

IEEE Std 3004.8™-2016

Recommended Practice
for Motor Protection in
Industrial and Commercial
Power Systems



IEEE Recommended Practice for Motor Protection in Industrial and Commercial Power Systems

Sponsor

Technical Books Coordinating Committee
of the
IEEE Industry Applications Society

Approved 7 December 2016

IEEE-SA Standards Board

Recognized as an American National Standard

Abstract: The protection of motors used in industrial and commercial power systems is covered. It is likely to be of greatest value to the power-oriented engineer with limited experience in the area of protection and control. It can also be an aid to all engineers responsible for the electrical design of industrial and commercial power systems.

Keywords: coordination, IEEE 3004.8, induction motors, inverse-time overcurrent element, motor protection, motor protection relay, negative sequence characteristics, overcurrent protection, permanent magnet motors, relay protection, resistive temperature detector, rotors, rotor thermal protection, stators, stator thermal protection, synchronous motors, temperature detector voting, temperature sensors, thermal model overload protection, unbalanced protection

The Institute of Electrical and Electronics Engineers, Inc.
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PDF: ISBN 978-1-5044-3608-3 STD22343
Print: ISBN 978-1-5044-3609-0 STDPD22343

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Rasheek Rifaat, *Chair*
Donald McCullough II, *Vice Chair*

Carey Cook	Claudio Mardegan	Louie Powell
Thomas Domitrovich	Chuck Mozina	Daniel Ransom
Robert Hoerauf	Dan Neeser	Marcelo E. Valdes
Ed Larsen	Lorraine Padden	

At the time this IEEE recommended practice was completed, the IEEE 3004.8 Project Working Group had the following membership:

Rasheek Rifaat, *Working Group Committee Chair*
Lorraine K. Padden, *Project Working Group Chair*

Partha Basu	Jim Crook	Byron Hohrein
Thomas Beckwith	Randall Groves	Umar Khan
Sirak Belayneh	Jeffrey Hensley	John Kay
Robert David Bredhold	Chris Heron	Daniel Leland Ransom
James Bryan		Bill Stewart

The following individuals contributed to the development of this recommended practice, but were not working group members at the time this recommended practice was completed:

Smit Bavishi	Duane Leschert	Malcolm Seltzer-Grant
Paul Cardinal	Daniel Neeser	Manish Singh
Jerry Franklin	Timothy O'Hearn	Louis Spence
David Hinchliffe	Pero Ostojic	Mike Thomasson
Mayank Jain	David C. Rains†	Marcelo E. Valdes
Ed Larsen		Sunil Verma

†Posthumous

The following members of the individual balloting committee voted on this standard. Balloters may have voted for approval, disapproval, or abstention.

Dave Aldrich	William Bush	Carl Fredericks
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When this project is completed, the technical material in the 13 IEEE Color Books will be included in a series of new standards—the most significant of which will be a new standard, IEEE Std 3000™, IEEE Recommended Practice for the Engineering of Industrial and Commercial Power Systems. The new standard will cover the fundamentals of planning, design, analysis, construction, installation, startup, operation, and maintenance of electrical systems in industrial and commercial facilities. Approximately 60 additional dot standards, organized into the following categories, will provide in-depth treatment of many of the topics introduced by IEEE Std 3000™:

- Power Systems Design (3001 series)
- Power Systems Analysis (3002 series)
- Power Systems Grounding (3003 series)
- Protection and Coordination (3004 series)
- Emergency, Standby Power, and Energy Management Systems (3005 series)
- Power Systems Reliability (3006 series)
- Power Systems Maintenance, Operations, and Safety (3007 series)

In many cases, the material in a dot standard comes from a particular chapter of a particular IEEE Color Book. In other cases, material from several IEEE Color Books has been combined into a new dot standard.

IEEE Std 3004.8

A general update was made to the material from Chapter 10 of the *IEEE Buff Book*™. Material added or expanded includes details for reduced-voltage motor starting, recommended protection functions using multifunction motor protection relays for contactor controlled fused starters and breaker controlled starters, along with single-line and three-line diagrams, adjustable speed drive applications, dc motor protection, motor bus transfer, partial discharge monitoring, and a detailed example of motor protection using a multifunction motor protection relay.

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IEEE Recommended Practice for Motor Protection in Industrial and Commercial Power Systems

1. Scope

This recommended practice covers the protection of motors used in industrial and commercial power systems. It is likely to be of greatest value to the power-oriented engineer with limited experience in the area of protection and control. It can also be an aid to all engineers responsible for the electrical design of industrial and commercial power systems.

2. Normative references

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API Std 541, Form-Wound Squirrel Cage Induction Motors—500 Horsepower and Larger, 5th Edition.¹

API Std 546, Brushless Synchronous Machines—500 kVA and Larger, 3rd Edition.

API Std 547, General-Purpose Form-Wound Squirrel Cage Induction Motors—250 Horsepower and Larger, 1st Edition.

IEEE Std 43™, IEEE Recommended Practice for Testing Insulation Resistance of Electric Machinery.^{2,3}

IEEE Std 112™, IEEE Standard Test Procedure for Polyphase Induction Motors and Generators.

IEEE Std 115™, IEEE Guide for Test Procedures for Synchronous Machines Part I—Acceptance and Performance Testing Part II—Test Procedures and Parameter Determination for Dynamic Analysis.

IEEE Std 141™-1993 (Reaff 1999), IEEE Recommended Practice for Electric Power Distribution for Industrial Plants (*IEEE Red Book™*).

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IEEE Std 241™-1990 (Reaff 1997), IEEE Recommended Practice for Electric Power Systems in Commercial Buildings (*IEEE Gray Book™*).

IEEE Std 242™-2001, IEEE Recommended Practice for Protection and Coordination of Industrial and Commercial Power Systems (*IEEE Buff Book™*).

IEEE Std 519™, IEEE Recommended Practices and Requirements for Harmonic Control in Electrical Power Systems.

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

IEEE Std 841™, IEEE Standard for Petroleum and Chemical Industry—Premium Efficiency, Severe-Duty, Totally Enclosed Fan-Cooled (TEFC) Squirrel Cage Induction Motors—Up to and Including 370 kW (500 hp).

IEEE Std 1015™-2006, IEEE Recommended Practice for Applying Low-Voltage Circuit Breakers Used in Industrial and Commercial Power Systems (*IEEE Blue Book™*).

IEEE Std 1349™, IEEE Guide for the Application of Electric Motors in Class I, Division 2 and Class I, Zone 2 Hazardous (Classified) Locations.

IEEE Std 1683™, IEEE Guide for Motor Control Centers Rated up to and including 600 V AC or 1000 V DC with Recommendations Intended to Help Reduce Electrical Hazards.

IEEE Std 3001.5™, IEEE Recommended Practice for the Application of Power Distribution Apparatus in Industrial and Commercial Power Systems.

IEEE Std 3001.8™, IEEE Recommended Practice for the Instrumentation and Metering of Industrial and Commercial Power Systems.

IEEE P3001.11 D8, IEEE Draft Recommended Practice for Application of Controllers and Automation to Industrial and Commercial Power Systems.⁴

IEEE Std 3003.2™, IEEE Recommended Practice for Equipment Grounding and Bonding in Industrial and Commercial Power Systems.

IEEE Std 3004.1™, IEEE Recommended Practice for the Application of Instrument Transformers in Industrial and Commercial Power Systems.

IEEE Std 3004.5™, IEEE Recommended Practice for the Application of Low-Voltage Circuit Breakers in Industrial and Commercial Power Systems.

IEEE Std 3006.5™, IEEE Recommended Practice for the Use of Probability Methods for Conducting a Reliability Analysis of Industrial and Commercial Power Systems.

IEEE Std 3006.7™, IEEE Recommended Practice for Determining the Reliability of 7×24 Continuous Power Systems in Industrial and Commercial Facilities.

IEEE Std 3006.9™, IEEE Recommended Practice for Collecting Data for Use in Reliability, Availability, and Maintainability Assessments of Industrial and Commercial Power Systems.

⁴Numbers preceded by P are IEEE authorized standards projects that were not approved by the IEEE-SA Standards Board at the time this publication went to press. For information about obtaining drafts, contact the IEEE.

IEEE Std 3007.1™, IEEE Recommended Practice for the Operation and Management of Industrial and Commercial Power Systems.

IEEE Std 3007.2™, IEEE Recommended Practice for the Maintenance of Industrial and Commercial Power Systems.

IEEE Std 3007.3™, IEEE Recommended Practice for Electrical Safety in Industrial and Commercial Power Systems.

IEEE Std C37.06™, IEEE Standard for AC High-Voltage Circuit Breakers Rated on a Symmetrical Current Basis—Preferred Ratings and Related Required Capabilities for Voltages Above 1000 V.

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

IEEE Std C37.13™, IEEE Standard for Low-Voltage AC Power Circuit Breakers Used in Enclosures.

IEEE Std C37.14™, IEEE Standard for DC (3200 V and below) Power Circuit Breakers Used in Enclosures.

IEEE Std C37.17™, IEEE Standard for Trip Systems for Low-Voltage (1000 V and below) and AC and General Purpose (1500 V and below) DC Power Circuit Breakers.

IEEE Std C37.46™, IEEE Specifications for High-Voltage (>1000 V) Expulsion and Current-Limiting Power Class Fuses and Fuse Disconnecting Switches.

IEEE Std C37.96™-2012, IEEE Guide for AC Motor Protection.

IEEE Std C37.110™, IEEE Guide for the Application of Current Transformers Used for Protective Relaying Purposes.

IEEE Std C62.21™, IEEE Guide for the Application of Surge Voltage Protective Equipment on AC Rotating Machinery 1000 V and Greater.

NEMA ICS 2, Industrial Control and Systems Controllers, Contactors and Overload Relays Rated 600 Volts.⁵

NEMA MG 1-2011, Motors and Generators.

NFPA 20-2013, Standard for the Installation of Stationary Pumps for Fire Protection.⁶

NFPA 70-2014, National Electrical Code® (NEC®).

UL 347, UL Standard for Safety Medium-Voltage AC Contactors, Controllers, and Control Centers.⁷

UL 845, UL Standard for Motor Control Centers.

⁵NEMA publications are available from Global Engineering Documents, 15 Inverness Way East, Englewood, CO 80112, USA (<http://global.ihs.com/>).

⁶NFPA publications are available from Publications Sales, National Fire Protection Association, 1 Batterymarch Park, P.O. Box 9101, Quincy, MA 02269-9101, USA (<http://www.nfpa.org/>).

⁷UL standards are available from Global Engineering Documents, 15 Inverness Way East, Englewood, Colorado 80112, USA (<http://www.global.ihs.com/>).

3. Definitions, abbreviations, and acronyms

For the purposes of this document, the following terms and definitions apply. The *IEEE Standards Dictionary: Glossary of Terms and Definitions* should be referenced for terms not defined in this clause.⁸

3.1 Definitions

abnormal operating condition: As applied to motors, including, but not limited to, starting, locked rotor, voltage unbalance, overload, and short-circuit. As applied to equipment in classified locations, equipment failure is considered to be an abnormal operating condition.

