



IEEE Guide for Rewind of Synchronous Generators, 50 Hz and 60 Hz, Rated 1 MVA and Above

IEEE Power and Energy Society

Developed by the
Electric Machinery Committee

IEEE Std 1665™-2024
(Revision of IEEE Std 1665-2009)

STANDARDS

IEEE Guide for the Rewind of Synchronous Generators, 50 Hz and 60 Hz, Rated 1 MVA and Above

Developed by the

Electric Machinery Committee
of the
IEEE Power and Energy Society

Approved 6 June 2024

IEEE SA Standards Board

Abstract: 50 Hz or 60 Hz synchronous generators driven by diesel engines, steam turbines, combustion gas turbines, and hydro-turbines are covered in this guide. The drive may be direct or through a gearbox or other device that permits different speeds for the prime mover and the generator. The guide generally applies to the stator and rotor of generators with rated outputs of 1 MVA and above. The guide does not address machine auxiliaries or the excitation system.

This guide will provide the generator Owner with insight into the considerations that are necessary when rewinding or refurbishing a generator. Emphasis is placed on the complete rewind of the stator and rotor.

Keywords: cylindrical-pole rotor, IEEE 1665™, insulation, rotor rewind, salient-pole rotor, stator rewind, synchronous generator

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

Copyright © 2025 by The Institute of Electrical and Electronics Engineers, Inc.
All rights reserved. Published 6 February 2025. 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 979-8-8557-1139-4 STD27265
Print: ISBN 979-8-8557-1140-0 STDPD27265

IEEE prohibits discrimination, harassment, and bullying.

For more information, visit <https://www.ieee.org/about/corporate/governance/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.

Important Notices and Disclaimers Concerning IEEE Standards Documents

IEEE Standards documents are made available for use subject to important notices and legal disclaimers. These notices and disclaimers, or a reference to this page (<https://standards.ieee.org/ipr/disclaimers.html>), appear in all IEEE standards and may be found under the heading “Important Notices and Disclaimers Concerning IEEE Standards Documents.”

Notice and Disclaimer of Liability Concerning the Use of IEEE Standards Documents

IEEE Standards documents are developed within IEEE Societies and subcommittees of IEEE Standards Association (IEEE SA) Board of Governors. IEEE develops its standards through an accredited consensus development process, which brings together volunteers representing varied viewpoints and interests to achieve the final product. IEEE standards are documents developed by volunteers with scientific, academic, and industry-based expertise in technical working groups. Volunteers involved in technical working groups are not necessarily members of IEEE or IEEE SA and participate without compensation from IEEE. 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.

IEEE makes no warranties or representations concerning its standards, and expressly disclaims all warranties, express or implied, concerning all standards, including but not limited to the warranties of merchantability, fitness for a particular purpose and non-infringement. IEEE Standards documents do not guarantee safety, security, health, or environmental protection, or compliance with law, or guarantee against interference with or from other devices or networks. In addition, IEEE does not warrant or represent that the use of the material contained in its standards is free from patent infringement. IEEE Standards documents are supplied “AS IS” and “WITH ALL FAULTS.”

Use of an IEEE standard is wholly voluntary. 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.

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 their 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.

IN NO EVENT SHALL IEEE BE LIABLE FOR ANY DIRECT, INDIRECT, INCIDENTAL, SPECIAL, EXEMPLARY, OR CONSEQUENTIAL DAMAGES (INCLUDING, BUT NOT LIMITED TO: THE NEED TO PROCURE SUBSTITUTE GOODS OR SERVICES; LOSS OF USE, DATA, OR PROFITS; OR BUSINESS INTERRUPTION) HOWEVER CAUSED AND ON ANY THEORY OF LIABILITY, WHETHER IN CONTRACT, STRICT LIABILITY, OR TORT (INCLUDING NEGLIGENCE OR OTHERWISE) ARISING IN ANY WAY OUT OF THE PUBLICATION, USE OF, OR RELIANCE UPON ANY STANDARD, EVEN IF ADVISED OF THE POSSIBILITY OF SUCH DAMAGE AND REGARDLESS OF WHETHER SUCH DAMAGE WAS FORESEEABLE.

Translations

The IEEE consensus balloting process involves the review of documents in English only. In the event that an IEEE standard is translated, only the English language version published by IEEE is the approved IEEE standard.

Use by artificial intelligence systems

In no event shall material in any IEEE Standards documents be used for the purpose of creating, training, enhancing, developing, maintaining, or contributing to any artificial intelligence systems without the express, written consent of IEEE SA in advance. “Artificial intelligence” refers to any software, application, or other system that uses artificial intelligence, machine learning, or similar technologies, to analyze, train, process, or generate content. Requests for consent can be submitted using the Contact Us form.

