

# IEEE Guide for AC Motor Protection

IEEE Power and Energy Society

Sponsored by the  
Power System Relaying Committee



IEEE  
3 Park Avenue  
New York, NY 10016-5997  
USA

IEEE Std C37.96™-2012  
(Revision of  
IEEE Std C37.96-2000)

20 February 2013



**This is a Redline Document produced by Techstreet, a business of Thomson Reuters.**

This document is intended to provide users with an indication of changes from one edition to the next. It includes a full-text version of the new document, plus an indication of changes from the previous version.

Redlines are designed to save time and improve efficiencies by using the latest software technology to find and highlight document changes. More professionals are using valuable new technologies like redlines, to help improve outcomes in a fastpaced global business world.

Because it may not be technically possible to capture all changes accurately, it is recommended that users consult previous editions as appropriate. In all cases, only the current base version of this publication is to be considered the official document.

## Redline Processing Notes:

1. ~~Red Text~~ - Red strikethrough text denotes deletions.
2. Blue Text - Blue underlined text denotes modifications and additions.

# IEEE Guide for AC Motor Protection

Sponsor

**Power System Relaying Committee**  
of the  
**IEEE Power and Energy Society**

Approved 5 December 2012

**IEEE-SA Standards Board**

**Abstract:** Generally accepted methods of protection for ac motors are provided. The functions necessary for adequate protection of motors based on type, size, and application are identified and summarized. The protective requirements of all motors in every situation is not purported to be detailed in this guide.

**Keywords:** ac motor protection, adjustable-speed drive motor protection, IEEE C37.96<sup>TM</sup>, induction motor protection, microprocessor-based motor protection, motor, motor bus transfer, rotating machinery protection, synchronous motor protection, wound rotor motor protection

---

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

Copyright © 2013 by The Institute of Electrical and Electronics Engineers, Inc.  
All rights reserved. Published 20 February 2013. Printed in the United States of America.

IEEE is a registered trademark in the U.S. Patent & Trademark Office, owned by The Institute of Electrical and Electronics Engineers, Incorporated.

PDF: ISBN 978-0-0-7381-8146-2 STD98099  
Print: ISBN 978-0-0-7381-8147-9 STDPD98099

*IEEE prohibits discrimination, harassment, and bullying.*

For more information, visit <http://www.ieee.org/web/aboutus/whatis/policies/p9-26.html>.

*No part of this publication may be reproduced in any form, in an electronic retrieval system or otherwise, without the prior written permission of the publisher.*

**Notice and Disclaimer of Liability Concerning the Use of IEEE Documents:** IEEE Standards documents are developed within the IEEE Societies and the Standards Coordinating Committees of the IEEE Standards Association (IEEE-SA) Standards Board. IEEE develops its standards through a consensus development process, approved by the American National Standards Institute, which brings together volunteers representing varied viewpoints and interests to achieve the final product. Volunteers are not necessarily members of the Institute and serve without compensation. While IEEE administers the process and establishes rules to promote fairness in the consensus development process, IEEE does not independently evaluate, test, or verify the accuracy of any of the information or the soundness of any judgments contained in its standards.

Use of an IEEE Standard is wholly voluntary. IEEE disclaims liability for any personal injury, property or other damage, of any nature whatsoever, whether special, indirect, consequential, or compensatory, directly or indirectly resulting from the publication, use of, or reliance upon any IEEE Standard document.

IEEE does not warrant or represent the accuracy or content of the material contained in its standards, and expressly disclaims any express or implied warranty, including any implied warranty of merchantability or fitness for a specific purpose, or that the use of the material contained in its standards is free from patent infringement. IEEE Standards documents are supplied "AS IS."

The existence of an IEEE Standard does not imply that there are no other ways to produce, test, measure, purchase, market, or provide other goods and services related to the scope of the IEEE standard. Furthermore, the viewpoint expressed at the time a standard is approved and issued is subject to change brought about through developments in the state of the art and comments received from users of the standard. Every IEEE standard is subjected to review at least every ten years. When a document is more than ten years old and has not undergone a revision process, it is reasonable to conclude that its contents, although still of some value, do not wholly reflect the present state of the art. Users are cautioned to check to determine that they have the latest edition of any IEEE standard.

In publishing and making its standards available, IEEE is not suggesting or rendering professional or other services for, or on behalf of, any person or entity. Nor is IEEE undertaking to perform any duty owed by any other person or entity to another. Any person utilizing any IEEE Standards document, should rely upon his or her own independent judgment in the exercise of reasonable care in any given circumstances or, as appropriate, seek the advice of a competent professional in determining the appropriateness of a given IEEE standard.

**Translations:** The IEEE consensus development process involves the review of documents in English only. In the event that an IEEE standard is translated, only the English version published by IEEE should be considered the approved IEEE standard.

**Official Statements:** A statement, written or oral, that is not processed in accordance with the IEEE-SA Standards Board Operations Manual shall not be considered the official position of IEEE or any of its committees and shall not be considered to be, nor be relied upon as, a formal position of IEEE. At lectures, symposia, seminars, or educational courses, an individual presenting information on IEEE standards shall make it clear that his or her views should be considered the personal views of that individual rather than the formal position of IEEE.

**Comments on Standards:** Comments for revision of IEEE Standards documents are welcome from any interested party, regardless of membership affiliation with IEEE. However, IEEE does not provide consulting information or advice pertaining to IEEE Standards documents. Suggestions for changes in documents should be in the form of a proposed change of text, together with appropriate supporting comments. Since IEEE standards represent a consensus of concerned interests, it is important to ensure that any responses to comments and questions also receive the concurrence of a balance of interests. For this reason, IEEE and the members of its societies and Standards Coordinating Committees are not able to provide an instant response to comments or questions except in those cases where the matter has previously been addressed. Any person who would like to participate in evaluating comments or revisions to an IEEE standard is welcome to join the relevant IEEE working group at <http://standards.ieee.org/develop/wg/>.

Comments on standards should be submitted to the following address:

Secretary, IEEE-SA Standards Board  
445 Hoes Lane  
Piscataway, NJ 08854  
USA

**Photocopies:** Authorization to photocopy portions of any individual standard for internal or personal use is granted by The Institute of Electrical and Electronics Engineers, Inc., provided that the appropriate fee is paid to Copyright Clearance Center. To arrange for payment of licensing fee, please contact Copyright Clearance Center, Customer Service, 222 Rosewood Drive, Danvers, MA 01923 USA; +1 978 750 8400. Permission to photocopy portions of any individual standard for educational classroom use can also be obtained through the Copyright Clearance Center.

## Notice to users

## Laws and regulations

Users of IEEE Standards documents should consult all applicable laws and regulations. Compliance with the provisions of any IEEE Standards document does not imply compliance to any applicable regulatory requirements. Implementers of the standard are responsible for observing or referring to the applicable regulatory requirements. IEEE does not, by the publication of its standards, intend to urge action that is not in compliance with applicable laws, and these documents may not be construed as doing so.

## Copyrights

This document is copyrighted by the IEEE. It is made available for a wide variety of both public and private uses. These include both use, by reference, in laws and regulations, and use in private self-regulation, standardization, and the promotion of engineering practices and methods. By making this document available for use and adoption by public authorities and private users, the IEEE does not waive any rights in copyright to this document.

## Updating of IEEE documents

Users of IEEE Standards documents should be aware that these documents may be superseded at any time by the issuance of new editions or may be amended from time to time through the issuance of amendments, corrigenda, or errata. An official IEEE document at any point in time consists of the current edition of the document together with any amendments, corrigenda, or errata then in effect. In order to determine whether a given document is the current edition and whether it has been amended through the issuance of amendments, corrigenda, or errata, visit the IEEE-SA Website at <http://standards.ieee.org/index.html> or contact the IEEE at the address listed previously. For more information about the IEEE Standards Association or the IEEE standards development process, visit IEEE-SA Website at <http://standards.ieee.org/index.html>.