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

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

adjustable speed drive: An electric drive designed to provide easily-operable means for speed adjustment of the motor, within a specified speed range.

ambient temperature: Ambient temperature is the temperature of the surrounding cooling medium, such as gas or liquid, which comes into contact with the heated parts of the apparatus. (See NEMA MG-1.)⁹

approved: Acceptable to the authority having jurisdiction. (See NFPA 70, National Electrical Code.)

arc flash detector (AFD): A device/function that detects an unintentional electrical arc in air.

autoignition temperature (AIT): The minimum temperature required to initiate or cause self-sustained combustion of a solid, liquid, or gas independently of the heating or heated element. (See NFPA 497-2008 [B47].)¹⁰

authority having jurisdiction (AHJ): An organization, office, or individual responsible for enforcing the requirements of a code or standard, or for approving equipment, materials, an installation, or a procedure. (See NFPA 70, National Electrical Code.)

basic impulse insulation level (BIL): A reference impulse insulation strength expressed in terms of the crest value of withstand voltage of standard full impulse voltage wave.

bypass contactor: A contactor that is connected in parallel with the drive system or reduced-voltage starter so as to effectively take the drive system or reduced-voltage equipment out of the circuit, allowing the machine to run (after starting) in across-the-line mode.

NOTE—Bypass contactors are often used with drive systems. There are two reasons for bypass. The most common is for maintenance purposes. If the drive is out for maintenance, the bypass contactor is closed to allow the motor to run across-the-line (ATL). The second reason is to allow the drive to bring one motor to full speed, then bypass the drive after coming to full speed and switch to another motor. This allows the user to have one drive for many motors. Adjustable speed drive (ASD) applications also require an isolation contactor on ASD output to prevent the ASD from being in parallel with the bypass contactor.¹¹

⁸IEEE Standards Dictionary Online subscription is available at: http://www.ieee.org/portal/innovate/products/standard/standards_dictionary.html.

⁹Information on references can be found in Clause 2.

¹⁰The numbers in brackets correspond to those of the bibliography in Annex A.

¹¹Notes to text, tables, and figures are for information only and do not contain requirements needed to implement the standard.

Class B rise: Based on a maximum 40 °C ambient, a motor stator temperature rise at 1.0 service factor of 80 °C (measured by resistance) or 80 °C, 85 °C, or 90 °C (measured by embedded detectors) in accordance with NEMA MG-1 depending on the motor size, motor type, enclosure type, and voltage rating. The rise at 1.0 service factor corresponds to Class B type of insulation system in the NEMA MG-1 temperature rise tables.

clear space (CS): Clear space time margin between time current characteristic curves; and if applicable, the upstream fuse minimum melting curve is adjusted for preload.

closed-transition transfer (parallel transfer): A motor bus transfer (MBT) designed to close the new source breaker before tripping the old source breaker with the result that both source breakers are closed briefly at the same time during the transfer process.

common-mode voltage (CMV): In the context of adjustable speed drives (ASDs), common-mode voltage is the displacement of the neutral point (and each phase voltage) of the ASD output from ground due to the switching of the solid-state devices in the drive. It is an alternating voltage whose magnitude and frequency components are dependent on the drive topology.

NOTE—All present drive topologies create CMV to some extent. CMV can also be created at the motor if phase circuit conductors, unsymmetrical with respect to the equipment grounding conductor(s) or grounded sheaths or raceways, are used between the ASD output and the motor.

continuous duty: Operation at a substantially constant load for an indefinitely long time. This is also known as continuous rating in NEMA MG-1.

corona: A type of localized discharge resulting from transient gaseous ionization on an insulation system when the voltage stress exceeds a critical value. The ionization is usually localized over a portion of the distance between the electrodes of the system. (Corona activity can result in surface discharges and surface tracking on motor windings.) Corona is visible partial discharges in gases adjacent to a conductor. (See IEEE Std 1434™ [B29].)

current-limiting (CL) fuse: A fuse that limits the peak-let-through current to less than the prospective current. CL fuses are used on low-voltage and medium-voltage motors as primary fault protection device and on some small motors as fault and overload protection devices.

explosionproof equipment: Equipment enclosed in a case that is capable of withstanding an explosion of a specified gas or vapor that may occur within it and of preventing the ignition of a specified gas or vapor surrounding the enclosure by sparks, flashes, or explosion of the gas or vapor within, and that operates at such an external temperature that a surrounding flammable atmosphere will not be ignited thereby. (See NFPA 70, National Electrical Code.)

exposed surface: A surface that is internal to an enclosure or an external surface of an enclosure which could be exposed to the surrounding flammable atmosphere, without the benefit of an enclosure that would contain an explosion or exclude the hazardous gas. (An exposed internal surface may be the rotor, stator, or space heater surfaces of open and totally enclosed fan-cooled [TEFC] motors. An exposed external surface is the exterior surface, which could be exposed to the surrounding flammable atmosphere such as the exterior surface of explosionproof, pressurized, or force ventilated enclosures.)

fast transfer—supervised: An open-transition method wherein the close is supervised to check that the voltage phase angle difference between the motor bus voltage and the new source voltage is within a predetermined acceptable limit.

fast transfer—unsupervised: An open-transition method wherein the close is implemented without a sync-check device or implemented with sync-check relays with performance and response time which may be inadequate.

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

NOTE—It is rare, but there are times when the field winding is stationary. This occurs mostly with brushless exciters.

high-inertia load: A load that has a moment of inertia that exceeds normal values, as described in NEMA MG-1, and for which the motor needs to be designed to have both thermal and mechanical capability to accelerate the load to operating speed without exceeding its limits. (See NEMA MG-1-2011 Table 12 through Table 7, 20–1, and 21–6.)

harmonic: A sinusoidal component of a periodic wave or quantity having any frequency within the spectra. There are three basic classes of harmonics: frequencies with an integer multiple of the fundamental frequency, frequencies with a non-integer multiple of the fundamental frequency (inter-harmonics), and frequencies that are below the fundamental frequency (sub-harmonics).

identified (as applied to equipment): Recognizable as suitable for the specific purpose, function, use, environment, application, and so forth, where described in a particular *Code* requirement. (See NFPA 70, National Electrical Code.)

IC Code: The IC Code designates the method of electrical machine cooling as described in NEMA MG-1, Part 6.

IP Code: The IP Code designates the degree of protection provided by the enclosure of a rotating machine as described in NEMA MG-1, Part 5.

in-phase transfer: An open-transition method wherein the close command to the new breaker occurs at a phase angle in advance of phase coincidence between the motor bus and the new source to compensate for the new breaker's closing time.

listed: Equipment, materials, or services included in a list published by an organization that is acceptable to the authority having jurisdiction and concerned with evaluation of products or services, that maintains periodic inspection of production of listed equipment or materials or periodic evaluation of services, and whose listing states that either the equipment, material, or service meets appropriate designated standards or has been tested and found suitable for a specified purpose. (See NFPA 70®, National Electrical Code.)

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

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

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

motor bus: An auxiliary system bus that primarily supplies power to motor loads.

motor bus transfer (MBT): The process of transferring motor bus loads from one power source to another source.

multisection motor: A motor whose construction utilizes a component block approach in the assembly of the enclosure, that is, the enclosure has a number of bolted joints which could connect together the stator frame, the ventilation hood, the motor base, the bearing supports, and enclosure covers.

NEMA Frame: This refers to the NEMA MG-1 system of a standardized frame designation for AC machines including 449 frame size and smaller. NEMA MG-1-2011, Part 4 provides critical mounting dimensions for each frame size.

normal operating condition: As applied to motors, a normal operating condition is operating at rated full load steady state conditions. (See NFPA 70, National Electrical Code, Section 500.8(B)(5).) Locked rotor, starting, single-phasing, and operating above base nameplate kilowatt or horsepower are not normal operating conditions.

open-transition transfer: A motor bus transfer (MBT) designed to trip the old source breaker before closing the new source breaker so that the two source breakers are open at the same time during the transfer process.

overload: Loading in excess of normal rating of equipment. For a motor, it is considered overloaded when operated above its base nameplate kilowatt or horsepower.

partial discharge: A localized electric discharge resulting from ionization in an insulation system when the voltage stress exceeds the critical value. This discharge partially bridges the insulation in the voids internal to the motor winding insulation.

residual voltage transfer: An open-transition method wherein the voltage magnitude at the motor bus falls below a predetermined level before the close command is issued to the new breaker. There is no supervision of the synchronous condition between the motor bus and the new source.

rotor: The rotating member of a machine.

NOTE—Most rotors have a current-carrying winding arranged in a fashion to generate a magnetic field. The current in the rotor winding may be induced from the stator or externally supplied, and may be either ac or dc. Certain rotors generate the magnetic field using permanently-magnetized regions; these typically do not have windings and thus do not carry current.

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

sequential transfer: An open-transition method wherein closing of the new source breaker is supervised by an auxiliary contact of the old source breaker. Sequential transfer can be applied with the fast, in-phase, and residual methods of transfer to prevent closing the new source breaker should the old source breaker not open.

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

simultaneous transfer: An open-transition method wherein there is no verification that the bus has been disconnected from the old source prior to closing the new source breaker. Simultaneous transfer can be applied with the fast, in-phase, and residual methods of transfer to prevent damage to equipment.

slow transfer: An open-transition method wherein a time interval, usually in excess of 20 cycles, occurs before the load is powered from another source. There is no supervision of the synchronous condition between the motor bus and the new source, or of the voltage magnitude of the motor bus.

spark: A sudden and irreversible transition from a stable corona discharge to a stable arc discharge. It is a luminous electrical discharge of short duration between two electrodes in an insulating medium. It is generally brighter and carries more current than corona, and its color is mainly determined by the type of insulating medium. It generates radio noise of wider frequency spectrum (extending into hundreds of megahertz) and wider magnitude range than corona. A spark is not classified as corona. Sparking can also include static discharge, sparking due to mechanical contact, and capacitive discharges (i.e., across bearing oil film and separating switch contacts).

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

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

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

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

synchronous bus transfer or reclose: An open-transition motor bus transfer or reclose employing the fast transfer-supervised or in-phase transfer methods wherein the breaker close is supervised by taking into account the rapid movement and acceleration of phase angle between the decaying motor bus voltage and frequency and the new source voltage and frequency to determine that the breaker contacts are closed at or near zero phase coincidence.

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

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

trip circuit monitor (TCM): A device/function that monitors an associated circuit breaker's trip circuit for continuity and for the presence of tripping voltage, and sets an externally readable alarm when continuity or tripping voltage is lost (a surrogate for the traditional red light on relay and control panels).

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

zone of protection: Zones of protection are logical divisions of the power system used to isolated faulted sections, i.e., generators, transformers, buses, transmission lines, distribution lines or cable circuits, and motors. Zones are classified as primary and/or backup.

3.2 Acronyms and abbreviations

AFD	adjustable frequency drive (ASD is the IEEE-preferred term)
AHJ	authority having jurisdiction
AIT	autoignition temperature
ASD	adjustable speed drive
CEC	Canadian Electrical Code
CMV	common-mode voltage
CS	clear space (for time current characteristic curves)
CT	current transformer
DCS	distributed control system
DPFV	drip-proof forced ventilated
FLC	full load current
FLT	full load torque
GOOSE	generic object-oriented substation event

HDO	high-drop out
HFCT	high frequency current transformers
HRG	high resistance ground
HSCT	high sensitivity current transformer
HVCC	high-voltage coupling capacitor
IC	IC Code
I/O	input/output
IOC	instantaneous overcurrent
IP	IP Code
LCI	load commutated inverter
LFL	lower flammable limit
LRC	locked rotor current
LV	low-voltage
LVPCB	low-voltage power circuit breaker
MBT	motor bus transfer
MCC	motor control center
MCCB	molded-case circuit breaker
MESG	maximum experimental safe gap
MIC	minimum igniting current
MIE	minimum ignition energy
MOV	metal oxide varistor
MV	medium-voltage
NEC [®]	National Electrical Code ¹²
NRTL	nationally recognized testing laboratory
NTC	negative temperature coefficient resistors
ODE	opposite drive end
ODP	open drip-proof
OEM	original equipment manufacturer
OLPD	online partial discharge
PD	partial discharge
pu	per unit
PTC	positive temperature coefficient resistors
PWM	pulse-width modulation
RP	recommended practice
RPM	revolutions per minute

¹²National Electrical Code, NEC, and NFPA 70 are registered trademarks of the National Fire Protection Association.

