning.* New York: Wiley, 1950.

[B125] *Electrical Transmission and Distribution Reference Book.* East Pittsburgh, PA, Westinghouse Electric Corporation, 1950.

[B126] *Industrial Power Systems Data Book.* Schnectady, NY, General Electric Company.

[B127] POWELL, R. W., HILEMAN, A. R., and MAXWELL, M. Lighting Protection of Rotating Machines Directly Connected to Overhead Lines. *AIEE Transactions on Power Apparatus and Systems*, vol 81, Feb 1963, pp 721-730.

[B128] SHANKEL, D. F., EDWARDS, R. F., and MOSES, G. L. Surge Protection for Pipeline Motors, *IEEE Transactions on Industry and General Applications*, vol IGA-4, Mar/Apr 1968, pp 171-176.

[B129] SEXTON, R. M. *A Survey of Turn Insulation on Large AC Motors.* IEEE 32C79-23.

[B130] AIEE COMMITTEE REPORT. Impulse Testing of Rotating AC Machines, *AIEE Transactions on Power Apparatus and Systems*, vol 79, Jun 1960, pp 182-188.

[B131] FORSTMAIER, F. X. Motor Surge Protection: At the Bus or at the Motor. *IEEE Transactions on Industry and General Applications*, vol IGA-1, Sep/Oct 1965, pp 349-360.

[B132] BEEMAN, D. *Industrial Power System Handbook.* New York: McGraw-Hill, 1955, ch 5.

[B133] McCANN, G. D., BECK, E., and FINZI, L. A. Lightning Protection for Rotating Machines. *AIEE Transactions*, vol 63, 1944, pp 319-332.

5.9 Miscellaneous, Bearings, Capacitors, Bus Transfer, etc

[B134] ESCHMANN, HASBARGEN, and WEIGAND, *Ball and Roller Bearings, Their Theory, Design, and Application.* Munich: R. Oldenbourg, 1958.

[B135] DAVIES, E. J. An Experimental and Theoretical Study of Eddy-Current Couplings and Brakes. *IEEE Transactions on Power Apparatus and Systems*, vol 82, Aug 1963, pp 401-419.

[B136] SIDWAY, C. L. and CONNER, J. E. Effect of Overvoltages and Surges on Machine Insulation. *AIEE Transactions on Power Apparatus and Systems*, vol 73, Aug 1954, pp 799-809.

[B137] YOUNG, C. C. and DUNKI-JACOBS, J. The Concept of In-Phase Transfer Applied to Industrial Systems Serving Essential Service Motors. *AIEE Transactions on Industry and General Applications*, vol 79, Jan 1961, pp 508-518.

[B138] BACKER, L. E., BARTH, P., HUSE, R. A., and TAYLOR, D. W. Transfer Tests on Station Auxiliary Busses. *AIEE Transactions on Power Apparatus and Systems*, vol 74, Feb 1956, pp 1441-1449.

[B139] LEWIS, D. G. and MARSH, W. D. Transfer of Steam Electric Generating Station Busses. *AIEE Transactions on Power Apparatus and Systems*, vol 74, Jun 1955, pp 322-334.

[B140] KELLY, A. R. Relay Response to Motor Residual Voltage during Automatic Transfers. *AIEE Transactions on Industry and General Applications*, vol 74, Sep 1955, pp 245-250.

[B141] WALSH, G. F. The Effects of Reclosing on Industrial Plants. *1961 Proceedings of the American Power Conference*, vol 23, pp 658-778.

[B142] OLSON, O. A. Shaft Currents in AC Machinery. *Power Generation*, Nov 1949, p 102.

[B143] BUCHANAN, W. Shaft Currents in Electric Machines. *Electrician*, (London), vol 75, May 28, 1915, pp 226-267.

[B144] HAUCK, T. A. *Motor Reclosing and Bus Transfer in Electric Utility Service.* Presented at the 1971 American Power Conference, Chicago, IL.

[B145] MOLLE, J., SHISHAKLY, R. W., and FAWCETT, D. V. Air-Purged Electric Systems for a Large Compressor Building Having Group B, Division 2 Classifications. *IEEE Transactions on Industry and General Applications*, vol 83, Jul 1964, pp 209-215.

[B146] PAULUS, C. F. and GREEN, D. R. Proper Motor Application Engineering Can Reduce Costs and Improve Reliability. *AIEE Transactions on Power Apparatus and Systems*, vol 81, Feb 1963, pp 886-891.

[B147] RAMSAUR, O. Performance of Overcurrent Relays on Cold Load Restoration. *1952 PEA Relay Committee Proceedings.*

[B148] JACKSON, DAVID W. Analysis of Surge Capacitor Lead Connections for Protection of Motors. *IEEE Transactions on Power Apparatus and Systems*, Sep 1984, pp 2605-2611.

5.10 Standards Publications

[B149] IEEE COMMITTEE REPORT. Bibliography of Rotating Electric Machinery for 1948-1961. *IEEE Transactions on Power Apparatus and Systems*, vol 88, Jun 1964, pp 589-606.

[B150] ANSI/IEEE C37.90-1978 (R1982), Relays and Relay Systems Associated with Electric Power Apparatus.

[B151] ANSI C50.10-1987, General Requirements for Synchronous Machines (IEC 34-1-1969).

[B152] NEMA AB 1-1986, Standards for Molded Case Circuit Breakers.

[B153] NEMA SG3-1981, 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 3-Phase, 60 Hz Motors.

[B154] NEMA FU1-1986, Standards for Low-Voltage Cartridge Fuses.

[B155] ANSI/IEEE Std 620-1987, IEEE Guide For Construction and Interpretation of Thermal Limit Curves for Squirrel-Cage Motors Over 500 hp.