Official statements

A statement, written or oral, that is not processed in accordance with the IEEE SA Standards Board Operations Manual is not, and shall not be considered or inferred to be, the official position of IEEE or any of its committees and shall not be considered to be, or be relied upon as, a formal position of IEEE or IEEE SA. At lectures, symposia, seminars, or educational courses, an individual presenting information on IEEE standards shall make it clear that the presenter’s views should be considered the personal views of that individual rather than the formal position of IEEE, IEEE SA, the Standards Committee, or the Working Group. Statements made by volunteers may not represent the formal position of their employer(s) or affiliation(s). News releases about IEEE standards issued by entities other than IEEE SA should be considered the view of the entity issuing the release rather than the formal position of IEEE or IEEE SA.

Comments on standards

Comments for revision of IEEE Standards documents are welcome from any interested party, regardless of membership affiliation with IEEE or IEEE SA. However, **IEEE does not provide interpretations, 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 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 subcommittees of the IEEE SA Board of Governors are not able to provide an instant response to comments or questions, except in those cases where the matter has previously been addressed. For the same reason, IEEE does not respond to interpretation requests. Any person who would like to participate in evaluating comments or revisions to an IEEE standard is welcome to join the relevant IEEE SA working group. You can indicate interest in a working group using the Interests tab in the Manage Profile & Interests area of the [IEEE SA myProject system](#).¹ An IEEE Account is needed to access the application.

Comments on standards should be submitted using the [Contact Us](#) form.²

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 constitute compliance to any applicable

¹ Available at: <https://development.standards.ieee.org/myproject-web/public/view.html#landing>.

² Available at: <https://standards.ieee.org/about/contact/>.

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.

Data privacy

Users of IEEE Standards documents should evaluate the standards for considerations of data privacy and data ownership in the context of assessing and using the standards in compliance with applicable laws and regulations.

Copyrights

IEEE draft and approved standards are copyrighted by IEEE under U.S. and international copyright laws. They are made available by IEEE and are adopted 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 these documents available for use and adoption by public authorities and private users, neither IEEE nor its licensors waive any rights in copyright to the documents.

Photocopies

Subject to payment of the appropriate licensing fees, IEEE will grant users a limited, non-exclusive license to photocopy portions of any individual standard for company or organizational internal use or individual, non-commercial use only. To arrange for payment of licensing fees, please contact Copyright Clearance Center, Customer Service, 222 Rosewood Drive, Danvers, MA 01923 USA; +1 978 750 8400; <https://www.copyright.com/>. Permission to photocopy portions of any individual standard for educational classroom use can also be obtained through the Copyright Clearance Center.

Updating of IEEE Standards 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.

Every IEEE standard is subjected to review at least every 10 years. When a document is more than 10 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 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 [IEEE Xplore](#) or [contact IEEE](#).³ For more information about the IEEE SA or IEEE's standards development process, visit the IEEE SA Website.

Errata

Errata, if any, for all IEEE standards can be accessed on the [IEEE SA Website](#).⁴ Search for standard number and year of approval to access the web page of the published standard. Errata links are located

³ Available at: <https://ieeexplore.ieee.org/browse/standards/collection/ieee>.

⁴ Available at: <https://standards.ieee.org/standard/index.html>.

under the Additional Resources Details section. Errata are also available in [IEEE Xplore](#). Users are encouraged to periodically check for errata.

Patents

IEEE standards are developed in compliance with the [IEEE SA Patent Policy](#).⁵

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 <https://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.

IMPORTANT NOTICE

Technologies, application of technologies, and recommended procedures in various industries evolve over time. The IEEE standards development process allows participants to review developments in industries, technologies, and practices, and to determine what, if any, updates should be made to the IEEE standard. During this evolution, the technologies and recommendations in IEEE standards may be implemented in ways not foreseen during the standard's development. In developing any safety recommendations, IEEE standards development activities consider research and information presented to the standards development group. Other information about safety practices, changes in technology or technology implementation, or impact by peripheral systems also may be pertinent to safety considerations during implementation of the standard. Implementers and users of IEEE Standards documents are responsible for determining and complying with all appropriate safety, security, environmental, health, data privacy, and interference protection practices and all applicable laws and regulations.

⁵ Available at: <https://standards.ieee.org/about/sasb/patcom/materials.html>.

Participants

At the time this IEEE guide was completed, the Generator Subcommittee/Generator Rewind Working Group had the following membership:

Rob Messel, *Chair*
Marc Zeidman, *Vice Chair*
Jim Lau, *Secretary*

William G. Bloethe
Stefano Bomben
Edson Bortoni
Andrew Brown
Derek Brown
Kay Chen
William Chen
Danila Chernetsov
Douglas Conley
Scott Cotner
Terra Donley
Robert Draper
Mohammed El Kahel
Yannick Ferland
Nancy Frost
Glenn Griffin

Randall Groves
Robert Hanna
Wenli Hong
John Horak
Inna Kremza
Lucas Kunz
James Lau
Joshua Lengwati
Benjamin Mancuso
Robert Messel
Bill Moore
Glenn Mottershead
Nils Nilsson
Krzysztof Pyc
John Ready