RTD	resistance temperature detector
SCR	silicon controlled rectifier
SF	service factor
SSC	stator slot couplers
T Code	Temperature Code or Identification Number per 2014 NEC Table 500.8(C)
TCM	Trip circuit monitor, alarm
TEAAC	totally enclosed air-to-air cooled
TEFC	totally enclosed fan-cooled
TEFV	totally enclosed force ventilated
TENV	totally enclosed nonventilated
TEPV	totally enclosed pipe-ventilated
TEWAC	totally enclosed water-to-air cooled
TFE	tetrafluoroethylene
TOC	time overcurrent
UFL	upper flammable limit
UPS	uninterruptible power supply
VFD	variable frequency drive (adjustable speed drive [ASD] is the IEEE-preferred term)
VSD	variable speed drive (adjustable speed drive [ASD] is the IEEE-preferred term)
VT	voltage transformer
WPI	weather protected type I
WPPI	weather protected type II

4. General discussion

4.1 Introduction

This recommended practice applies specifically to ac single-phase and three-phase motors and dc motors. Many factors should be considered in choosing motor protection: motor importance, load importance and characteristics, motor rating (from one to several thousand horsepower), thermal limit of rotor or stator, environment, power system source and system grounding method, type of motor controller, etc. Protection for each specific motor installation should meet the requirements of the application. Power quality of the plant distribution system should be given appropriate attention, especially with regard to voltage sags and surges, harmonics, service interruptions, and operation of distribution line reclosers.

Items in [Clause 5](#) and [Clause 6](#) should be considered as checklists when deciding upon protection for a given motor installation. After the types of protection have been selected, manufacturers' bulletins should be studied to improve proper application of the specific protection chosen.

The selection of the motor protection schemes, starting method, etc. depend on the overall power system. The information contained in the IEEE Color Book® series and the new replacement IEEE 3000® series documents provide valuable information for the overall system design and protection. Refer to IEEE Std 3001.5™, IEEE Std 3001.8™, IEEE P3001.11 D8, IEEE Std 3003.2™, IEEE Std 3004.1™, IEEE Std 3004.5™, IEEE Std 3006.5™, IEEE Std 3006.7™, IEEE Std 3006.9™, IEEE Std 3007.1™, IEEE Std 3007.2™, and IEEE Std 3007.3™.

4.2 Low-voltage systems

Low-voltage (LV) systems are nominally 1000 V or less. NEMA MG-1-2011 lists the standard motor nameplate ratings along with the preferred size limits for several standard motor voltages. At present, a maximum of 575 V and 750 kW (1000 hp) exists for motor nameplate ratings. [Table 1](#) below shows typical LV motor ratings for various 60 Hz system voltages.

NOTE—The nominal system voltage is generally rated higher to allow for voltage drop between the source and the terminal of the motor.

Table 1—Nameplate voltage ratings of standard LV induction motors

Nominal system voltage	Typical motor nameplate voltage
Single-phase system 120 V 240 V	Single-phase motor 115 V 230 V
Three-phase system 208 V 240 V 480 V 600 V	Three-phase motor 200 V 230 V 460 V 575 V

4.3 Medium-voltage systems

Medium-voltage (MV) systems range above 1000 V and up to 69 kV. Industrial and commercial power systems typically operate with distribution voltages of 2.4 kV, 4.16 kV, 6.9 kV, and 13.8 kV and above. The selection of the motor voltages is described in Clause 3.4 of IEEE Std 141™-1993 (*IEEE Red Book™*). [Table 2](#) below shows typical MV motor ratings for various 60 Hz system voltages.

Table 2—Nameplate voltage ratings of standard MV induction motors

Nominal system voltage	Typical motor nameplate voltage
Three-phase system 2400 V 4160 V 6900 V 13.8 kV	Three-phase motor 2300 V 4000 V 6600 V 13.2 kV

5. Factors to consider in protection of motors

5.1 Motor characteristics

Motor characteristics include type (i.e., induction or synchronous), speed, voltage, power rating (kW or hp), service factor, NEMA design (i.e., A, B, C, or D, which are the torque and speed characteristics for LV and MV motors as described in NEMA MG 1-2011), application, power factor rating, type of motor enclosure, bearing lubrication types, arrangement of windings and their temperature limits, thermal capabilities of rotor and stator during starting, running, and stall conditions. See [Table 3](#).

Table 3—Typical characteristics and applications of fixed frequency medium ac squirrel-cage induction motors (NEMA MG 10-2013 [B44])

Polyphase characteristics	Locked rotor torque (% rated load torque)	Pull-up torque (% rated load torque)	Breakdown torque (% rated load torque)	Locked rotor current (% rated load current)	Slip	Typical applications	Relative efficiency
Design A Normal locked rotor torque and high locked rotor current	70 to 275 ^a	65 to 190 ^a	175 to 300	Not defined	0.5% to 5%	Fans, blowers, centrifugal pumps and compressors, motor to generator sets, etc., where starting torque requirements are relatively low	Medium or high
Design B Normal locked rotor torque and normal locked rotor current	70 to 275 ^a	65 to 190 ^a	175 to 300 ^a	600 to 800	0.5% to 5%	Fans, blowers, centrifugal pumps and compressors, motor-generator sets, etc., where starting torque requirements are relatively low	Medium or high
Design C High locked rotor torque and normal locked rotor current	200 to 285 ^a	140 to 195 ^a	190 to 225 ^a	600 to 800	1% to 5%	Conveyors, crushers, stirring machines, agitators, reciprocating pumps and compressors, etc., where starting under load is required	Medium
Design D High locked rotor torque and high slip	275	Not defined	275	600 to 800	≥ 5%	High peak loads with or without flywheels such as punch presses, shears, elevators, extractors, winches, hoists, oil-well pumping, and wire-drawing machines	Medium

Table continues

Table 3—Typical characteristics and applications of fixed frequency medium ac squirrel-cage induction motors (NEMA MG 10-2013 [B44]) (continued)

Polyphase characteristics	Locked rotor torque (% rated load torque)	Pull-up torque (% rated load torque)	Breakdown torque (% rated load torque)	Locked rotor current (% rated load current)	Slip	Typical applications	Relative efficiency
IEC Design H High locked rotor torque and high locked rotor current	200 to 285 ^a	140 to 195 ^a	190 to 225 ^a	800 to 1000	1% to 5%	Conveyors, crushers, stirring machines, agitators, reciprocating pumps and compressors, etc., where starting under load is required	Medium
IEC Design N Normal locked rotor torque and high locked rotor current	75 to 190 ^a	60 to 140 ^a	160 to 200 ^a	800 to 1000	0.5% to 3%	Fans, blowers, centrifugal pumps and compressors, motor-generator sets, etc., where starting torque requirements are relatively low	Medium or high
NOTE—These typical characteristics represent common usage of the motors—for further details consult the specific performance standards for the complete requirements.							

^aHigher values are for motors having lower horsepower ratings.

Reprinted by permission of the National Electrical Manufacturers Association from NEMA MG10–2013, Table 1.

5.2 Motor-starting conditions

5.2.1 General

Motor-starting conditions include across-the-line (full voltage non-reversing or reversing) or reduced voltage, adjustable speed drive (ASD), voltage drop and degree of inrush current during starting, repetitive starts, and frequency and total number of starts. For the number and frequency of starts refer to NEMA MG-1-2011, Section 12.54 and NEMA MG-10-2013, Table 7 [B44]. See Figure 1 and Padden and Pillai [B48].

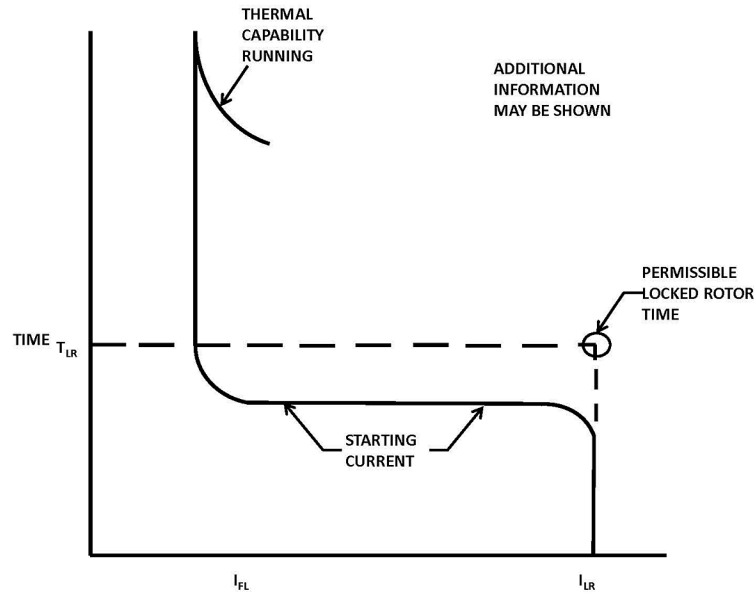


Figure 1—Typical motor-starting and capability curves (specific motor terminal voltage and for cold start)

Protection methods and settings are also affected by the starting methods. A comparison of electro-mechanical reduced-voltage starters is given in Table 4, similar to Table 10–17 in IEEE Std 141-1993 (*IEEE Red Book*TM). Various starting methods are discussed in 5.2.2 through 5.2.8. In Clause 9 of IEEE Std 399TM, motor starting studies are described in more detail. If for example in Table 4, normal inrush is 6 times full load current and an 80% tap autotransformer start is applied, the actual inrush multiplier used for determining the appropriate motor representation in the calculations is $(6 \times 0.67) \times \text{full load current} = (4.02) \times \text{full load current}$. Resistor or reactor starting limits the line starting current by the same amount as motor terminal voltage is reduced (that is, 65% of applied bus voltage gives 65% of normal line starting current). Wye (Y) -start, delta (Δ) -run starting delivers 33% of normal starting line current with full voltage at the motor terminals. The starting current at any other voltage is, correspondingly, reduced by the same amount. Part winding starting allows 60% of normal starting line current at full voltage and reduces inrush according to other voltages. As shown in Table 4, the starting torque is also affected by the starting method.

Table 4—Comparison of electro-mechanical reduced-voltage starters

	Autotransformer ^a			Primary resistor or reactor		Part winding ^b	Wye start-delta run
	50% Tap	65% Tap	80% Tap	65% Tap	80% Tap	2-step	
Starting current drawn from line as percentage of that which would be drawn upon full-voltage starting ^c	28%	45%	67%	65%	80%	60% ^c	33 $\frac{1}{3}$ %
Starting torque developed as percentage of that which would be developed on full-voltage starting	25%	42%	64%	42%	64%	50%	33 $\frac{1}{3}$ %
	Increases slightly with speed			Increases greatly with speed			
Smoothness of acceleration	Second in order of smoothness			Smoothest of reduced-voltage types in Table 4. As motor gains speed, current decreases. Voltage drop across resistor decreases and motor terminal voltage increases.		Fourth in order of smoothness	Third in order of smoothness
Starting current and torque adjustment	Adjustable within limits of various taps			Adjustable within limits of various taps			Fixed

^aClosed transition.