## Errata

Errata, if any, for this and all other standards can be accessed at the following URL: <http://standards.ieee.org/findstds/errata/index.html>. Users are encouraged to check this URL for errata periodically.

## Patents

Attention is called to the possibility that implementation of this standard may require use of subject matter covered by patent rights. By publication of this standard, no position is taken by the IEEE with respect to the existence or validity of any patent rights in connection therewith. If a patent holder or patent applicant has filed a statement of assurance via an Accepted Letter of Assurance, then the statement is listed on the IEEE-SA Website at <http://standards.ieee.org/about/sasb/patcom/patents.html>. Letters of Assurance may indicate whether the Submitter is willing or unwilling to grant licenses under patent rights without compensation or under reasonable rates, with reasonable terms and conditions that are demonstrably free of any unfair discrimination to applicants desiring to obtain such licenses.

Essential Patent Claims may exist for which a Letter of Assurance has not been received. The IEEE is not responsible for identifying Essential Patent Claims for which a license may be required, for conducting inquiries into the legal validity or scope of Patents Claims, or determining whether any licensing terms or conditions provided in connection with submission of a Letter of Assurance, if any, or in any licensing agreements are reasonable or non-discriminatory. Users of this standard are expressly advised that determination of the validity of any patent rights, and the risk of infringement of such rights, is entirely their own responsibility. Further information may be obtained from the IEEE Standards Association.

## Participants

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

**Prem Kumar, *Chair***  
**Dale Finney, *Vice Chair***

Hasnain Ashrafi  
Matt Basler  
Steve Conrad  
Tom Farr  
Dale Fredrickson  
Jon Gardell

Wayne Hartmann  
Nicholas Hoch  
Pat Kerrigan  
Mohamed Khalek  
Jeff Long  
Subhash Patel

Suhag Patel  
Mike Reichard  
Chris Ruckman  
Sam Sambasivan  
Sudhir Thakur  
Joe Uchiyama

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

William Ackerman  
Ali Al Awazi  
Mohammed Ashraf Ali  
G Bartok  
Matt Basler  
Martin Best  
Steven Bezner  
Wallace Binder  
Thomas Blair  
Chris Brooks  
Bill Brown  
Derek Brown  
Gustavo Brunello  
William Bush  
William Byrd  
Paul Cardinal  
Larry Conrad  
Steve Conrad  
Randall Crellin  
Glenn Davis  
Gary Donner  
Randall Dotson  
Ahmed Elneweihi  
Dan Evans  
Dale Finney  
Rabiz Foda  
Dale Fredrickson  
Doaa Galal  
Jalal Gohari  
Stephen Grier  
Randall Groves  
Ajit Gwal

Roger Hedding  
Scott Hietpas  
Robert Hoerauf  
Gerald Johnson  
James Jones  
Innocent Kamwa  
John Kay  
Mohamed Khalek  
Yuri Khersonsky  
Joseph L. Koepfinger  
Boris Kogan  
Jim Kulchisky  
Prem Kumar  
Chung-Yiu Lam  
Raluca Lascu  
Michael Lauxman  
Albert Livshitz  
Greg Luri  
Bruce Mackie  
John McAlhaney, Jr.  
Kenneth McClenahan  
John Miller  
Jeffery Mizener  
Jerry Murphy  
R. Murphy  
Arthur Neubauer  
Michael S. Newman  
Joe Nims  
Gary Nissen  
Lorraine Padden  
Mirko Palazzo

Donald Parker  
Christopher Petrola  
Robert Pettigrew  
Iulian Profir  
Daniel Leland Ransom  
Michael Roberts  
Charles Rogers  
M Sachdev  
Bartien Sayogo  
Robert Schuerger  
Robert Seitz  
Gil Shultz  
Veselin Skendzic  
James Smith  
Jerry Smith  
Gary Stodter  
Richard Taylor  
John Tengdin  
Michael Thompson  
Wayne Timm  
Demetrios Tziouvaras  
Joe Uchiyama  
Eric Udren  
John Vergis  
Ilia Voloh  
John Wang  
William Waudby  
Kenneth White  
Phil Winston  
Larry Yonce  
Jian Yu  
Luis Zambrano

When the IEEE-SA Standards Board approved this guide on 5 December 2012, it had the following membership:

**Richard H. Hulett**, *Chair*  
**John Kulick**, *Vice Chair*  
**Robert M. Grow**, *Past Chair*  
**Konstantinos Karachalios**, *Secretary*

Satish Aggarwal  
Masayuki Ariyoshi  
Peter Balma  
William Bartley  
Ted Burse  
Clint Chaplin  
Wael Diab  
Jean-Philippe Faure

Alexander Gelman  
Paul Houzé  
Jim Hughes  
Joseph L. Koepfinger\*  
David J. Law  
Thomas Lee  
Hung Ling  
Oleg Logvinov

Ted Olsen  
Gary Robinson  
Jon Walter Rosdahl  
Sam Sciacca  
Mike Seavey  
Yatin Trivedi  
Phil Winston  
Don Wright

\*Member Emeritus

Also included are the following nonvoting IEEE-SA Standards Board liaisons:

Richard DeBlasio, *DOE Representative*  
Michael Janezic, *NIST Representative*

Patrick Gibbons  
*IEEE Standards Program Manager, Document Development*

Erin Spiewak  
*IEEE Standards Program Manager, Technical Program Development*

## Introduction

This introduction is not part of IEEE Std C37.96<sup>-2012™</sup>-2012, IEEE Guide for AC Motor Protection.

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

Clause 3, a glossary of component and terminology definitions, has been added.

Clause 4.4 has been added and Clause 6.3 has been enhanced to comprehensively discuss ASD protection.

Clause 5 has been modified to include information on failure mechanisms of motors.

Clause 5.2 has been enhanced to provide information insulation class in motor that is relevant to protection.

Clause 5.2.8 has been enhanced to include discussion on reduced voltage starting and high inertia motor protection.

Clause 5.4.3 has been added to discuss considerations for application low ratio CTs.

Clause 5.8 has been enhanced to add information on how to apply surge capacitors (protection) to motors.

Clause 6.4 has been added to discuss issues with motor bus transfers.

Clause 6.5 has been added for discussion of placement considerations of power factor correction capacitors relative to motor relay sensing CT.

Clause 7.2.10.3 has been enhanced to add coordination/application considerations for when fuses and relays overlap for motor protection such as motors protected by fused contactors.

Clause 7.2.10.8 has enhanced discussion on motor ground fault protection.

Clause 7.2.11 has been added to discuss breaker protection for small motors.

Clause 8 has been enhanced to include a section (8.2) to understand several motor data such as cooling time constants needed to set modern microprocessor relays.

Annex A.2 has been added to provide relevant tutorial type material for understanding motor dynamics relevant to relay settings such as motor acceleration time, accelerating torque, and impact of voltage on motor torque.

Annex A.3 has added a motor modern microprocessor relay setting example.