John Roach
Emad Sharifi-Ghazvini
Shannon Sitler
Nick Stranges
Marcus Sun
Roberto Teixeira Siniscalchi
Robert Thornton-Jones
Wayne Timm
Kailey Vishwinder
John Wilson
Iain Wright
Dean Yager
John Yagielski
John Yale
Marc Zeidman
Hugh Zhu

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

Blake Bailey
Thomas Bishop
William G. Bloethe
Stefano Bomben
Andrew Brown
Derek Brown
Gustavo Brunello
Koti Reddy Butukuri
William Chen
Ritwik Chowdhury
Douglas Conley
Scott Cotner
Gary Donner
Jorge Fernandez Daher
Rostyslaw Fostiak
Carl Fredericks
Nancy Frost

Shubhanker Garg
Glenn Griffin
J. Travis Griffith
Keith Grzegorzcyk
Paul Hamer
Werner Hoelzl
Wenli Hong
Lucas Kunz
Mikhail Lagoda
James Lau
Joshua Lengwati
Lawrence Long
Kevin Mayor
Robert Messel
James Michalec
Sivaraman P

Lorraine Padden
Eli Pajuelo
Howard Penrose
Ryandi Ryandi
Bartien Sayogo
Ashfak Shaikh
Shannon Sitler
Gary Smullin
Nick Stranges
Wayne Timm
John Vergis
Iain Wright
Dean Yager
John Yagielski
John Yale
Marc Zeidman
Hugh Zhu

When the IEEE SA Standards Board approved this guide on 6 June 2024, it had the following membership:

David J. Law, *Chair*
Jon Walter Rosdahl, *Vice Chair*
Gary Hoffman, *Past Chair*
Alpesh Shah, *Secretary*

Sara R. Biyabani
Ted Burse
Stephen Dukes
Doug Edwards
J. Travis Griffith
Guido R. Hiertz
Ronald W. Hotchkiss

Hao Hu
Yousef Kimiagar
Joseph L. Koepfinger*
Howard Li
Xiaohui Liu
John Haiying Lu
Kevin W. Lu
Hiroshi Mano

Paul Nikolich
Robby Robson
Lei Wang
F. Keith Waters
Sha Wei
Philip B. Winston
Don Wright

*Member Emeritus

Introduction

This introduction is not part of IEEE Std 1665-2024, IEEE Guide for the Rewind of Synchronous Generators, 50 Hz and 60 Hz, Rated 1 MVA and Above.

Note that the photographs in this guide are in color. If the guide is to be printed, consider printing in color for the full benefits of the details in the photos. Color photos in this document are on page numbers 32, 33, 36, 37, 38, 69, 72, 73, and 86.

At the turn of the 21st century, many of the generators used by electric utilities and industrial plants had reached their design life. Because of today's economics, many of these generators may be called upon to supply reliable service for an additional 20 to 30 years or more. Any generator Owner intending to significantly extend the life of the generating plant by rewinding and refurbishing the generator should address three key areas: economics, developing a technical specification, and performance upgrades through better materials/design.

A comprehensive economic study should be carried out (for the plant as well as the generator) before significant resources are invested. This should include plant load forecasts, reserve margins, new capacity plans, cost-benefit analyses, operating costs, capital costs, and continued reliability/availability.

Once a financial decision has been made to rewind, it is essential that a technical specification be developed. The technical specification should establish a clear understanding between the Owner and the Vendor, with regard to what the final product will be. Doing so creates an understanding of the level of performance and reliability expected by the Owner/Customer and what is required in the manufacturing process to achieve it. In addition, to help ensure a quality product is achieved, specific tests, measurements and inspections that are to be required in the manufacturing process need to be clearly spelled out. The technical specification is a means for these requirements and expectations to be stated.

New materials, major component replacement, and other design changes may also affect the life extension decision. For example, the industry has been developing better insulation systems for many years. Upgrading the nameplate output with these new materials may make rewind and refurbishment cost-effective.

Throughout this guide, the term "generator" has been used instead of "rotating machinery " to simplify the text. Many of the items contained herein are also appropriate for large synchronous motors and synchronous condensers. However, this guide does not address machine auxiliaries or the excitation system, nor does it address the generators found in modern wind turbines. The reader is directed to the latest version of the IEEE Std 421™ series of standards for excitation systems.

The intent of this guide is to help the Owner understand and address all the aspects involved in the process of rewinding a synchronous generator. To help achieve this goal, this guide is written in sequential order and is intended to be read and used in that same order as related to the applicable potential work scope (i.e., rotor sections only for rotor rewind). Many later chapters assume that the relative information in previous chapters has been read and applied and is not reproduced to keep the guide at a reasonable size. The intent of this statement is to discourage readers from going to just the chapter with the sample specification and missing some of the earlier discussions and information that is relevant to the topic but not duplicated in these later chapters.

Acknowledgments

Grateful acknowledgments for the use of short-circuit ratio (SCR) in 3.1 reprinted with permission from the International Electrotechnical Commission (IEC), IEC 60050-411-50-21.