^bApproximate values only. Exact values can be obtained from motor manufacturer.

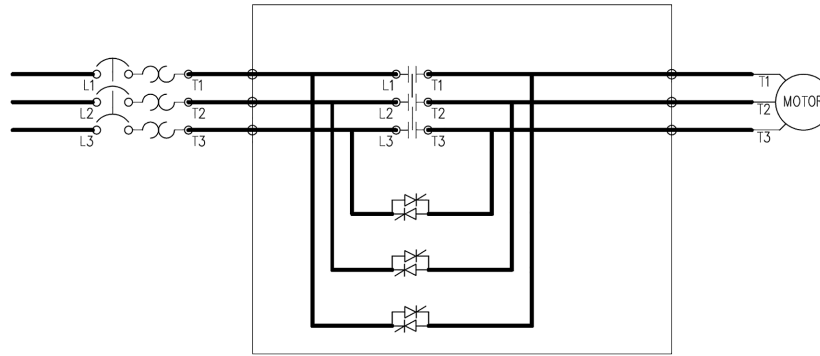
^cFull-voltage start usually draws between 500% and 600% of full load current.

5.2.2 Solid-state reduced-voltage motor start

As discussed in more detail in 10.6.3.6 of IEEE Std 141-1993 (*IEEE Red Book*TM), solid-state motor starters can control the starting cycle and provide reduced-voltage starting for standard ac squirrel-cage induction motors. They provide an adjustable, controlled acceleration and eliminate high power demands during starting. These starters are available in standard models for motors rated from fractional sizes to over 4500 kW (6000 hp). One type of reduced-voltage starter uses six thyristors in a full-wave configuration to vary the input voltage from zero to full on, so that the motor accelerates smoothly from zero to full running speed. The thyristors are activated by an electronic control section that has an initial step voltage adjustment. This adjustment, combined with a ramped voltage and current limit override, provides constant current (torque) to the motor until it reaches full speed. Figure 2 shows a typical solid-state reduced-voltage motor starter schematic with internal shorting device. Figure 3 shows a typical solid-state reduced-voltage motor starter schematic with external shorting device controlled by an “End of Start” relay. For short-circuit protection, refer to the manufacturer’s recommendations and literature, and also to NEC[®] Article 430 and Section 430.52(C)(5).

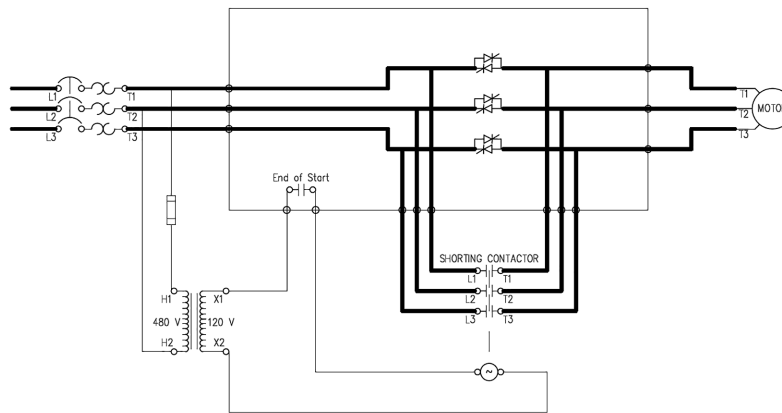
Variations in the design of starting circuit are as follows:

- The solid-state reduced-voltage motor starter maintains a constant level of kilovolt-amperes and reduces sudden torque surges to the motor. The current limiter, in conjunction with the acceleration ramp, holds the current constant at a preset level during the start-up period. When the start cycle is complete, the motor is running at almost full voltage with, essentially, a sine wave in each phase.
- Thyristors are used only during the starting phase. At full voltage, a shorting contactor closes and the circuit operates as a conventional electromechanical starter.
- A starter with linear-timed acceleration uses a closed-loop feedback system to maintain the motor acceleration at a constant rate. The required feedback signal is provided by a tachometer (ac, dc, or encoded) coupled to the motor.



Courtesy of Schneider Electric.

Figure 2—Typical solid-state reduced-voltage motor starter with internal shorting device, schematic



Courtesy of Schneider Electric.

Figure 3—Typical solid-state reduced-voltage motor starter with external shorting device controlled by “End of Start” relay, schematic

5.2.3 ASD start

ASDs can also be used as a soft-start with the added features of multiple starts per hour, adjustable acceleration and deceleration rates, and 100% or higher starting torque. Refer to 9.3.8 for a discussion on using ASDs to start and operate multiple motors.

An example of ASD starting is detailed in a PCIC paper presented by LeDoux, et al., “Starting Large Synchronous Motors in Weak Power Systems” [B35].

5.2.4 Autotransformer start

Subclause 10.6.3.3 of IEEE Std 141-1993 (*IEEE Red Book*TM) discusses autotransformer start in more detail. Autotransformers are used for limiting starting current and torque on polyphase induction motors to comply with power supply regulations or to avoid excessive shock to the driven machine, or to limit excessive voltage

drop. Overload and undervoltage protection are provided. These are equipped with mechanical interlock to assure proper starting sequence. Taps are provided on the autotransformer for adjusting starting torque and current. Since the autotransformer controller reduces the voltage by transformation, the starting torque of the motor will vary almost directly as does the line current, even though the motor current is reduced directly with the voltage impressed on the motor.

Autotransformer magnetic systems are the same as the manual systems described above, but suitable for remote control. They have a timing relay for adjustment of time at which full voltage is applied.

To overcome the objection of the open-circuit transition associated with an autotransformer starter, a circuit known as the Korndorfer connection is in common use. This type of starter requires a two-pole and a three-pole start contactor. The two-pole contactor opens first on the transition from start to run, opening the connections to the neutral of the autotransformer. The windings of the transformer are then momentarily used as series reactors during the transfer, allowing a closed-circuit transition. Although it is somewhat more complicated, this type of starter is frequently used on high-inertia centrifugal compressors to obtain the advantages of low line-current surges and closed-circuit transition.

5.2.5 Primary resistor or reactor start

As discussed in 10.6.3.3 of IEEE Std 141-1993 (*IEEE Red Book*TM), automatic reduced-voltage starter designed for geared or belted drive where sudden application of full-voltage torque must be avoided. Inrush current is limited by the value of the resistor or reactor; starting torque is a function of the square of the applied voltage. Therefore, if the initial voltage is reduced to 50%, the starting torque of the motor will be 25% of its full-voltage starting torque. A compromise must be made between the required starting torque and the inrush current allowed on the system. It provides both overload and undervoltage protection and is suitable for remote control. The resistor or reactor is shorted out as speed approaches rated rpm.

5.2.6 Part-winding start

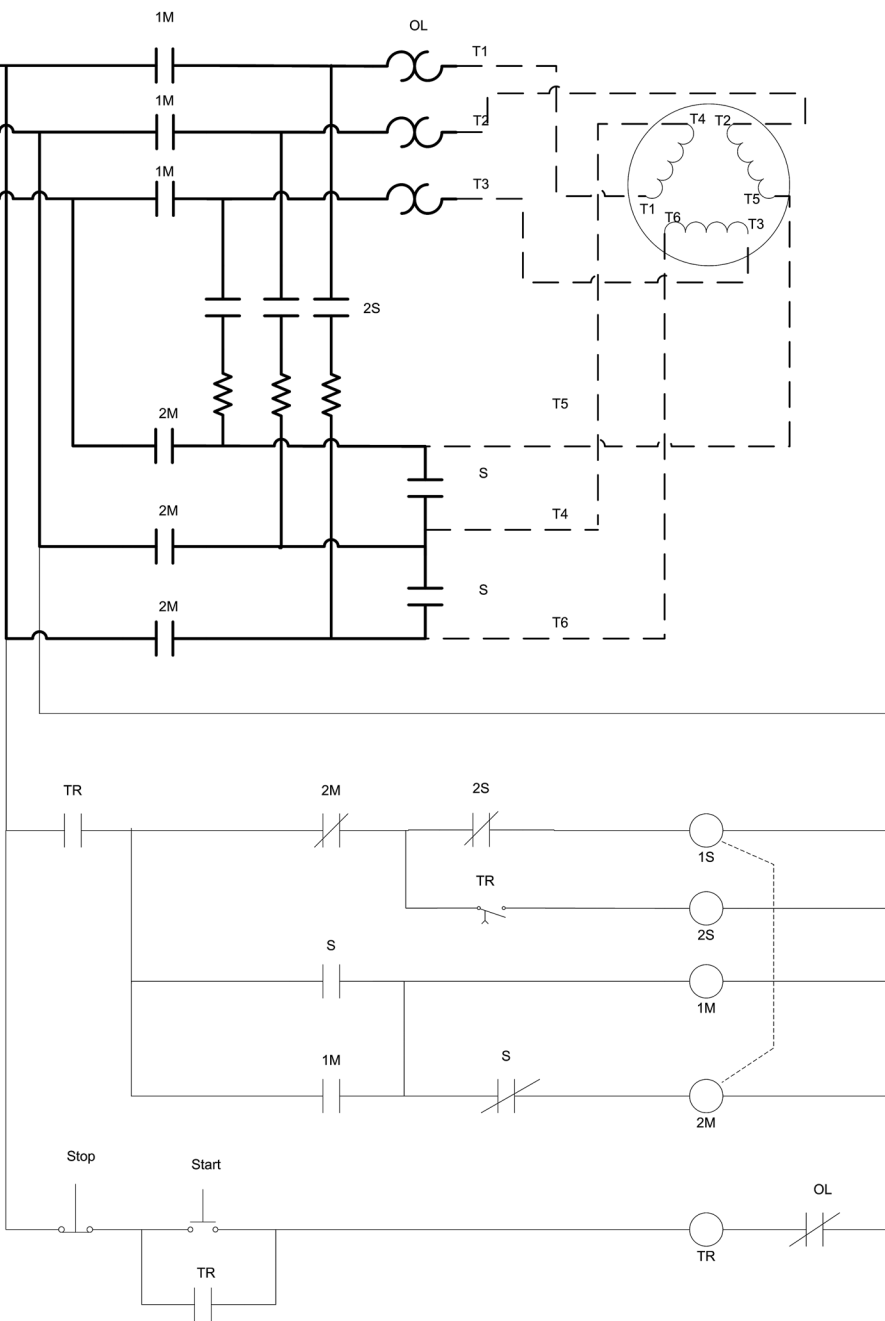
As discussed in more detail in 10.6.3.3 of IEEE Std 141-1993 (*IEEE Red Book*TM), part-winding starters are used on light or low-inertia loads where the power system requires limitations on the increments of current inrush. The torque characteristics are discussed in more detail in section 14.38 of NEMA MG-1-2011. It consists of two magnetic starters, each selected for one of the two motor windings, and a time-delay relay controlling the time at which the second winding is energized. It provides overload and undervoltage protection and is suitable for remote control.