## Contents

|                                                                                            |     |
|--------------------------------------------------------------------------------------------|-----|
| 1. Scope .....                                                                             | 1   |
| 2. Normative references .....                                                              | 1   |
| 3. Definitions .....                                                                       | 3   |
| 4. Equipment description .....                                                             | 7   |
| 4.1 Induction motors .....                                                                 | 7   |
| 4.2 Synchronous motors .....                                                               | 8   |
| 4.3 Switching and control .....                                                            | 8   |
| 4.4 Adjustable speed drives (ASD) .....                                                    | 15  |
| 5. Motor protection requirements .....                                                     | 19  |
| 5.1 Pullout and stall protection .....                                                     | 19  |
| 5.2 Stator winding protection .....                                                        | 21  |
| 5.3 Rotor thermal protection .....                                                         | 40  |
| 5.4 Stator fault protection .....                                                          | 41  |
| 5.5 Rotor fault protection .....                                                           | 53  |
| 5.6 Bearing protection .....                                                               | 55  |
| 5.7 Abnormal power supply conditions .....                                                 | 58  |
| 5.8 Surge protection .....                                                                 | 65  |
| 5.9 Motors or motor controls used in class 1E nuclear exposure .....                       | 68  |
| 6. Motor protection specifications .....                                                   | 68  |
| 6.1 General considerations .....                                                           | 68  |
| 6.2 Motor protection tables .....                                                          | 69  |
| 6.3 Adjustable-speed motor protection .....                                                | 78  |
| 6.4 Motor bus transfer (MBT) .....                                                         | 89  |
| 6.5 CT placement considerations .....                                                      | 102 |
| 7. Setting and adjustment of protective devices .....                                      | 102 |
| 7.1 General discussion .....                                                               | 102 |
| 7.2 Protective device settings .....                                                       | 103 |
| 8. Device 11—multifunction, microprocessor-based protection systems .....                  | 119 |
| 8.1 General .....                                                                          | 119 |
| 8.2 Derivation of motor protection settings from nameplate and datasheet information ..... | 119 |
| 8.3 Thermal protection in microprocessor-based motor protection systems .....              | 121 |
| 8.4 Multiple functions generally incorporated into one package .....                       | 123 |
| 8.5 Control functions and features .....                                                   | 124 |
| 8.6 Data collection, reporting, and remote communications .....                            | 125 |
| 8.7 Application issues .....                                                               | 126 |
| Annex A (informative) Basics of motor protection .....                                     | 128 |
| Annex B (informative) Bibliography .....                                                   | 138 |



# IEEE Guide for AC Motor Protection

IMPORTANT NOTICE: IEEE Standards documents are not intended to ensure safety, health, or environmental protection, or ensure against interference with or from other devices or networks. Implementers of IEEE Standards documents are responsible for determining and complying with all appropriate safety, security, environmental, health, and interference protection practices and all applicable laws and regulations.

This IEEE document is made available for use subject to important notices and legal disclaimers. These notices and disclaimers appear in all publications containing this document and may be found under the heading "Important Notice" or "Important Notices and Disclaimers Concerning IEEE Documents." They can also be obtained on request from IEEE or viewed at <http://standards.ieee.org/IPR/disclaimers.html>.

## 1. Scope

This application guide presents generally accepted methods of protection for ac motors. It identifies and summarizes the functions necessary for adequate protection of motors based on type, size, and application. This guide does not purport to detail the protective requirements of all motors in every situation. What it does provide is enough information and guidance for the user to implement adequate protection for particular applications. The recommendations in this guide are based on typical ~~types of~~ installations. ~~However, sufficient background~~ Information relating to protection requirements, including microprocessor based protection systems, applications, and setting philosophy is provided to enable the reader to determine required protective functions for motor installations. Relay protection of squirrel-cage, wound-rotor induction motors, and synchronous motors is presented herein, ~~with a review of the generally accepted forms of motor protection~~. This guide also summarizes the uses of relays and devices, individually and in combination, so the user may select the necessary equipment, to obtain adequate motor protection. This guide is concerned primarily with the protection of three-phase, integral horsepower motors and adjustable-

speed drives where specifically indicated. This guide does not purport to detail the protective requirements ~~Its recommendations are~~ of all motors in every situation. What it does provide is enough a general nature, designed to cover typical motor installations. Sufficient background information on objectives, application, and guidance to implement adequate protection for most applications. ~~setting philosophy is presented~~

## 2. Normative references

The following referenced documents are indispensable for the application of this document (i.e., they must be understood and used, so each referenced document is cited in text and its relationship to this document is explained). For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments or corrigenda) applies.

IEC 60034-15:2009, Rotating electrical machines—Part 15: Impulse voltage withstand levels of form wound stator coils for rotating a.c. machines.<sup>1</sup>

IEEE Std 1<sup>TM</sup>-2000, IEEE Recommended Practice—General Principles for Temperature Limits in the Rating of Electrical Equipment and for the Evaluation of Electrical Insulation.<sup>2,3</sup>

IEEE Std 112<sup>TM</sup>-2004, IEEE Standard Test Procedure for Polyphase Induction Motors and Generators.

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

- ~~a) Clause 2 lists applicable references.~~
- ~~b) Clause 3 contains a glossary of terminology.~~

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

<sup>1</sup>IEC publications are available from the Sales Department of the International Electrotechnical Commission, 3 rue de Varembe, PO Box 131, CH-1211, Geneva 20, Switzerland (<http://www.iec.ch/>). IEC publications are also available in the United States from the Sales Department, American National Standards Institute, 25 West 43rd Street, 4th Floor, New York, NY 10036, USA (<http://www.ansi.org>)

<sup>2</sup>The IEEE standards or products referred to in this clause are trademarks of The Institute of Electrical and Electronics Engineers, Inc.

<sup>3</sup>IEEE publications are available from The Institute of Electrical and Electronics Engineers, 445 Hoes Lane, Piscataway, NJ 0854, USA (<http://standards.ieee.org/>).

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

provide

## 2. References

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

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

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

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

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

~~ANSI C50.41-1982, American National Standard for Polyphase Induction Motors~~

IEEE Std 242-[2001](#) ~~1986 (Reaff 1991)~~, IEEE Recommended Practice for Protection and Coordination of Industrial and Commercial Power Systems—IEEE Buff Book ([Color Book Series](#)).

[IEEE Std 493<sup>TM</sup>-2007, \(The IEEE Gold Book\) IEEE Recommended Practice for Design of Reliable Industrial and Commercial Power Systems.](#)

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

IEEE Std [519<sup>TM</sup>-1992](#) ~~620-1996~~, IEEE [Recommended Practices and Requirements for Harmonic](#)

[Control in Electrical Power Systems.](#)

[IEEE Std 620<sup>TM</sup>-1996 \(Reaff 2008\), IEEE Guide for the Presentation of Thermal Limit Curves for Squirrel Cage Induction Machines.](#)

[IEEE Std C37.06<sup>TM</sup>-2009, 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 C37.13](#) ~~NEMA AB1-1993, Standards for Molded Case Circuit Breakers.~~<sup>3</sup>

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

~~NEMA MG1-1998, Motors and Generators.~~

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

~~NEMA SG3-1995, Standards~~ [IEEE Std C37.46<sup>TM</sup>-2010, IEEE Standard for Low-Voltage AC Power Circuit Breakers Used in Enclosures.](#)

[IEEE Std C37.16<sup>TM</sup>-2009, IEEE Standard for Preferred Ratings, Related Requirements, and Section SG3, 28-9.5, Application Recommendations for Low-Voltage AC \(635 V and below\) and DC \(3200 V and below\) Power of Fused Circuit Breakers to Full Voltage Motor Starting and Running Duty of Three Phase, 60-Hz Motors.](#)

[IEEE Std C37.2<sup>TM</sup>-2008, IEEE Standard Electrical Power System Device Function Numbers and Contact Designations.](#)

[IEEE Std C37.46<sup>TM</sup>-2010, IEEE Specifications for High-Voltage \(>1000 V\) Expulsion and Current Limiting Power Class Fuses and Fuse Disconnecting Switches.](#)

IEEE Std C37.101<sup>TM</sup>-2006, IEEE Guide for Generator Ground Protection.