Grateful acknowledgments for the following figures reprinted with permission as noted:

Figure 1 through Figure 4 from Bill Moore
Figure 5 through Figure 9 from Stefano Bomben
Figure C.1 and Figure C.2 from Scott Cotner
Figure C.3 from Dean Yager
Figure C.4 from Francois Panfili

Contents

1. Overview	14
1.1 Scope	14
1.2 Purpose	14
1.3 Word usage.....	14
1.4 Cautions.....	15
2. Normative references.....	15
3. Definitions, acronyms, and abbreviations	16
3.1 Definitions	16
3.2 Special terms.....	17
3.3 Acronyms and abbreviations	17
4. General issues, strategies, and objectives for rewinding	17
4.1 General	17
4.2 Future operating modes	18
4.3 Reliability issues.....	18
4.4 Competitive bidding	19
4.5 Generator capability issues	20
5. Generator stator winding considerations	22
5.1 General	22
5.2 Winding design considerations.....	22
5.3 Stator coil/bar construction.....	22
5.4 Winding groundwall insulation	23
5.5 Stator coil/bar testing.....	25
5.6 Stator coil/bar fit.....	25
5.7 Generator end winding and connection rings support	25
5.8 Slot support systems	27
5.9 Series/phase electrical connections and insulation	28
6. Generator rotor considerations	28
6.1 Cylindrical rotors.....	28
6.2 Salient-pole rotors.....	33
7. Writing the technical specification	39
7.1 General	39
7.2 Objective.....	39
7.3 Project description	39
7.4 Definitions	40
7.5 Scope	40
7.6 Work conditions	40
7.7 Foreign material exclusion	41
7.8 Deliverables	41
7.9 Commercial issues	41
7.10 Attachments	41
8. Testing	41
8.1 General	41
8.2 Stator core.....	42
8.3 Stator winding.....	44
8.4 Rotor winding.....	47
8.5 Performance tests.....	52

Annex A (informative) Bibliography	53
Annex B (informative) Glossary of commonly used generator terms	56
Annex C (informative) Generator components and auxiliaries	66
C.1 Stator frame and core [turbo-generators]	66
C.2 Stator frame and core [hydro-generators]	67
C.3 Generator monitoring instrumentation	74
Annex D (informative) Stator rewind information	78
D.1 Winding construction.....	78
D.2 Stator winding insulation	78
D.3 End winding support (for hydro-generators)	83
D.4 Stator slot support systems	83
D.5 Vibration concerns.....	84
Annex E (informative) Cylindrical rotor rewind information	85
E.1 Rotor forgings	85
E.2 Rotor winding.....	87
Annex F (informative) Salient-pole rotor rewind information	93
F.1 Shaft	93
F.2 Rotor construction	93
F.3 Rotor windings	94
F.4 Rotor electrical connections	95
F.5 Rotor spider and rim cleaning	95
Annex G (informative) Information typically supplied in a specification by Owner or Vendor for a generator rewind.....	98
Annex H (informative) Typical preparations for a rewind specification.....	103
H.1 General.....	103
H.2 Stator rewind.....	104
H.3 Rotor rewind	106
Annex I (informative) Typical stator rewind specification for turbo-generators.....	108
I.1 Description of the project.....	108
I.2 Owner's responsibility (as required)	111
I.3 Requirements.....	111
Annex J (informative) Typical rotor rewind specification for turbo-generators.....	115
J.1 Description of the project.....	115
J.2 Scope of work and supplies.....	117
J.3 Supplemental work conditions	120
J.4 Job progress	121
J.5 Deliverables	121
J.6 Commercial.....	122
J.7 Attachments	122
Annex K (informative) Typical stator rewind specification for hydro-generators	123
K.1 Description of the project	123
K.2 General requirements.....	126
K.3 Material requirements.....	128
K.4 Required information.....	129
K.5 Tests.....	129

K.6 Warranty	130
Annex L (informative) Typical rotor rewind specification for hydro-generators.....	131
L.1 Description of the project.....	131
L.2 Rotor rim/spider cleaning.....	133
L.3 Material requirements and workmanship	133
L.4 Testing.....	134
L.5 Required information	134
L.6 Shipping	134
L.7 Warranty.....	134
Annex M (informative) Prototype and production run testing of stator coils/bars for hydro-generators	135
M.1 General.....	135
M.2 Stator coil/bar prototype testing.....	135
M.3 Stator coil/bar production testing	136
M.4 Testing information.....	137
M.5 Change of manufacturing location during coil/bar production run	139
Annex N (informative) Prototype and production run testing of field coils for hydro-generators	140
N.1 General.....	140
N.2 Technical requirements and considerations	141
N.3 Rotor pole rehabilitation process overview	141
N.4 Materials	142
N.5 Factory electrical tests	143
N.6 Field testing and acceptance	144
N.7 Spare field pole coils	145
N.8 Documentation requirements	145

IEEE Guide for the Rewind of Synchronous Generators, 50 Hz and 60 Hz, Rated 1 MVA and Above

1. Overview

1.1 Scope

The general parameters for this guide apply to 50 Hz or 60 Hz synchronous generators driven by reciprocating engines, steam turbines, combustion turbines, and hydro-turbines. The guide generally applies to the stator and rotor of generators with rated outputs of 1 MVA and above. The guide does not address machine auxiliaries or the excitation system.