5.2.7 Wye-delta start

Subclause 10.6.3.3 of IEEE Std 141-1993 (*IEEE Red Book*TM) discusses wye-delta, also known as star-delta, in more detail. This type starter is most applicable to starting motors that drive high-inertia loads with resulting long acceleration times, such as a centrifuge that takes 45 minutes to an hour to accelerate to full speed, while other loads accelerate in seconds. When the motor has accelerated on the wye (or star) connection, it is automatically reconnected by contactors for normal delta operation. This type of starter requires six motor leads.

In selecting the type of reduced-voltage starter, consideration should be given to the motor control transition from starting to running. In a closed-circuit transition, power to the motor is not interrupted during the starting sequence as shown in [Figure 5](#), whereas an open-circuit transition power to the motor is interrupted as shown in [Figure 4](#). Closed-circuit transition, such as [Figure 5](#), is recommended for all wye-delta starter applications to reduce inrush voltage disturbances and torque pulses.

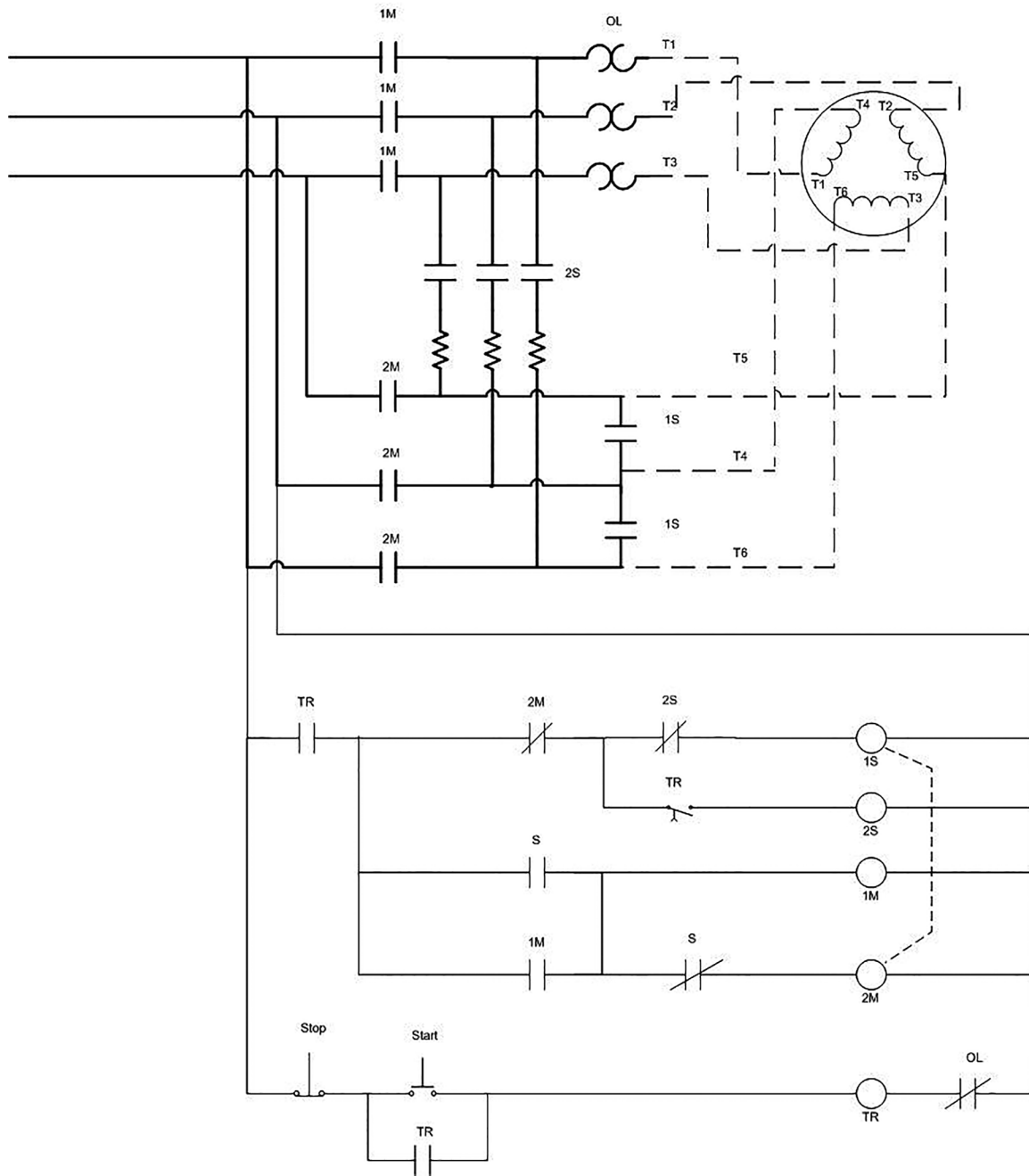
Wye-Delta Type Reduced Voltage Controllers. Closed Transition.



Courtesy of Schneider Electric.

Figure 4—Wye-delta reduced-voltage starter, open transition

Wye-Delta Type Reduced Voltage Controllers. Closed Transition.



Courtesy of Schneider Electric.

Figure 5—Wye-delta reduced-voltage starter, closed transition

5.2.8 Multi-speed motor start

Subclause 10.6.3.5 of IEEE Std 141-1993 (*IEEE Red Book*TM) discusses this in more detail. Multi-speed motor controllers are designed for the automatic control of two-, three-, or four-speed squirrel-cage motors of

either the consequent-pole or separate-winding types. They are available for constant-horsepower, constant torque, or variable torque three-phase motors used on fans, blowers, refrigeration compressors, and similar machinery.

CAUTION

Caution should be taken when the motor is slowing down to not energize the slow speed winding while the motor is rotating above synchronous speed because it can cause high torque, voltage spikes, and current spikes.

5.3 Ambient conditions

Ambient conditions include maximum and minimum temperatures, altitude, adjacent heat sources, and ventilation arrangement. NEMA designed motor temperature rises are based upon a reference ambient temperature of 40 °C and a maximum altitude of 1000 m.

5.4 Driven equipment

Load characteristics are important in the selection and protection of the motor; otherwise, the driven equipment may lead to a locked rotor condition, failure to reach normal speed (stalling), excessive heating during acceleration, or overloading. See [Figure 6](#), which illustrates the relationship between the accelerating current of a motor versus the thermal damage limits of the motor during accelerating and running conditions. Present practice is to add a solid-state reduced-voltage starter or an ASD for motors that may have accelerating problems or to add an ASD for motors that could be operated at a reduced speed for some period of the duty cycle. The protection of motors driven by ASDs is discussed in [Clause 9](#). For a detailed study of reduced-voltage starting, refer to the subclauses of [5.2](#), Chapter 7 of IEEE Std 241™-1990, and IEEE P3001.11/D8.

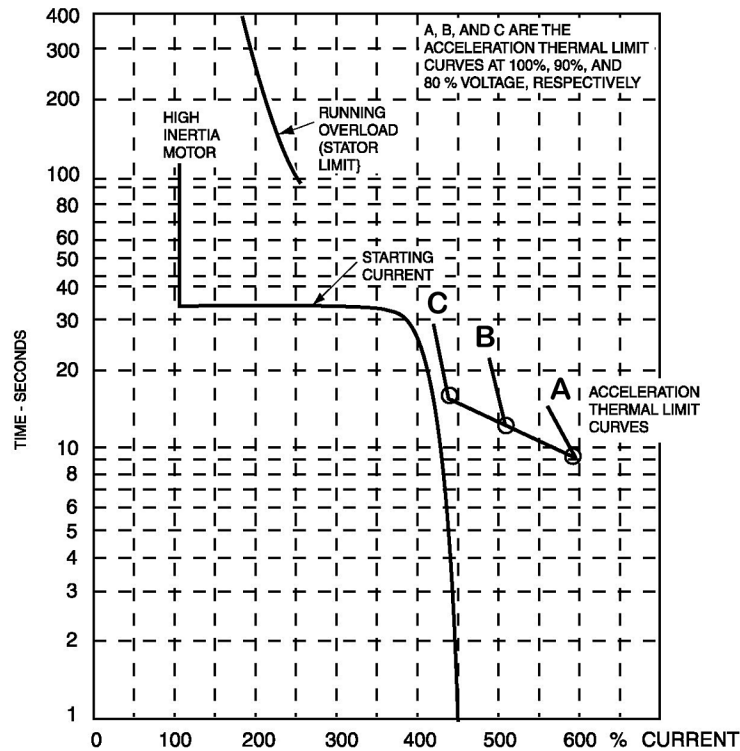


Figure 6—Typical time-current and thermal limit characteristic curves

5.5 Power system quality

Power system quality issues include types of system grounding, exposure to lightning and switching surges, capacitors and their controls for power-factor correction, fault capacity, exposure to automatic reclosing or transfer, possibilities of single-phase supply (e.g., broken conductor, open disconnect switch or circuit breaker pole, opened fuse), and other loads that can cause voltage unbalance. Another factor is harmonics, which may cause motor overheating and affect the performance of electronic protective devices; see IEEE Std 519™.

5.6 Motor importance

Factors that determine motor importance include motor cost, forced outage costs, amount of maintenance and operating supervision to be provided, and ease and cost of repair or replacement. For example, in processing facilities, large unsparred pumps and compressors are typically of high importance because loss of the motor normally means the process unit can no longer operate; and due to their size, these motors take a long time to repair or replace. A motor that is important to a plant's operating continuity or process safety should include a pre-trip alarm for operator intervention as a first step. An example would be to initiate an alarm when the stator winding temperature has risen to a point above full load temperature rise and the rated temperature rise of the winding insulation. This alarm could mean the motor is being overloaded or there has been a failure of the cooling system such as dirty filters or loss of cooling water.

5.7 Load side faults for motor controllers

Although most of 5.7 concerns low-voltage applications, the principles apply to MV applications of motor controllers as well. Calculation of available fault current in a circuit is described in Chapter 2 of IEEE Std 242™-2001 (*IEEE Buff Book*™), and IEEE Std 399 (*IEEE Brown Book*™) [B27]. Fuse and circuit breaker pro-

tection for conductors in feeder and branch circuits are described in Chapter 5, Chapter 6, and Chapter 7 of IEEE Std 242-2001 (*IEEE Buff Book*TM).

NOTE—Fuses and circuit breakers are rated for connection to available fault current sources on the basis of protecting the conductors on the load side of the circuit breaker or fuse.

In a motor controller, the above philosophy does not necessarily extend to protect the motor controller or its compartment. For proper protection of the motor controller, the fuse or circuit breaker (or motor circuit protector) that the controller manufacturer has had tested by a nationally recognized testing laboratory (NRTL) for the rated fault current available at its line terminals should be used. A motor circuit protector has an instantaneous only trip element, similar in construction to a molded-case circuit breaker (MCCB), and is described in 7.1.4 of IEEE Std 242-2001 (*IEEE Buff Book*TM), IEEE Std 1015TM-2006 (*IEEE Blue Book*TM), and IEEE Std 3004.5.

Such motor controllers for best results should bear an NRTL listing for connection to available currents higher than the currents found in the power supply of the plant system under consideration or projected plant expansion fault duty. The NRTL-listed controller may still be substantially damaged by a load side fault downstream of the controller. If protection is necessary to reduce damage to the controller itself, the controller manufacturer should be consulted, or Type 2 protection should be specified in accordance with IEC 60947-4-1-2012 [B22]. Type 1 protection will reduce major damage but replacement of some motor control center components may be necessary after a fault occurs.