IEEE Std C37.110<sup>TM</sup>-2007, Guide for the Application of Current Transformers Used for Protective Relaying Purposes.

IEEE Std C57.110<sup>TM</sup>-2008, IEEE Recommended Practice for Establishing Liquid-Filled and Dry-Type Power and Distribution Transformer Capability When Supplying Nonsinusoidal Load Currents.

IEEE Std C62.21<sup>TM</sup>-2003 (Reaff 2009), IEEE Guide for the Application of Surge Voltage Protective Equipment on AC Rotating Machinery 1000 V and Greater.

IEEE C62.92.1<sup>TM</sup> 2000 (Reaff 2005), IEEE Guide for the Application of Neutral Grounding in Electrical Utility Systems.

NEMA/ANSI C50.41-2000, Polyphase Induction Motors for Power Generating Stations.<sup>4</sup>

NEMA ICS 1-2000 (R2005, R2008, E2010), Industrial Control and Systems General Requirements.

NEMA ICS 2-2000 (R2005), Industrial Control and Systems Controllers, Contactors, and Overload Relays Rated 600 Volts—Incorporates Errata: March 2008.

[NEMA MG1-2009 \(R2010\), Motors and Generators—Revision 1:2010.](#)

[NFPA 70-2011, National Electrical Code<sup>®</sup> \(NEC<sup>®</sup>\).<sup>5</sup>](#)

[UL 3472009, UL Standard for Safety Medium-Voltage AC Contactors, Controllers, and Control Centers.<sup>6</sup>](#)

### 3. Definitions ~~AC motor terminology glossary~~

For the purposes of this document guide, the following terms and definitions apply. The IEEE Standards Dictionary Online ~~These terms and definitions are commonly used in the industry and found in both IEEE 100-1996 [B152]<sup>4</sup> and NEMA MG-1 1998. IEEE 100-1996~~ should be consulted ~~referenced~~ for terms not defined in this clause.<sup>7</sup>

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

<sup>4</sup>NEMA publications are available from Global Engineering Documents, 15 Inverness Way East, Englewood, CO 80112, USA (<http://global.ihs.com/>).

<sup>5</sup>NFPA 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/>).

<sup>6</sup>UL standards are available from Global Engineering Documents, 15 Inverness Way East, Englewood, Colorado 80112, USA (<http://www.global.ihs.com/>).

<sup>7</sup>IEEE Standards Dictionary Online subscription is available at: [http://www.ieee.org/portal/innovate/products/standard/standards\\_dictionary.html](http://www.ieee.org/portal/innovate/products/standard/standards_dictionary.html).

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

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

**active front end:** A self-commutated converter that is used to connect the network voltage to the dc-link.

**adjustable speed drive:** A drive designed to provide easily operable means for speed adjustment of the motor within a specified speed range.

**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.

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

**bypass contactor:** 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.

**closed-transition transfer (parallel transfer):** An 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.

**commutation:** The transfer of current from one switching device to another. Line-commutation utilizes the ac system voltage for the transfer of current from one device to another. Self-commutation is achieved by utilization of the turn-off switching capability of a device such as an insulated-gate bipolar transistor (IGBT)/gate turn-off thyristor (GTO), or gate-controlled turn-off thyristor (GCT). These devices can interrupt a current. The interruption forces the current to flow through another device.

**converter:** A machine or device for changing ac power into dc<sup>c</sup> power (rectifier operation) or dc power into ac power (inverter operation). Other types of converters can change ac power directly to an ac power of a different frequency (cycloconverter).

**current limiting fuse (CL):** 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.

**current source converter:** A current source converter is characterized by a controlled dc current in the intermediate dc link. The line side network voltage is converted in a controlled dc current. A current source converter uses an SCR bridge or an active front end to control the dc current.

**current source inverter (CSI):** An inverter, in which the dc terminal is inductive and, as a consequence, the dc current is relatively slow to change. Modulation of the CSI acts to control the voltage at the ac terminal. The switches in a CSI need to block either voltage polarity, but are only required to conduct current in one direction.

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

**drive:** The equipment used for converting electrical power into mechanical power suitable for the operation of a machine. A drive is a combination of a converter and any motor-mounted auxiliary devices. Sometimes a motor may be a part of the complete drive system. Examples of motor mounted auxiliary devices are encoders, tachometers, thermal switches and detectors, air blowers, heaters, and vibration sensors.

**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 weakening range:** Defines when a motor is operated at a speed above its nameplate r/min, the drive needs to hold nameplate voltage while increasing the frequency thus weakening the rotor field (air gap flux). This is also known as the constant horsepower range.

**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.

**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).

**high-inertia load:** A load that has a moment of inertia that exceeds normal values, as described in NEMA MG-1-2009 ~~1993~~, and for which the motor needs to be designed to have both thermal and mechanical capability to accelerate the load to operating speed without exceeding its limits.

**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.

**inverter:** A converter in which the direction of power flow is predominately from the dc terminal to the ac terminal.

**inverter duty motor:** A motor that is designed to work with an inverter fed supply. This motor is designed with better insulation to protect from voltage spikes and better cooling for operation at low speed. It also has a shaft voltage discharge mechanism to prevent shaft current flowing through bearings.

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

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

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

**locked-rotor thermal limit (permissible locked-rotor time):** The maximum permissible safe time

vs. locked-rotor current flowing in the windings at rated voltage and frequency.

**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.

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

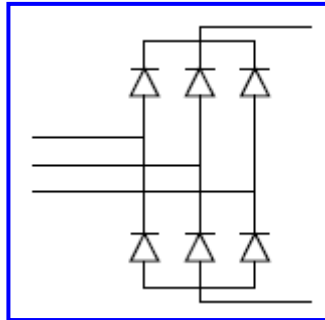
**open-transition transfer:** An MBT designed to trip the old source breaker before closing the new source breaker so that the two source breakers are open at the same time during the transfer process.

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

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

**pulse number:** The pulse number of a converter defines the number of commutations, which are used within one fundamental period, to convert ac to dc. The basic converter for a three-phase system is a B6 topology. The B6 converter uses six commutations within one fundamental period. This results in a commutation every 60°. Common pulse numbers are: 6-pulse (based on 1 B6

[circuit\), 12-pulse \(2 B6 circuits\), 18-pulse \(3 B6 circuits\), 24-pulse \(4 B6 circuits\), and 36-pulse \(6 B6 circuits\).](#)



[\(New\)](#)

### **B6 Topology**

**pulsewidth modulation (PWM):** A control method for a converter wherein the control of the frequency and magnitude of the output voltage or current is accomplished by variation of the operating duration of the switching devices (duty cycle of turn on and off). This method is typically used to control a selfcommutated converter.

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

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

**running thermal capability:** A plot of maximum permissible time vs. 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 which, when applied to the rated horsepower, indicates a permissible horsepower loading that may be carried under the conditions specified for the service factor.

**silicon controlled rectifier (SCR):** A solid-state switching device with three terminals: an anode, a cathode, and a gate (also known as a thyristor). The SCR will conduct electricity when the anode has a positive potential with respect to the cathode and a pulse is applied to the gate. The SCR will continue to conduct until the potential difference between the anode and cathode is reduced below a certain threshold value. SCRs can only be switched on. The switch off occurs when the current changes direction in the SCR.

**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.

**slip cycle:** When a synchronous motor slips out of step (loss of synchronism) a complete  $360^\circ$  with respect to the supply source.