1.2 Purpose

This guide will provide the generator Owner with insight into the considerations that are necessary when rewinding or refurbishing a generator. Emphasis is placed on the complete rewind of each of the components of the stator and rotor.

1.3 Word usage

The word *shall* indicates mandatory requirements strictly to be followed in order to conform to the standard and from which no deviation is permitted (*shall* equals *is required to*).^{6,7}

The word *should* indicates that among several possibilities one is recommended as particularly suitable, without mentioning or excluding others; or that a certain course of action is preferred but not necessarily required (*should* equals *is recommended that*).

The word *may* is used to indicate a course of action permissible within the limits of the standard (*may* equals *is permitted to*).

The word *can* is used for statements of possibility and capability, whether material, physical, or causal (*can* equals *is able to*).

⁶ The use of the word *must* is deprecated and cannot be used when stating mandatory requirements, *must* is used only to describe unavoidable situations.

⁷ The use of *will* is deprecated and cannot be used when stating mandatory requirements, *will* is only used in statements of fact.

1.4 Cautions

CAUTION: HAZARDOUS MATERIAL WARNING

On some generators there may be hazardous materials such as asbestos, lead carbonate, or lead paint. As an example, many Vendors used asbestos in the stator or rotor insulation system. Some hydrogen-cooled units may contain lead carbonate. The presence of lead carbonate is due to a reaction of the water, carbon dioxide, and lead in the solder used to manufacture the coolers. In such cases, abatement work, cleaning, and disposal of hazardous materials shall be performed according to appropriate government regulations. The Vendor should provide the safety data sheets (SDS) for all materials used on-site for a rewind. Excess material brought in by the Vendor should be removed by the Vendor at the completion of the rewind. However, on most projects, the Owner is responsible for the removal of hazardous materials.

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.

IEEE Std 43™, IEEE Recommended Practice for Testing Insulation Resistance of Electric Machinery. ^{8,9}

IEEE Std 95™, IEEE Recommended Practice for Insulation Testing of AC Electric Machinery (2300 V and Above) with High Direct Voltage.

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

IEEE Std 286™, IEEE Recommended Practice for Measurement of Power Factor Tip-Up of Electric Machinery Stator Coil Insulation.

IEEE Std 522™, IEEE Guide for Testing Turn Insulation of Form-Wound Stator Coils for Alternating-Current Electric Machines.

IEEE Std 1434™, IEEE Guide for the Measurement of Partial Discharges in AC Electric Machinery.

IEEE Std 1799™, IEEE Recommended Practice for Quality Control Testing of External Discharges on Stator Coils, Bars, and Windings.

IEEE Std C37.102™, IEEE Guide for AC Generator Protection.

IEEE Std C50.12™, IEEE Standard for Salient-Pole 50 Hz and 60 Hz Synchronous Generators and Generator/Motors for Hydraulic Turbine Applications Rated 5 MVA and Above.

IEEE Std C50.13™, IEEE Standard for Cylindrical-Rotor 50 Hz and 60 Hz, Synchronous Generators Rated 10 MVA and Above.

IEC 60034-1, Rotating Electrical Machines – Part 1: Rating and Performance.

⁸ The IEEE standards or products referred to in this clause are trademarks of the Institute of Electrical and Electronics Engineers, Inc.

⁹ IEEE publications are available from the Institute of Electrical and Electronics Engineers, 445 Hoes Lane, Piscataway, NJ 08854, USA (<http://standards.ieee.org>).

IEC 60034-32, Rotating Electrical Machines – Part 32: Measurement of Stator End-Winding Vibration at Form-Wound Windings.

3. Definitions, acronyms, and abbreviations

3.1 Definitions

For the purposes of this document, the following terms and definitions apply. The *IEEE Standards Dictionary Online*¹⁰ and the glossary in Annex B should be referenced for terms not defined in this clause. Note that Annex B contains a practical glossary of commonly used terminology for generators. The Annex B glossary is included in this guide as an informative annex for information only and is not an official part of the guide.

bar: In electric machinery, the terms “bar” and “coil” are not interchangeable. A bar is considered to be half coil, typically of a single turn (conductor). Two bars are assembled to form a full coil.

bonding: The term “bonding,” with respect to electrical insulation, refers to a physical bonding, or structural uniting between two physical materials.

hydro-generator: The term hydro-generator refers to a synchronous ac generator, typically having salient-pole rotors, and driven by a hydraulic turbine or waterwheel. (Also known as a hydro-electric generator.)

interlaminar insulation: The stator core is made up of many thin sheets of electrical grade steel (laminations), and interlaminar insulation is used to insulate the sheets from one another, to reduce eddy current losses between the laminations.