Controllers should be protected with fuses or circuit breakers where the combination controllers are rated for the available fault current. This subject is covered more thoroughly under protection of low-voltage motors in 7.1 of IEEE Std 242-2001 (*IEEE Buff Book*TM), IEEE Std 1015-2006 (*IEEE Blue Book*TM), and IEEE Std 3004.5.

5.8 Ground faults

The magnitude of ground fault currents depends on the type of system grounding employed. Assuming no other ground exists on the power system, the level of damage experienced in a motor from an internal ground fault increases as the system grounding utilized goes from a high resistance grounded system to a low resistance grounded system to a solidly grounded system. Low values of internal ground fault currents on high resistance or low resistance grounded systems will normally create damage to the windings, but not the core material of the machine as long as they are removed within normal clearing times. However, on solidly grounded systems, the high ground fault currents can quickly lead to severe damage to the windings and escalate to stator iron damage and even possibly damage to the rotor as well. Detection of these high level ground faults should lead to very fast clearing times of the ground fault. The cost and time to repair a machine increases as the level of the ground fault current increases and the time to clear the fault increases. As the level of damage increases, the potential for having to replace the machine increases as well because there comes a point where repair of the machine no longer makes economic sense as long as a replacement can be found. This subject is treated in more depth in Chapter 8 of IEEE Std 242-2001 (*IEEE Buff Book*TM).

5.9 Maintenance capability and schedule

5.9.1 Introduction

Maintenance capability and schedule are important factors. Selection of complex protection that cannot or will not be appropriately maintained can lead to inadequate protection. Likewise, the selection and setting of overload protection does not prevent inadvertent setting changes due to normal vibration or ambient conditions, such as low-voltage controllers with non-ambient compensated bi-metallic overloads. Backup protection should be coordinated to operate if primary protection fails to operate. Maintenance is covered in Chapter 16 of IEEE Std 242-2001 (*IEEE Buff Book*TM), IEEE 3007 series of standards particularly IEEE Std 3007.2, NFPA 70B [B45], and the manufacturer's recommendations. Refer to IEEE Std 1068TM-2015 [B28] for repair

and rewinding of motors and ANSI/EASA AR100–2015 [B2] for repair of rotating electrical apparatus. Protective device settings should be verified prior to returning a motor to service that has been repaired.

Motors are rotating machinery and proper condition monitoring should be performed for reliable operation especially for critical motors.

5.9.2 Condition monitoring, online (trending)

Typical condition monitoring that can be done online is as follows:

- Vibration analysis (see 8.5.5)
- On-line partial discharge (OLPD) (see 8.5.4.6 and C.1) [B10], [B52], [B53], [B56], [B60], [B61], [B65], and [B66]
- Monitoring motor insulation online (see C.2)

5.9.3 Condition monitoring, periodic (trending)

Typical condition monitoring that can be done periodically off-line is as follows:

- Winding insulation resistance test, e.g., IEEE Std 112™ and IEEE Std 115™
- Polarization index, e.g., IEEE Std 43™
- Partial discharge (PD), e.g., ASTM D 1868, British Standards Institution [B9], and Stranges, Dunn, and Stone [B61]
- Power factor/tip up test for MV motors, e.g., IEEE Std 286™ [B25]

5.10 Service factor

The service factor (SF) of a motor is a multiplier which, when applied to the rated horsepower, indicates a permissible horsepower loading that may be carried under the conditions specified for the service factor. A service factor of 1.0 is the same as the nameplate rating. Refer to sections 1, 1.42, and 14.37 of NEMA MG 1-2011 for standard conditions.

5.11 Application considerations

For motors applied in general applications, the authority having jurisdiction (AHJ) may have general requirements for motor protection, such as low-voltage motors (reference NEC Article 430 III, IV, and V), motors over 1000 V (reference NEC Article 430 XI), and motors applied on ASD systems (reference NEC Article 430 X).

For motors applied in certain applications, the local codes and standards may have specific protection requirements such as continuity of power or selective coordination. The following list is a sample of applications and is not all-inclusive: elevators, dumbwaiters, escalators, moving walks, platform lifts, and stairway chairlifts (reference NEC Article 620); emergency systems (reference NEC Article 700); legally required standby systems (reference NEC Article 701); and fire pumps (reference NEC Article 695).

5.12 Motor and conductor protection

While the focus of this document is motor protection, it should be acknowledged by the designers and protection engineers that the motor protection devices also protect the motor circuit conductors. The motor circuit conductor protection should be included in the time-current coordination plots. The conductor protection

should comply with applicable codes and standards for the AHJ. The conductor size should be selected to provide adequate voltage during starting and running and adequate ampacity during running (see NEC Article 430 II and XI). In addition, during short-circuit the conductor insulation should maintain its integrity and be protected. For example, consider selecting higher temperature-rated insulation system such as thermoset with a short-circuit current temperature rating of 250 °C versus thermoplastic with some conductors with a short-circuit current temperature rating of 150 °C (Padden and Pillai [B48]).

When using the conductor damage curves the designer should know 1) the type of insulation, 2) the maximum continuous temperature rating of the insulation, and 3) the maximum short-circuit current temperature rating of the insulation. Table 5 below provides some examples of conductor types and temperature ratings. For Table 5, also refer to 2014 NEC Section 310.104. Data should be gathered from the manufacturer for the specific conductor used. Conductor damage curve data are available from some coordination software programs as well, but the engineer should know the insulation properties.

Table 5—Examples of 600 V conductor insulation types and their maximum short-circuit temperature^a

Type of insulation NEC designation, trade name	Type letter	Continuous temperature rating (°C): Dry	Continuous temperature rating (°C): Wet	Short-circuit current temperature rating (°C)
Thermoset				
Cross-linked polyethylene Thermoset Moisture-resistant thermoset	RHH	90 dry	90 damp	250
	XHH	90 dry	90 damp	
	RHW	75 dry	75 wet	
	RHW-2	90 dry	90 wet	
	XHHW	90 dry	90 damp/75 wet	
	XHHW-2	90 dry	90 wet	
Cross-linked polyvinyl chloride Moisture-resistant thermoset	XHHW	90 dry	90 damp/75 wet	250
Chlorinated polyethylene Thermoset Moisture-resistant thermoset	RHH	90 dry	90 damp	250
	RHW-2	90 dry	90 wet	
Ethylene propylene rubber Thermoset Moisture-resistant thermoset	XHH	90 dry	90 damp	250
	RHH	90 dry	90 damp	
	XHHW-2	90 dry	90 wet	
	RHW-2	90 dry	90 wet	
Styrene butadiene rubber Moisture-resistant thermoset	RHW	75 dry	75 wet	200
Butyl rubber Thermoset Moisture-resistant thermoset	RHH	90 dry	90 damp	200
	RHW	75 dry	75 wet	
	RHW-2	90 dry	90 wet	
Silicone rubber Silicone	SA SA (special)	90 dry 200 dry	90 damp 200 damp	250
Thermoplastic				
Polyvinyl chloride Heat-resistant thermoplastic Moisture and heat-re- sistant thermoplastic	THHN	90 dry	90 damp	150
	THHW	90 dry	75 wet	
	THW	75 dry	75 wet	
	THW-2	90 dry	90 wet	
	THWN	75 dry	75 wet	
	THWN-2	90 dry	90 wet	

^aConsult the conductor manufacturer for specific conductor properties. Temperature ratings may also vary with the year of manufacture.

Courtesy of Padden Engineering, LLC.

The conductor damage curve is plotted on the coordination plot. The damage curve should be above and to the right of the motor overload and short-circuit protective device curves with clear space (CS) between the curves. Also refer to IEEE Std 242-2001 (*IEEE Buff Book*TM).

5.13 Fixed capacitor applications

Fixed power factor correction capacitor applications should consider the following:

- Dependent upon the capacitor location, motor overload set point should be adjusted. Refer to 7.2.2 and Figure 15 for examples.
- Fixed capacitor will extend motor open circuit time constant and will increase the minimum time for blocking the motor starting to allow for motor residual voltage to reach an acceptable level. Contact the motor manufacturer for the motor equivalent circuit data with and without the fixed capacitor. Refer to Annex E for sample equations and calculations.
- Many process plants tend to implement motor re-acceleration scheme. Therefore, motor capacitor application may not be recommended for re-acceleration motors in the process plants unless there will be sufficient time to decay motor residual voltages as shown in Annex E. This should be discussed with plant process engineers.

6. Types of protection

6.1 Purpose of motor protection

6.1.1 Introduction

In a power system, the basic premise is that the delivered power is of acceptable quality to satisfy the needs of the facility. However, an abnormal condition can exist because of plant or site conditions or the external power supply. Depending upon the plant size, location, and on-site generation, conditions such as voltage transients, surges and sags, overfrequency and underfrequency, harmonics, and discontinuity may develop that require corrective action. For large facilities, the incoming power is likely monitored, and methods have probably been taken to protect the facility from abnormal conditions. These methods are important, because this recommended practice focuses upon only motor protection. For smaller installations or unusual locations, plant or site protection may be more integrated with motor protection.

The motor protective devices permit the motor to start and run, and initiate tripping and removal of the motor circuit from the power system when the motor stalls, does not accelerate, draws excessive current, overheats, vibrates excessively, and/or shows other symptoms of improper motor conditions. Detection of improper conditions are through measurement of voltage, current, temperature, frequency, harmonics, vibration, and speed, where appropriate. However, for the majority of small motors (i.e., less than 220 kW [300 hp]), overcurrent is the most prevalent means of detection.

In the discussion of protective devices in this recommended practice, reference is made to device numbers, which are described in IEEE Std C37.2TM and Annex B herein. In general, MV protection uses device numbers (or function numbers) especially because most of those schemes are much more complex than LV schemes, in lieu of using repetitive descriptions.

6.1.2 Typical protection functions

Typically, selecting motor protection is based on the motor output rating (hp or kW) and the voltage level (low or medium voltage). Refer to Table 6 for typical motor protection functions for commercial and industrial applications and refer to Annex B for descriptions of the functions. In Figure 7 and Figure 8, the one-line and three-line diagrams respectively are provided for the typical fused E2 contactor controlled protection

functions for a MV induction motor application using a fused disconnect for short-circuit protection, a vacuum contactor for control, and a multifunction motor protection relay (Device 11M) for overload protection. The multifunction motor protection relay can open the contactor for various conditions except short-circuit protection which is provided by the fuses. The 51N residually connected ground fault protection or the 50G zero sequence current transformer (CT) ground fault protection can be used in a MV low resistance grounded power system where the ground fault current does not exceed the break rating for the vacuum contactor in this example. For high resistance grounded power systems, ground fault elements typically alarm; however, for each individual motor, most industrial owners choose to trip the end device (e.g., motor) that has a ground fault, even if they are maintaining the system during the fault.