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

**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.

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

**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 and frequency.

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

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

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

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

**voltage source converter:** A voltage source converter is characterized by a stiff dc voltage in the intermediate dc-link. The line side network voltage is converted to a constant dc voltage. A voltage source converter uses a diode bridge (6-pulse, 12-pulse, 18-pulse, 24-pulse or 36-pulse) or an active front end to connect the dc-link to the network voltage.

**voltage source inverter (VSI):** An inverter in which the dc terminal is capacitive and, as a consequence, the dc voltage is relatively stiff. Modulation of the VSI acts to control the current at

[the ac terminal. The switches in a VSI need to block dc voltage, but be able to conduct current in either direction.](#)

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

## 4. Equipment description

### 4.1 Induction motors

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

### 4.2 Synchronous motors

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

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

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

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

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

### 4.3 Switching and control

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

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

c) Stator switching means

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

In this subclause, the general types of stator and field interrupting and control devices are described. These devices have been primarily specified with the protection of the motor in mind. In some cases, the question of interruption to production is a very vital consideration for the user, and protection of certain motors may be secondary. In this case, see 5.7.2.2 and 5.7.2.3.

#### 4.3.1 AC line-interrupting control devices

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

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

These controllers consist of a magnetic contactor used for starting or stopping the motor. The controller is equipped with thermal overload (heaters) and loss-of-voltage protection. Loss-of-voltage protection is inherent with magnetic contactors when used with integral control power supply and three-wire control circuits. Loss-of-voltage protection in this context indicates that the supply power is interrupted and the disconnection is maintained. The voltage needs to ~~must~~ fall sufficiently to permit the contactor to open and break the seal-in circuit, and may not protect the motor against undervoltage operation. Short-circuit protection may be provided either by the magnetic trip of the circuit breaker or by fuses. The circuit breaker may also serve as the disconnecting means, whereas a separate disconnecting means is required in fused starters.

#### 4.3.1.2 NEMA Class E1 ~~medium~~ ~~high~~-voltage motor controllers (~~2001 V to 7200 V~~ ~~2200-4800~~)

Standards for these motor controllers are given in ~~ANSI~~/NEMA ICS 2-~~2000~~<sup>8</sup> ~~1988~~, and the ratings are listed in Table 2-324-2 of that document. These controllers consist of a medium-voltage magnetic contactor used for starting and stopping the motor, with thermal overload and undervoltage protection similar to that listed for the low-voltage units. In addition, fault protection is provided by instantaneous overcurrent (IOC) relays to trip a circuit breaker. Other relaying is added as described in Clause 6. The circuit breaker may also serve as the disconnecting means.

#### 4.3.1.3 NEMA Class E2 ~~medium~~ ~~high~~-voltage motor controllers (~~2001 V to 7200 V~~ ~~2200-4800~~)

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

### 4.3.2 Switchgear-type motor control

Power circuit breakers can be used for motor control of all stator-disconnecting, fault-interrupting, and switching functions. Standards are available that cover the application and limitations of ac power circuit breakers for these functions. For example, ~~IEEE~~ ~~ANSI~~ C37.16-~~2009~~ ~~1988~~ shows the application of low-voltage ac power circuit breakers for full-voltage motor starting and running duty of three-phase, 60 Hz, 40 °C rise motors; whereas ~~IEEE~~ ~~ANSI~~ C37. ~~13-2008~~ ~~16-1988~~ covers the limitations related to repetitive duty and normal maintenance. ~~IEEE~~ ~~ANSI~~ C37.06-~~2009~~ ~~1987~~ shows the number of operations for various operating conditions that can be performed on medium-

voltage circuit breakers before maintenance is required.

<sup>8</sup>[Information on references can be found in Clause 2.](#)

### 4.3.3 Field switching equipment

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

### 4.3.4 Effect of ac and dc control equipment

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

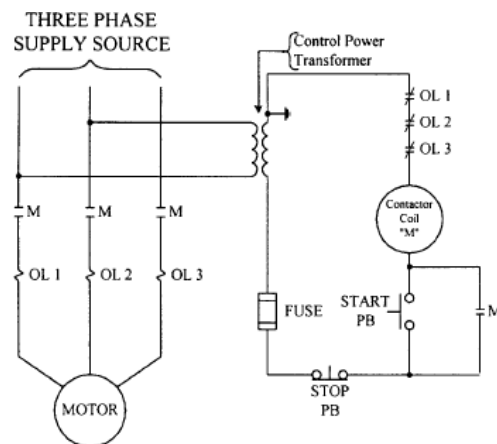


**Figure 1—Three-wire control circuit with loss-of-voltage protection  
(field control not shown)**

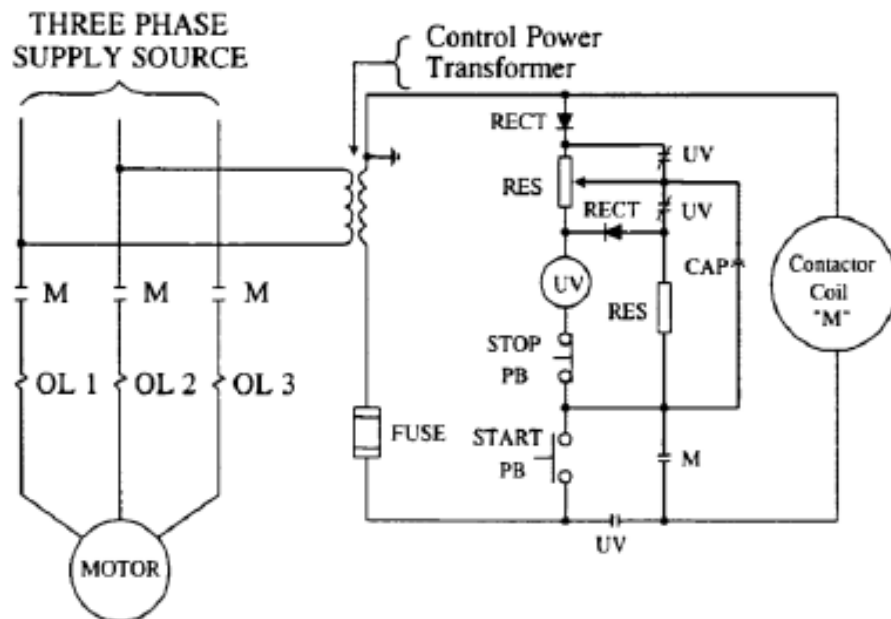
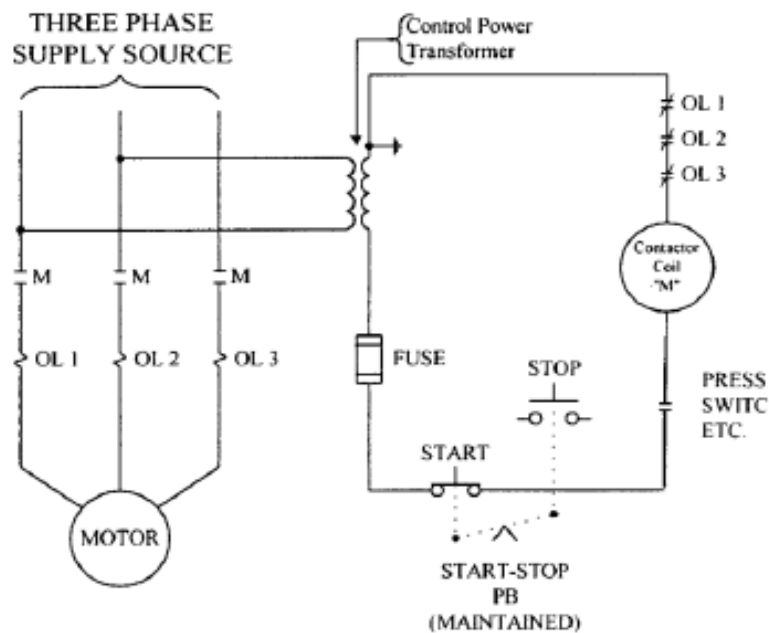