mil: One thousandth of an inch.

re-insulation: The partial or total removal and replacement of all of the generator’s winding(s) insulation. The winding insulation comprises all of the insulating materials that envelope the current-carrying conductors and their components. Winding insulation separates the conductors from each other and/or from the grounded components of the generator. Insulating materials typically include armor tape, tying cord, slot fillers, slot groundwall insulation, support ring insulation, pole body insulation, and rotor-retaining ring insulation.

rewind: The disconnection and removal of the generator stator winding, support systems, and temperature monitoring detectors for the purpose of replacing this assembly, in all or part, with new. On rotors, rewind means the removal of the winding and replacement of all insulating materials and, in some cases, the copper of the coils.

Roebel bar: Stator bars manufactured with Roebel transpositions of the copper strands.

short-circuit ratio (SCR): The ratio of the field current for rated armature voltage on open circuit to the field current for rated armature current on sustained symmetrical short-circuit, both with machine running at rated speed.

strand insulation: The stator coil/bar conductor is made up of multiple strands. Strand insulation is applied to insulate the strands from one another, in order to reduce eddy current loss effects.

turn insulation: On multi-turn coils, the strand insulation may not be sufficient to withstand the turn-to-turn voltage stress. Additional insulation tape is often applied to the turns by hand or machine to give adequate strength to withstand the voltage stress of normal service and the impulse voltages of abnormal events. This insulation also serves as part of the groundwall insulation.

Insulation between turns to withstand voltage surges in multi-turn coils or bars.

¹⁰*IEEE Standards Dictionary Online* is available at: <http://dictionary.ieee.org>. An IEEE Account is required for access to the dictionary, and one can be created at no charge on the dictionary sign-in page.

3.2 Special terms

In this guide, the following special terms and definitions apply.

Bidder: Throughout this guide the terms “Bidder” and “Bidders” have been used to represent the potential Vendor that is bidding on the generator rewind work. The Vendor could be an original equipment manufacturer (OEM), or an independent repair firm.

Customer: See Owner

Owner: Throughout this guide the terms “Owner” and “Owners” have been used to represent the generator Owner/operator/user. It is typically a utility, a municipality, or an industrial firm.

Supplier: Throughout this guide the term “Supplier” and “Suppliers” have been used to represent the company from which the materials and components are sourced. This could be an original equipment manufacturer (OEM), or an independent company.

Vendor: Throughout this guide the terms “Vendor” and “Vendors” have been used to represent the company that will conduct the generator rewind. This could be an original equipment manufacturer (OEM), or an independent repair firm.

3.3 Acronyms and abbreviations

ETPC	electrolytic tough pitch copper
FME	foreign material exclusion
SDS	safety data sheets
NDE	non-destructive examination
OEM	original equipment manufacturer
OFC	oxygen-free copper
OFHC	oxygen free, high conductivity
PD	partial discharge
RF	radio frequency
RTD	resistance temperature detector
TC	thermocouple
VPI	vacuum pressure impregnation

4. General issues, strategies, and objectives for rewinding

4.1 General

Many of the generators used by electric utilities and industrial plants have reached the end of their design life. Because of today’s economics, many of these generators may be called upon to supply reliable service for an additional twenty to thirty years or more. In some cases, these old generators are being uprated in order to deliver the additional power of a turbine rating increase. This guide provides the generator Owner with some insight into the many technical issues that are involved when rewinding or refurbishing a generator with or without considering an uprate.

4.2 Future operating modes

There are several different operating modes for the aging generator, which can depend on the prime mover constraints, the economics of load dispatching, and other technical and economic factors. These operating modes include base loading, load following, load cycling, peaking, operating as a synchronous condenser, and, in the case of pumped storage units, switching between generating and motoring in short periods of time. A change in operating mode can occur as newer machines displace older machines in the dispatching order. It is not uncommon, for example, for a generator to be base loaded when new and then later become load-following or load cycling when older. Any of the latter operating modes are more stressful to the windings than base loading. Therefore, any change of operating mode should be accounted for in the requirements specified for a rewind. Frequently, a generator nearing the end of winding life is put into a last-on, first-off mode of operation to extend life until a rewind can take place.

4.3 Reliability issues

Advancements in the area of insulating materials and composites allow significant reliability improvements to be achieved by replacing older materials in the generator that are near the end of their operational life. In addition to replacing the generator windings with new insulation systems, significant enhancements can be obtained by upgrading the design of the winding support systems or by improving the cooling arrangement of the generator rotor. For example, the stator slot wedging system can be upgraded to a modern wedge and slot packing design, thus reducing the potential for damage due to winding movement in the slot.