Table 6—Typical motor protection functions¹

Description	Induction motors protection functions			Synchronous motors protection functions
	Minimum	Fused E2 contactor controlled	Critical service breaker controlled	Critical service breaker controlled
Distance relay				21 (or 51V)
Volts (U/O)	27	27	27/59	27/59
Directional power				32
Undercurrent			37	37
Bearing temperature protection		38	38	38
Vibration protection			39	39
Loss of field				40
Current balance		46	46	46
Negative sequence		47	47	47
Incomplete sequence				48
Thermal overload relay Overload operated by motor current (replica)	49	49	49	49
Stator winding thermal overload (also embedded detectors)	49S	49S	49S	49S
Breaker failure (breaker only)			50BF	50BF
IOC ground (zero sequence CT) (delayed on start) — Breaker trip or — Vacuum contactor within rating	50G	50G	50G	50G
TOC ground (residually connected) — Breaker trip or — Vacuum contactor within rating	51N	51N	51N	51N
IOC-locked rotor (delayed on start)		50LR	50LR	
TOC (V-voltage restrained)	51		51	51V (or 21)
Short-circuit	Fuse or Breaker, 50	Fuse	50	50
Current inhibit (blocks contactor opening) ²	50B	50B		
Excitation check relay				53
Power factor				55
Field application relay				56
Voltage balance (loss of phase)			60	60
Number of starts	66	66	66	66
Directional overcurrent				67

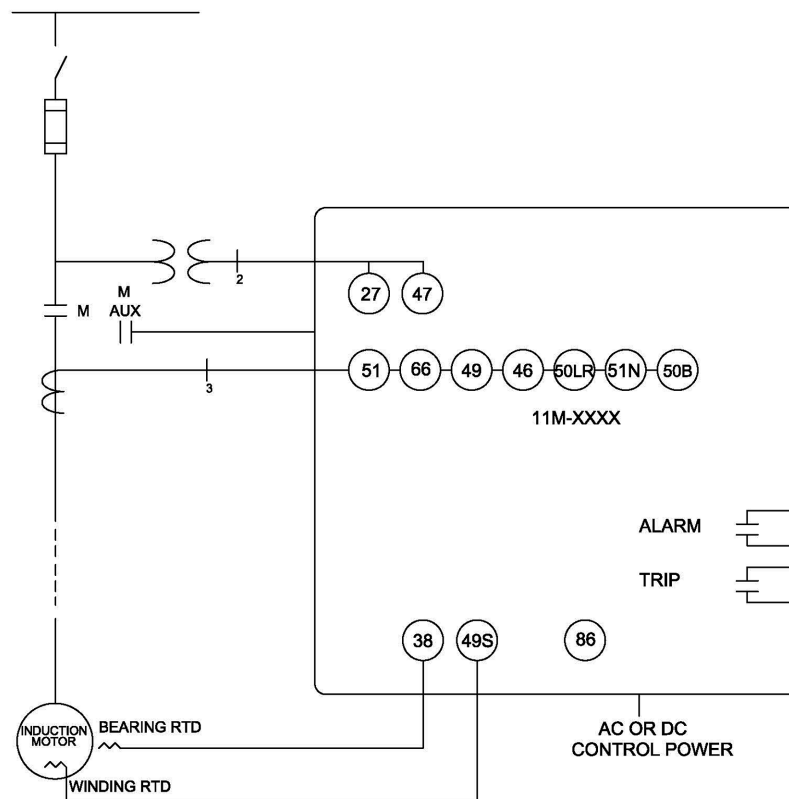
Table continues

Table 6—Typical motor protection functions¹ (continued)

Description	Induction motors protection functions			Synchronous motors protection functions
	Minimum	Fused E2 contactor controlled	Critical service breaker controlled	Critical service breaker controlled
Trip circuit monitor, alarm			TCM	TCM
Out-of-step				78
Frequency			81U/O	81R, 81U/O
Lockout		86	86	86
Motor differential			87M	87M

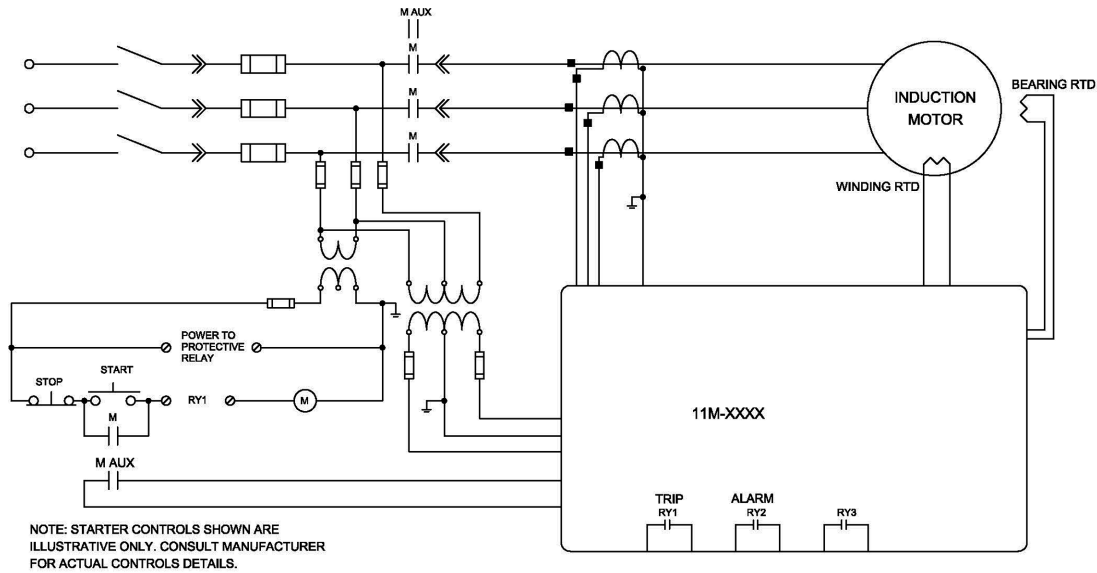
¹See also Table B.3, Security, communication, and other protection functions.

²*Current inhibit*: instantaneous phase overcurrent (50B) function blocks opening of the motor contactor when the fault current exceeds the interrupting rating of the contactor.



Courtesy of C&I Engineering.

Figure 7—MV induction motor 1-line diagram, typical minimum protection functions with fuses



Courtesy of C&I Engineering.

Figure 8—MV induction motor 3-line diagram, typical minimum protection functions with fuses

6.1.3 Protection relay testing

Protective relays should have provisions for testing and calibrating the relays using external power supplies without disconnecting the permanent wiring (e.g., test switches that are used for secondary injection testing and calibration). The AHJ, site experience, and manufacturer's recommendations provide information on the testing interval for electromechanical and solid-state relays.

For critical applications or for personnel considerations, each relay (e.g., 11M device) should have CT, voltage transformer (VT), and relay digital inputs and outputs wired to a relay test switch to allow for testing the relay with the motor circuit switching device in service. Testing provisions should include shorting of CT circuits and consideration for selectively disconnecting the relay from the trip circuits, as well as CTs, VTs, auxiliary power, and other circuits controlled by the relay. After a microprocessor type relay is commissioned and in service, some have self-diagnostics or self-testing to alarm if the relay malfunctions.

6.2 Abnormal power supply conditions

6.2.1 Introduction

Although overvoltage conditions have some consideration, that phenomenon draws less attention than undervoltage because of protection by surge arresters for momentary conditions and by relays for the less-common sustained overvoltage. Undervoltage conditions for LV and MV systems are discussed in this section. Further discussions concerning large motors can be found in 8.10.

6.2.2 Undervoltage (Device 27)

Undervoltage protection is used as follows:

- To prevent a motor from automatically restarting when voltage returns following an interruption, as might happen with single-service arrangements or automatic transfer operations. Consideration should also be given as to the importance of the motor and whether conditions warrant that the motor*

ride through voltage sags or drop out at some specific voltage, not to be energized until other conditions may have been met.

- b) *To avoid excessive inrush to the total motor load on the power system following a voltage sag or when voltage returns following an interruption.*
- c) *To avoid reaccelerating a motor before the field collapses.* Fast reclosing with the source voltage significantly out-of-phase with the motor bus voltage has been damaging and can occur if cooperation is lacking between the industrial plant and its power supplier. Consult the power supplier to learn their automatic reclosure timing and set the undervoltage relay timing accordingly. This delay is not a panacea, and some other forms of protection might be required, such as underfrequency relaying (Device 81).

For undervoltage use with bus transfer or reclosing, refer to 6.11.

6.2.3 Device 27, instantaneous or time delay

Undervoltage protection is either instantaneous (i.e., no intentional delay) or time-delay. Time-delay undervoltage protection should be used with motors important to continuity of service, providing it is satisfactory in all respects, to avoid unnecessary tripping on voltage sags that accompany external short-circuits. Examples follow of non-latching starters where time-delay undervoltage protection is not satisfactory and instantaneous undervoltage should be used:

NOTE—The limitations in item a) and item b) below could be overcome by using either a separate ac power source for control or battery control on the contactor to prevent its instantaneous dropout. In other words, the time-delay undervoltage feature can be applied directly to the main contactor. In addition, for synchronous machines, a voltage sag can result in a drop of field voltage when the field voltage is derived from the control power transformer for the magnetically held starter. This voltage drop can result in a reduction in field voltage to the point where there is a trip of the synchronous motor on field protection even before the contactor drops out. This situation can be avoided by deriving the field voltage from a reliable power supply not depended on steady control power transformer, such as from the output of a small uninterruptible power supply (UPS) included in the synchronous controller.

- a) *Fusible switch or circuit breaker combination motor starters having ac magnetically held contactors used on systems of low three-phase fault capacity.* With the time-delay undervoltage scheme (without “off” time-delay), the contactor could drop out because of the low voltage accompanying a fault on the load side of the contactor before the supply fuse or circuit breaker opens to remove the fault. Unless provided with blocking for automatic restart, the contactor could then reclose into the fault. This problem does not exist if the available fault capacity is high enough to open the external fuse or circuit breaker before the contactor interrupts the fault current.
- b) *Synchronous motors used with starters having ac magnetically held contactors.* With the time-delay undervoltage scheme (without “off” time-delay), the contactor could drop out on an externally caused system voltage sag, then reclose, and reapply the system voltage to an out-of-phase internal voltage in the motor. The high initial inrush could damage the motor winding, shaft, driven equipment, or foundation. For synchronous motors, an underfrequency relay might be required to avoid an out-of-step trip on reclose.
- c) *Induction motors used with starters having ac magnetically held contactors.* The high inrush problem described in b) could also occur for large, two-pole squirrel-cage induction motors. If significantly out-of-phase reclosing represents a risk to the motor, then undervoltage protection alone might not suffice and underfrequency relay might be required. Reclosing may not be a problem with the 150 kW (200 hp) and smaller induction motors with magnetically held contactor starters because the internal voltages of these motors decay quite rapidly.

- d) *Motors used on systems having fast automatic transfer or reclosing where the motor must be tripped to protect it before the transfer or reclosure takes place. See b) and c) above regarding needing under-frequency relays also.*
- e) *When the total motor load having time-delay undervoltage protection results in excessive inrush current and voltage drop after an interruption, a problem could arise of not having sufficient system capacity to restart the motors. Options include designing for a larger power capacity than needed for normal operations, removing some of the motor loads from automatic restarting, and grouping the auto-restarting motors into several smaller time-sequenced groups, each of which can successfully auto-restart as a group. Less-important motors should use instantaneous undervoltage protection. Time-delay undervoltage protection with varying time delays could be used on the motors with inrush that the system can handle. Sequencers are available for selecting the order of motor restarts, thus reducing the need for oversized transformers or lower transformer impedances. Caution should be observed when placing numerous controls within one device where common-mode failure could negate the benefits. A more thorough discussion can be found in 6.11.*

6.2.4 Device 27, with latching contactor or circuit breaker

Motor switching devices, such as latching contactors or circuit breakers, inherently remain closed during periods of low or zero ac voltage. The following methods are used to trip open the devices:

- a) Energize shunt trip coil from a battery.
- b) Energize shunt trip coil from a separate, reliable source of ac. This ac source should be electrically isolated from the motor ac source to enhance reliability.
- c) Energize shunt trip coil from a capacitor charged through a rectifier from the ac system. This method is commonly referred to as capacitor trip.
- d) De-energize a solenoid and allow an undervoltage release to trip the contactor or circuit breaker. Refer to 7.5.3.