**Figure 2—Three-wire control circuit with time-delay loss-of-voltage protection**



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

### 4.3.5 Stator control equipment

Protection from extremely low or complete loss of line voltage is an inherent feature of the nonlatched type of ac motor controllers. These devices are not designed to release at any specific level of voltage. A measure of protection against low line voltage is available because the contactors are maintained closed by potential taken directly from the motor line or from a control power transformer. The line contactors must be closed at 85% of rated line voltage, according to ~~ANSI~~/NEMA ICS 2-~~2000~~ ~~1988~~, 110.41 (b), while the dropout point is not defined and may vary from 20% to 70% of rated voltage (typically 70%). The line contactor will drop open if a severe voltage dip or complete loss of line voltage should occur while a motor is running.

#### 4.3.5.1 Three-wire control with loss-of-voltage protection

When the circuit shown in Figure 1 is used, the contactor (M) is maintained through an auxiliary contact in parallel with the start pushbutton. If the contactor should open due to low line voltage, the coil circuit is broken by the auxiliary control contact, and the motor cannot restart until the start pushbutton is operated. This type of protection is referred to as three-wire control with loss-of-voltage protection. During a condition of low line voltage, a synchronous motor acts as a source of reactive power for a short period of time and, therefore, tends to maintain its ac terminal voltage for a considerably longer period than an induction motor. Voltage-sensitive contactors cannot be relied upon in this instance, since the motor may generate sufficient voltage to prevent the contactor from dropping out. See 5.7.2.3 for information on the protection of the motor for this condition.

#### 4.3.5.2 Three-wire control with time-delay loss-of-voltage protection

When it is desired to ~~maintain~~ ~~ensure that the~~ motor ~~will continue to~~ operation during voltage dips or outages of short duration, a control circuit similar to that shown in Figure 2 can be used. This is referred to as three-wire control with timedelay loss-of-voltage protection; it consists of a time-delay undervoltage (UV) relay that maintains a sealing contact for a definite period after a

voltage failure. It should be noted that the contactor (M) may drop out during the voltage dip, but will pick up again when the voltage is restored if the undervoltage time delay has not been exceeded.

#### 4.3.5.3 Two-wire control

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

#### 4.3.5.4 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 the closed position](#) and are tripped by operating a specific device or contact.

#### 4.3.6 Field-control equipment

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

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

Generally, the field application circuit will:

- a) 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.
- b) Apply field at a suitable speed (95% to 99%) and (with some equipment) at a favorable position of the rotor poles with respect to the rotating flux.
- c) Automatically remove field on impending pullout.



## Figure 4 — Typical brush-type synchronous motor control

The motor accelerates as an induction motor with its field connected across its starting (and discharging) resistor. A thermal relay (26F) for damper winding protection is in series with this resistor. Should the motor fail to start and accelerate, the relay operates to open the line-contactor coil circuit. This protection is discussed in 7.2.3. It is frequently important that the field be applied at the proper speed and at a favorable position of the rotor with respect to the rotating flux in the machine. To accomplish this, coordination is required between the field application or synchronizing relay (56 dc) and an ac holding coil (56 ac). When the line contactor (M) closes, its auxiliary contact energizes the closing coil (56 dc), which energizes the timing relay (2) and opens the field contactor (41) coil circuit. The timing relay is used to prevent the application of field until the proper time. When the timer reaches its actuating position, the field application relay closing coil (56 dc) is de-energized, leaving the operation of this relay dependent upon the variable ac voltage signal appearing across the starting resistor, as detected by the holding coil (56 ac). This relay will drop out when the time interval between half waves of the rectified induced field current exceeds the relay setting. This occurs at 94% to 98% of synchronous speed, at which time its contacts will close, energizing the field contactor (41).

#### 4.3.6.2 Brushless-type

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

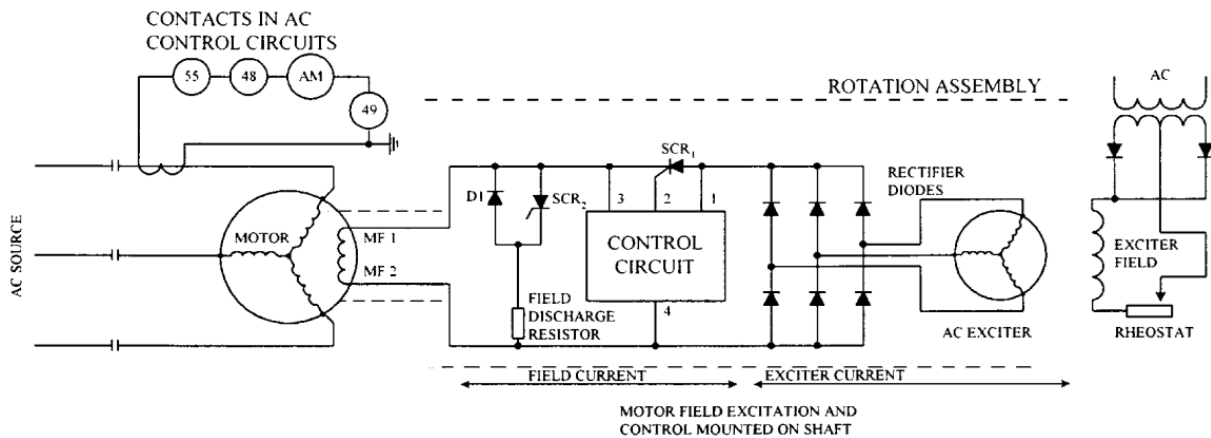


**Figure 5 – Typical brushless-type synchronous motor control**

#### 4.4 Adjustable speed drives (ASD)

AC drives have been used since the early twentieth century on a limited basis. The principles applied for varying speed have been well understood by motor designers and application engineers, but the advent of power electronics is what fostered this application of technology. Two key benefits of using ASDs are improved process control and efficiency.

Other benefits derived from applying adjustable speed drives are the following:

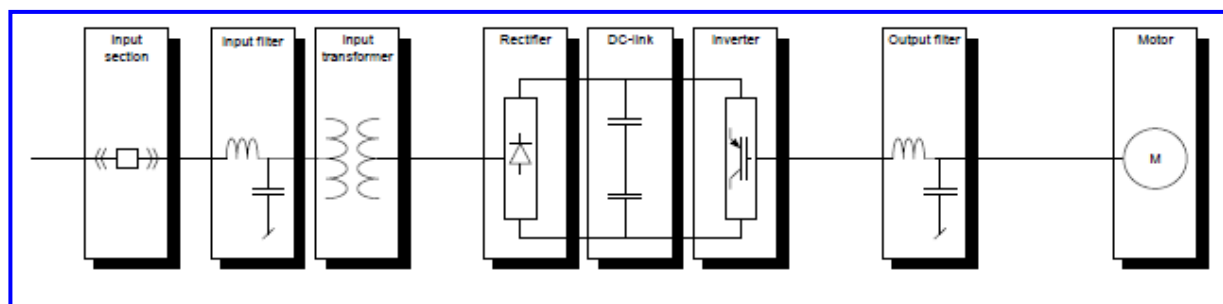
- a) Soft-start capability
- b) Short circuit reduction
- c) Replacement of older process control technologies

These benefits may be important from an operational and design point of view. For example, a system using larger horsepower motors will not be burdened with the traditional negative impacts such as large inrush currents and excessive short circuit contribution. In some system applications, it may be possible to add more motors and horsepower capacity without exceeding the voltage drop limits for motor starting and short circuit ratings of the associated breakers.