If the Owner is looking to upgrade the generator's output, and/or increase efficiency, the designer may often take advantage of the improvements in withstand voltage of modern dielectrics by placing more stress on these dielectrics. This means that reliability is not always increased. There is a trade-off with capability and efficiency. In some cases, a winding may continue to operate with strand-to-strand shorts, but not with turn-to-turn faults. In multi-turn coils, each conductor (i.e., bundle of strands), should be properly insulated to help prevent short circuits between adjacent turns. Failure of the turn-to-turn insulation will rapidly cause machine failure because high currents will circulate between the shorted turns, resulting in arcing and very high temperature at the location of the shorted turn(s). The turn-to-turn fault arcing will quickly melt the copper strands. The heat will quickly destroy the groundwall insulation. In this light, on multi-turn coils, one might want to evaluate if additional turn insulation is warranted since turn-to-turn insulation failures are quite common.

While this guide is focused on rotor and stator rewinds, it is important to consider other generator equipment and auxiliaries that should be part of any major generator rebuilding project. Some of these other items are as follows:

- Control cabinets
- Bearings and journals
- Brushes, brush rigging, and brush holders
- Excitation system
- Generator coolers
- Generator bushings
- Governors and their controls
- Hydrogen seals
- Stator core
- Stator frame
- Surge arresters and surge capacitors

The above list is only a partial list of the many generator components and appurtenances. It is only for illustration, and it neither purports to list all the generator components nor implies the importance of one component over another. Annex C contains a detailed discussion on the inspection and testing of the generator's vital components and auxiliaries. This discussion is included in this guide for information only and is not an official part of the guide.

4.4 Competitive bidding

From an Owner's perspective, a competitive bid for a generator rewind may be preferable to a single-source procurement. However, it is imperative that the Owner ascertain that all Bidders are qualified and capable of performing the required work. In a competitive bid situation, the original manufacturer may start with an advantage, because the original manufacturer should have all the dimensions and design information.

Potential Bidders need access to the machine in advance of the bids to verify that their designs can be implemented in the given machine and to achieve more precision in their bids.

Unless it is specified in the bidding document, some Bidders may limit the rewind to the replacement of the stator coils/bars, while reusing many components such as the parallel rings and end winding support systems. Obviously, the Owner can specify that all these items be replaced, but in so doing, the Owner may incur an unnecessary and possibly significant cost increase. If re-using any components is an option, the Owner's bid specification should have stringent testing and acceptance requirements, to verify that the old components are in optimum condition.

In a competitive bid situation, the outage duration, rather than the bottom-line cost, may be the deciding factor in selecting a rewind Vendor. In recent years, there have been major improvements in tooling and techniques that have produced a significant reduction in the time needed to rewind a unit. If one Bidder's previous rewind experience is 45 days, and another is 30 days, the shorter duration of the outage can have economic advantages. Owners may impose bonus and penalty clauses in the contract for timely outage completion, but this may place significant and possibly detrimental pressure upon the field crew that does the work.

It can become economically advantageous to purchase a spare core and frame so all rewinds in a multi-unit plant can be performed elsewhere in the powerhouse, and the actual outage reduced to an integrated frame, core, and winding assembly switch-out. This is only an option if the plant overhead cranes and lifting devices are sufficient to support and move a fully assembled and/or wound stator with sufficient staging area that can physically support the weight.

Generally, Bidders do their best to interpret and tailor the equipment and installation methods that are most advantageous for the Owner. Sometimes, technical specifications may not clearly communicate what is desired leaving the Supplier to provide a bid that does not fully meet the Owner's desires. If information such as efficiency evaluation (\$/kW), output evaluation (\$/kW) and outage evaluation (\$/outage day) is available, Suppliers can more clearly interpret what is of value to the Owner, and likely the portfolio of bids received will more closely meet the most important factors. For example, options like procurement of a new core and stator, as discussed in the previous paragraphs in this subclause, are often avoided due to the known higher costs and without a \$/day measurement Suppliers cannot determine themselves if the economics associated are worth the customer's interest.

The Owner should have a bid specification that helps ensure all Bidders are meeting the same technical requirements. In addition, the Owner should devise an evaluation process that compares the benefits of design improvements and outage duration and other considerations important to the Owner. Specific knowledge of the equipment is essential, and this standard may not provide that information.

4.5 Generator capability issues

There are many reasons why an Owner may need a generator rewind. A failure may have occurred; or the insulation may be in poor condition and near the end of its useful life. Quite often in these cases, the Owner will elect to retain the same original generator design capacity or capability.

Modern insulating materials provide an opportunity to design and manufacture coils/bars with thinner groundwall insulation. This has two advantages: a) the thermal resistance of the groundwall is reduced because of thinner material; and b) potential electrical upgrade, due to the thinner material, which allows more copper to be included in the winding. However, thinner groundwall designs may result in higher partial discharge (PD) energy levels, which may reduce the winding life expectancy. Of course, the opportunity will vary depending on the vintage and type of the original machine design. But this opportunity can create the erroneous impression that the complete machine has greater capability than before the rewind, simply because there is more copper. An increase in stator winding capability may not translate into a higher machine output until the other components of the machine are evaluated for operation at higher outputs than the original design rating. To avoid new source performance requirement issues, it may be preferred that Bidders describe the benefits of additional conductor material in terms of lower operating temperature and longer reliable life of the winding. The old resistance temperature detector (RTD) temperatures cannot be used for margin increases in rating, as the thinner insulation will show higher temperatures. The possible increase in rating has to be calculated by a design engineer.