Item a) through c) are usually used in conjunction with voltage-sensing relays (see 6.2.7). For item d), it could have the solenoid operating directly, either on the ac system voltage or from a battery, where a relay would sense loss of ac voltage and de-energize the solenoid. The solenoid could be either instantaneous or time-delay.

6.2.5 Device 27, with ac magnetically held main contactor

Because the ac magnetically held main contactor (which supplies the motor) drops out on a loss of ac power, it provides an instantaneous undervoltage function. If automatic restart is required because of the process, two common approaches achieve time-delay undervoltage protection:

- a) Permit the main contactor to drop out instantaneously, but provide a timing scheme (that starts timing when ac voltage is low or zero) to reclose the main contactor when normal ac voltage returns within some preset timing interval. Some of the timing schemes in use are as follows:
 - 1) Capacitor charged through a rectifier from the ac system. The charge keeps an instantaneous dropout auxiliary relay energized for an adjustable interval, which is commonly 2 s to 4 s.
 - 2) Standard timer that times when de-energized (e.g., pneumatic or inverse time-undervoltage relay).
- b) Use a two-wire control. This control uses a maintained closed start button or operates from an external contact responsive to some condition such as process pressure, temperature, or level. The main contactor drops out with loss of ac, and recloses when ac voltage returns.

Neither arrangement provides perfect undervoltage protection and should not be used if automatic restarting could endanger personnel or equipment. Refer to 6.11 and [Annex E](#).

6.2.6 Device 27, with separate control power for main contactor

Separate control power for the main contactor may be a dc magnetically held contactor sourced from a reliable battery system or ac power supplied from a separate source (i.e., UPS). With a separate control power source, the main motor contactor remains closed during low or zero ac voltage to the motor. Time-delay undervoltage protection is achieved using voltage-sensing relays (see [6.2.7](#)). For this scheme, the separate control voltage should be monitored as well.

6.2.7 Device 27, with voltage-sensing relays

A commonly used type of voltage-sensing relay is the single-phase inverse time-undervoltage relay. There are also definite time undervoltage relays. Because an opened control fuse could cause tripping, two or three such time-undervoltage relays are sometimes used, connected to different phases, and wired so that all Device 27 relays must operate before tripping occurs or re-energization can be permitted.

Three-phase undervoltage relays are available. Many operate in response to the area of the voltage triangle formed by the phasors of the three-phase voltages. Alternatively, a voltage-balance relay (Device 60) could be used for opened fuse protection.

Although many older starters with individual protection relays exist in older facilities, the voltage sensing relay functions today are normally included in multifunction motor protection relays (Device 11M). These multifunction relays can provide single-phase inverse time undervoltage functions as well as definite time protection. Some of these multifunction relays also offer logic that detects one, two, or three open VT fuses. Some of these multifunction relays operate in response to the area of the voltage triangle formed by the phasors of the three-phase voltages.

When applying undervoltage protection with time delay, the time-delay setting should be chosen so that time-delay undervoltage tripping does not occur before all external fault-detecting relays have had an opportunity to clear faults from the system. This practice recognizes that the most frequent causes of low voltage are system faults; and when these faults are cleared, most induction motors can continue normal operation. For inverse time-undervoltage relays, their trip time versus system short-circuit current should be plotted to verify that these trip only after the system overcurrent protective relays. This procedure should be done for the most critical coordination condition, which exists when the system short-circuit capacity is minimum. This study should be included with normal systems studies concerning voltage drop, short-circuits, etc. Typical time delay at zero voltage is 2 s to 5 s.

For motors extremely important to continuity of service, such as some auxiliaries in electric generating plants, the undervoltage relay functions are used only to alarm. The motors providing fire pump service should be protected in accordance with applicable standards such as NFPA 20-2013 and NFPA 70-2014.

6.3 Phase unbalance protection (Device 46, current) (Device 47, voltage) (Device 60)

6.3.1 Devices 46, 47, and 60; relays

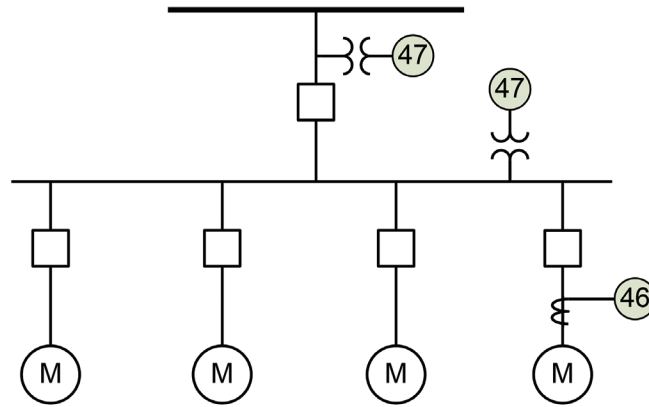
Several types of relays are available to provide phase unbalance protection, including single phasing. Most of these relays are described in Chapter 4 of IEEE Std 242-2001 (*IEEE Buff Book™*) and in IEEE Std C37.96™-2012. Further information about specific relays should be obtained from the various manufacturers. Most of the commonly used relays or functions in Device 11M are classified below. The user should select the protection functions necessary for the application and disable unused functions.

- a) Phase current unbalance (Device 46). A device in a polyphase circuit that operates when polyphase currents are unbalanced. Mechanical phase current unbalance relays are induction disk devices that detect unbalance in the currents in the three phases. As such these devices have an inherent time delay. Occasionally, a timer is used to obtain additional delay. Because this relay cannot protect for unbalances less than 25%, its selection is questionable except for complete loss of one phase. Unfortunately, this device shares the same device number as the negative sequence overcurrent relay (Device 46) in item d).
- b) Phase current unbalance high resistance ground (HRG) (Device 46). If users set current unbalance relay to trip in an HRG system and a ground fault occurs on the system, the Device 46 may initiate an undesired trip. Some protection relays for LV applications have a blocking function to avoid this situation. However, if the Device 46 relay does not block this situation, alarm only should be considered.
- c) Reverse-phase (Device 46). A device in a polyphase circuit that operates when the polyphase currents are of reverse phase sequence.
- d) Negative sequence overcurrent (Device 46). A negative sequence overcurrent relay is a time overcurrent relay with extremely inverse characteristics that operates at very small levels of negative sequence current. Settings are available to alarm before trip and to trip upon a limit of I_2^2t .
- e) Negative sequence voltage (Device 47). Because negative sequence voltage relays operate instantaneously on negative sequence overvoltage, some external time delay might be necessary.
- f) Voltage balance (Device 60). The voltage balance (60) element compares voltage sources to determine if there is a difference in voltage, i.e., for VTs determining if both input sources are present or if there is an open fuse losing one source. If a source is not present, then the output of this element blocks (removes permission) from tripping or starting elements. The voltage balance 60 relay is an older method than voltage-unbalance 47 protection, which is based on sequence components.

6.3.2 Devices 46, 47, and 60; purpose

The purpose of phase unbalance protection is to prevent motor overheating damage. Motor overheating occurs when the phase voltages are unbalanced. A small voltage unbalance produces a large negative sequence current flow in both synchronous and induction motors. The per-unit negative sequence impedance of either motor 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 equal to six times rated current, the motor has a negative sequence impedance of approximately 0.167 per unit (16.7%) on the motor rated input kilovoltampere base. When voltages having a 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 equal to 30% of full load current. This situation can lead to a 40% to 50% increase in temperature rise.

Current unbalance (46) is measured in the motor feeder and has the advantage of being applied at each motor. It is easy to implement in multifunction motor protection relays, Device 11M. Measuring algorithms include the true negative sequence measurement and the difference between the maximum and minimum phase currents. For a negative sequence type element, the I_2 percent setting (20% to 25% of nameplate rated current) is approximately 4 to 5 times the percent voltage unbalance for the worst case nominal load condition. Refer to [Figure 9](#) for optional VT locations for Device 47 and CT location for Device 46.

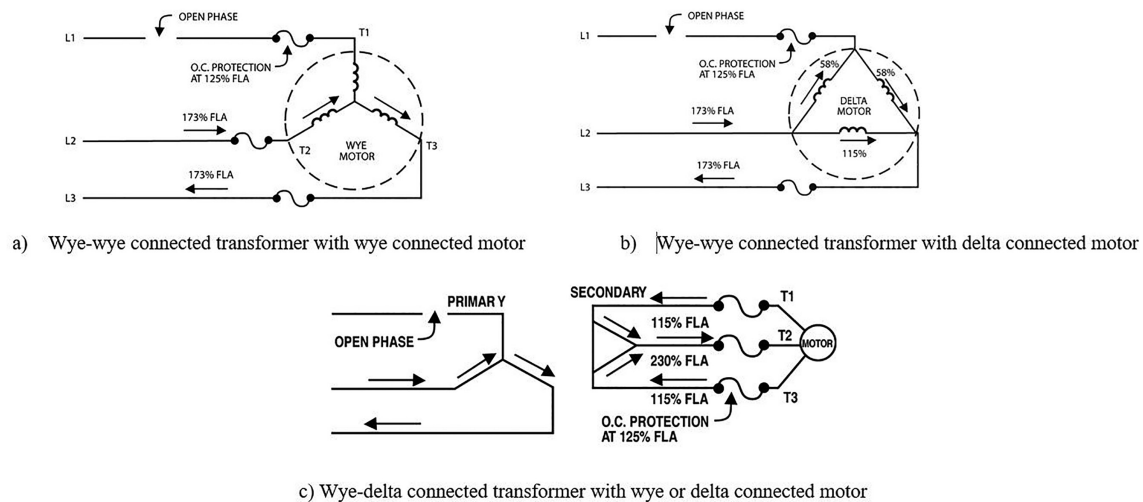


Courtesy of Basler Electric Company.

Figure 9—Device 47 VT locations and Device 46 CT location for motor protection

6.3.3 Devices 46, 47, and 60; single phasing

The extreme form of unbalance is the complete loss of voltage in one phase. Under these conditions, a three-phase motor is unable to start. If the single phasing occurs during full load running conditions, the current in the two energized phases increases above full load current for a wye connected motor (see Figure 10a). If the motor is delta connected, the current in the motor phase coils that are connected to the energized phases will see greater than full load amps and the two phase coils that are bisected by the lost phase will see less than full load current (see Figure 10b). These figures are applicable if the transformer is wye-wye connected. If the transformer is wye-delta connected, the same problem exists only the current values are different as shown in Figure 10c). In each case, adequate phase overcurrent protection is required.



Courtesy of EASA.

Figure 10—Loss-of-phase currents for various transformer and motor winding configurations

Many motors, especially in the higher horsepower ratings, can be seriously damaged by negative sequence current heating, even though the stator currents are low enough to go undetected by overload (overcurrent)