ASDs are ideal on loads in which torque increases with speed, such as fans, blowers, centrifugal pumps, and most kinds of compressors. Constant-torque loads such as reciprocating compressors, positive displacement pumps, conveyers, center winders, and drilling/milling machines require the same torque regardless of speed. The ASD should be carefully sized to provide adequate starting torque for those applications. Loads in which torque decreases with speed usually involve very high inertia loads such as vehicular (drives or flywheel) loaded applications. Custom-engineered solutions are often required for those applications.

#### 4.4.1 ASD Topology

The basic blocks of an ASD system are shown in Figure 6.



(New)

**Figure 6 – Basic blocks of an ASD system**

All of the blocks shown in Figure 6 are not necessarily needed for an ASD system. Depending on the topology, some blocks are required and some not. A short explanation of each basic block is provided as follows:

**Input section:** Provides isolation of the ASD from the main supply. Typically, it also provides the last level of protection.

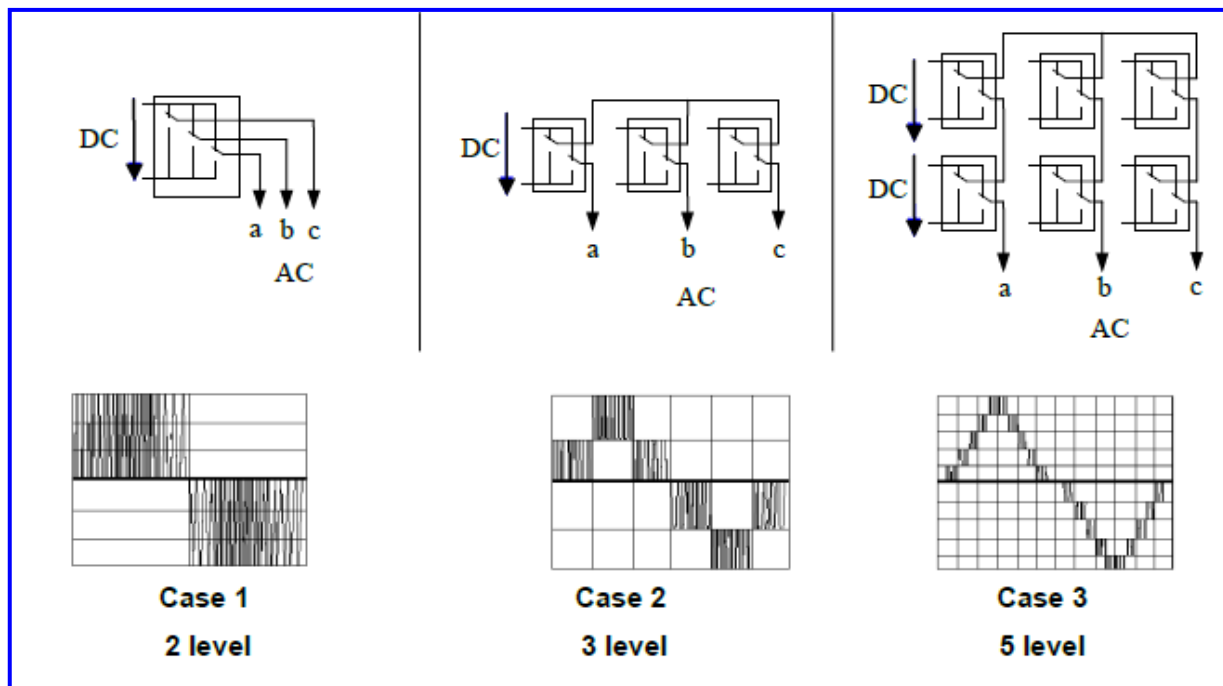
**Input filter:** Limits the harmonic currents induced to the network and improves displacement power factor. A harmonic filter is usually used in conjunction with an active front end or a current source inverter (CSI).

**Input transformer:** Typically has two basic functions. The transformer provides a multi-winding secondary system in order to connect a rectifier with a pulse number greater than 6. For example a 12-pulse rectifier requires at least a 3-winding transformer, or a 36-pulse rectifier requires at least a 7-winding transformer. The transformer also provides galvanic separation of the ASD system from the network. Specifically, the zero sequence or common mode voltage can be isolated between the network and the motor.

**Rectifier:** Typically is built up of a diode rectifier. For low-voltage (LV) ASD systems, a 6-pulse rectifier or an active front end are very common. For medium-voltage (MV) ASD systems, a 12-pulse rectifier in most cases meets the network harmonic limit requirements defined in IEEE Std 519-1992. However, for higher power ASD systems (typically above 5000 hp), pulse numbers greater than 12 are very common. The rectifier for a CSI is built up by a silicon controlled rectifier (SCR) rectifier. Typical pulse numbers are between 6-pulse and 24-pulse. However, since in most cases an input filter is required to meet the harmonic limits defined in IEEE Std 519-1992, 12-pulse configurations are very common. Where SCRs are used in the rectifier, the power factor of the rectifier is, at certain operation points, very poor. The power factor is basically equal to the firing angle of the SCR. Therefore, the harmonic filter is also used for power factor compensation.

**DC-link:** Used to decouple the line side converter (rectifier) from the motor side converter (inverter). In an ideal case, the intermediate dc link provides infinite energy storage to filter all harmonics, which can couple effects from each side to the other. A voltage source inverter (VSI) converter uses a capacitor bank to decouple both sides, whereas a CSI uses an inductor to decouple both sides. Both elements provide energy storage and act as filters.

Inverter (also called the motor side converter): Used to convert dc to ac. The inverter is the most advanced block in an ac ASD system. There are many different inverter topologies. The most common topology is a 2-level inverter. This topology is widely used for all kind of LV ASD systems. CSI converters are also based on a 2-level inverter. Especially for MV ASD systems, higher levels of inverter configurations are built. Figure 7 shows the principle of the inverter levels.



(New)

NOTE— The two switching devices that make up a leg of the VSI are never turned on simultaneously. Therefore, for purpose of illustration, they can be represented as an ideal single pole double throw switch.<sup>9</sup>

**Figure 7 — Inverter Levels**

Case 1 shows a 2-level inverter. The output of this inverter can be switched to two different levels: dc plus and dc minus.

<sup>9</sup>Notes in text, tables, and figures of a standard are given for information only and do not contain requirements needed to implement this standard.

Case 2 shows a 3-level inverter. The output of this inverter can be switched to three different levels: 0, dc plus, and dc minus.

Case 3 shows a 5-level inverter. The output of this inverter can be switched to five different levels: 0, dc plus, 2·dc plus, dc minus, and 2·dc minus

**Output filter:** Used to smooth the output waveform. Especially for VSI topologies, an output filter is used to limit the voltage rise time or even eliminate all major harmonics.

**Motor:** Converts the electrical energy into mechanical energy.

Table 1 provides an overview of the most common types of ASDs and their characteristics.

**Table 1 – ASD types**

| <u>Topology</u>                                                                               | <u>Characteristics</u>                                                                                                                                                                                                                                                   | <u>Typical minimum requirements</u>                                                                                                                                                |
|-----------------------------------------------------------------------------------------------|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| <u>DC Drive</u>                                                                               | <u>The ASD uses a dc motor. This was historically the first topology for ASD systems. Today, it is only used in special applications, such as drilling.</u>                                                                                                              | <u>Input section</u><br><u>SCR – Rectifier</u><br><u>DC motor</u>                                                                                                                  |
| <u>LCI (Load Commutated Inverter)</u><br><u>Line commutated Current Source Inverter (CSI)</u> | <u>The LCI is a commonly used CSI topology. The LCI uses SCRs on the line side to control the dc current, and uses SCRs on the motor side to control the speed of the motor.</u><br><u>LCIs are used for gas turbine starters or large drive systems &gt; 20,000 hp.</u> | <u>Input section</u><br><u>Input filter</u><br><u>Input transformer</u><br><u>SCR rectifier</u><br><u>DC link with inductor</u><br><u>SCR inverter</u><br><u>Synchronous motor</u> |

| <u>Topology</u>            | <u>Characteristics</u>                                                                                                                                                                                                                                                                                                                                                                                                                                                                                      | <u>Typical minimum requirements</u>                                                                                                                                                                                                                                                                   |
|----------------------------|-------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| <u>Self commutated CSI</u> | <p><u>The self-commutated CSI doesn't use SCRs at the motor side.</u></p> <p><u>This topology uses a semiconductor, which can be turned off as well. Since the CSI acts as a 2-level inverter, it creates significant output harmonics. Therefore, this converter type is usually equipped with a large output filter.</u></p> <p><u>Typically, symmetric gate-commutated thyristors (SGCT) are used for self-commutated CSIs.</u></p> <p><u>The line-side converter can be based on SCRs or SGCTs.</u></p> | <p><u>Input section</u></p> <p><u>Input filter</u></p> <p><u>Input transformer (for SCR rectifiers)</u></p> <p><u>SCR or SGCT rectifier DC link with inductor SGCT inverter (2-level)</u></p> <p><u>Sine wave output filter</u></p> <p><u>Motor</u></p>                                               |
| <u>2-level VSI</u>         | <p><u>A 2-level VSI topology is the most common topology for LV ASD systems. Most LV ASD systems are based on a 2-level VSI topology with a 6-pulse diode rectifier.</u></p>                                                                                                                                                                                                                                                                                                                                | <p><u>Input section</u></p> <p><u>Input filter Electromagnetic Compatibility (EMC)</u></p> <p><u>Rectifier, 6-pulse diode bridge</u></p> <p><u>DC link with capacitor</u></p> <p><u>Inverter [Transistor or Insulated Gate Bipolar Transistor (IGBT)]</u></p> <p><u>Output filter (EMC) Motor</u></p> |

| <u>Topology</u>                                                | <u>Characteristics</u>                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                           | <u>Typical minimum requirements</u>                                                                                                                                                                                                                                        |
|----------------------------------------------------------------|------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| <u>3-level VSI</u>                                             | <p>The 3-level VSI topology is the most common topology for MV ASD systems for high performance. Such VSI systems are built up to 40,000HP and are widely used in metals industry, where performance and reliability is very important.</p> <p>Depending on the application, this topology is equipped with a multi pulse rectifier or an active front-end rectifier.</p> <p>Since the voltage steps on the output are relatively large, an inverter duty motor is required for the ASD system, unless an output filter is provided to reduce the harmonics.</p> | <p><u>Input section</u></p> <p><u>Input transformer</u></p> <p><u>Diode rectifier (12-pulse or 24pulse) or active front end</u></p> <p><u>DC link with capacitor</u></p> <p><u>3-level inverter</u></p> <p><u>Output filter (EMC) or sine wave</u></p> <p><u>Motor</u></p> |
| <u>Multi-level VSI (Typically VSIs with 5 levels and more)</u> | <p>A multi-level VSI provides more than three basic steps in the output voltage waveform. It is considered that such an inverter can be connected to a standard motor without requiring derating of the motor due to current harmonics induced to the motor.</p> <p>Multi-level VSIs are equipped with a multi-pulse rectifier and require an input transformer.</p>                                                                                                                                                                                             | <p><u>Input section</u></p> <p><u>Input transformer</u></p> <p><u>Diode rectifier (18-pulse, 24pulse, or 36-pulse)</u></p> <p><u>DC link with capacitor</u></p> <p><u>Multi-level inverter Output filter EMC</u></p> <p><u>Motor</u></p>                                   |

## 5. Motor protection requirements

Table 2 provides information on failure of various components in large motors and is based on Table 10-19 in IEEE Std 493-2007. The information is based on data reported for 380 failures on 1141 large motors in industrial and commercial facilities. However, the information is also expected to give a good idea of failures in power plant motors. Generally applied protections for these failures have been added to Table 2.

**Table 2 – Failure of various components in large motors**

| <u>Failed component</u>                                                                 | <u>Induction motors</u> | <u>Synchronous motors</u> | <u>Wound rotor motors</u> | <u>Direct current motors</u> | <u>Total (all types) numbers</u> | <u>Total (all types) percentage</u> | <u>Protection*</u>                                   |
|-----------------------------------------------------------------------------------------|-------------------------|---------------------------|---------------------------|------------------------------|----------------------------------|-------------------------------------|------------------------------------------------------|
| <u>Bearings</u>                                                                         | <u>152</u>              | <u>2</u>                  | <u>10</u>                 | <u>2</u>                     | <u>166</u>                       | <u>43.7%</u>                        | <u>38, 39</u>                                        |
| <u>Windings</u>                                                                         | <u>75</u>               | <u>16</u>                 | <u>6</u>                  | <u>-</u>                     | <u>97</u>                        | <u>25.56%</u>                       | <u>26, 46, 49, 50, 50N, 51, 51N, 51R, 59, 87</u>     |
| <u>Rotor</u>                                                                            | <u>8</u>                | <u>1</u>                  | <u>4</u>                  | <u>-</u>                     | <u>13</u>                        | <u>3.4%</u>                         | <u>21, 26, 46, 49, 50, 50N, 51, 51N, 51R, 59, 87</u> |
| <u>Shaft or coupling</u>                                                                | <u>19</u>               | <u>-</u>                  | <u>-</u>                  | <u>-</u>                     | <u>19</u>                        | <u>5.0%</u>                         | <u>37, 39</u>                                        |
| <u>Brushes or slip ring</u>                                                             | <u>-</u>                | <u>6</u>                  | <u>8</u>                  | <u>2</u>                     | <u>16</u>                        | <u>4.2%</u>                         | <u>40, 53, 55</u>                                    |
| <u>External devices</u>                                                                 | <u>10</u>               | <u>7</u>                  | <u>1</u>                  | <u>-</u>                     | <u>18</u>                        | <u>4.7%</u>                         | <u>27, 32, 40, 47, 53, 55, 60, 63, 64, 78, 81</u>    |
| <u>Not</u>                                                                              | <u>40</u>               | <u>9</u>                  | <u>-</u>                  | <u>2</u>                     | <u>51</u>                        | <u>13.4%</u>                        |                                                      |
| <u>Total</u>                                                                            | <u>304</u>              | <u>41</u>                 | <u>29</u>                 | <u>6</u>                     | <u>380</u>                       | <u>100%</u>                         | <u>N/A</u>                                           |
| <u>NOTE—Some respondents reported more than one failed component per motor failure.</u> |                         |                           |                           |                              |                                  |                                     |                                                      |

\* Denotes protections applied for various failure detection.

[The following subclauses discuss the protection applied for various components and fault and abnormal operating conditions.](#)

## 5.1 Pullout and stall protection

### 5.1.1 Induction-motor stalling

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

### 5.1.2 Synchronous motor loss of synchronism (pullout)

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

- a) Excessive load is applied to the shaft
- b) The supply voltage is reduced excessively
- c) 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.