4.5.1 Upgraded stator windings

When additional generator capability is desired (such as in the case of a concurrent turbine efficiency upgrade), there are many more issues to be considered. Will the improved insulation system operate at an MVA level that is consistent with the reactive needs of the power system? With no changes to the rotor or excitation system, the machine may operate at a higher power factor (closer to unity) and thus will produce less reactive power (MVARs) at higher real power (MW) levels.

When rewinding a stator there may be an opportunity to improve the temperature class of the insulation system. Older generators were equipped with windings typically having Class 130 (Class B) insulation. A typical replacement winding today will have Class 155 (F) insulation that can operate continuously at higher temperature. However, if the machine was originally designed to operate at Class 130 (B) temperatures, there could be mechanical issues associated with an uprate to Class 155 (F). For example, the risk of stator core buckling should be evaluated. Also, the allowable hotter stator temperature may have a negative impact on the rotor winding insulation and the stator core lamination insulation. Therefore, it is quite common today for a rewind specification to call for the modern Class 155 (F) insulation, but to operate within the Class 130 (B) temperature range.

Providing a stator winding with increased thermal capability does not allow an adjustment of the capability curve without completing further study of all other components such as mechanical shaft capability, rotor capability, and regulatory rules. If a generator uprate is required, it is best for the Owner to complete a full study and inform the Bidders the desired rating so that a winding design can be formulated.

In addition to stator and rotor windings, there are other related electrical components and systems that should also be evaluated to determine if they can operate in concert with an upgraded stator. Examples include the following:

- a) Prime mover capability
- b) Generator bushings (current rating)
- c) Generator current transformers (current rating)
- d) Generator step-up transformers (MVA rating)
- e) Generator isolated phase-bus-duct (current rating)
- f) Generator switchgear or circuit breaker (current rating)

- g) Generator neutral equipment (current rating and protection coordination)
- h) Powerhouse grounding network (current rating)
- i) Auxiliary equipment—reactor, bus bars, cables, switchgear and circuit breakers (current rating)
- j) Protective systems (coordination, limiter, alarm, and trip settings)
- k) Excitation system
- l) Penstock limitations
- m) Rotor mechanical structure, coupling, maximum speed/overspeed, torque, magnetic attraction
- n) Stator frame and core
- o) Generator collector ring ampacity (if so equipped)

NOTE—The above list is only a partial list of the many generator components and systems that should be evaluated. This list is only for illustration and does not purport to set forth all the generator hazards, nor to indicate that other issues or hazards do not exist.¹¹

Any time that a machine is being uprated, some of the components may be operated closer to their design limits. As a result, not only should protection systems be reviewed for setting changes, but also additional state of the art protection systems should be considered for application. Reference IEEE Std C37.102¹².

This is particularly true regarding the changeover from a rotating exciter to a static exciter. This is a major upgrade/redesign that may require a fault study, a shaft torsional study, and major protective relay modifications. Startup and shutdown sequences and procedures also will be impacted. A source for the static exciter and associated protection and switching should also be provided. Standard operating procedures and black start procedures will also have to be modified.

Prior to the replacement of an old rotating exciter with a static excitation system, the Owner should evaluate the existing rotor insulation's ability to withstand any field voltage surges that may be created by the new system thyristors.

Obviously, it will be necessary to work more closely with the Bidders than in the case where no change is planned in machine capability. Clause 5 offers some considerations for stator rewinds, and Annex D provides some fundamental information on stator windings.

4.5.2 Rotor rewinds or re-insulation upgrades

The rotor may be upgraded with no change in the stator capability or in concert with a stator upgrade. In either case, the goal of the rotor upgrade is usually to provide more reactive power (MVARs). Care should be taken to coordinate with other electrical and mechanical system components as described in Clause 4.5.1. One important issue that is occasionally overlooked is whether the excitation system can provide the power for the new rotor capability.

Upgrading the rotor may also be coordinated with other rotor design changes. For turbo-generators, this could include the installation of new retaining rings, made of 18% manganese and 18% chromium, (18Mn-18Cr) to replace older designs such as 18Mn-5Cr retaining rings. In addition, all rotating components should be carefully inspected and non-destructively examined (NDE), including the rotor forging. Clause 6 offers some considerations for rotor rewinds; and Annex E and Annex F provide some fundamental information on generator rotors, and rotor windings. Design changes, such as eliminating the ventilating holes in magnetic retaining rings can be included.

¹¹ Notes in text, tables, and figures of a standard are given for information only and do not contain requirements needed to implement this standard.

¹² Information on references can be found in Clause 2.

5. Generator stator winding considerations

5.1 General

There are several components in a stator winding. In this clause, important considerations relating to each of these components are discussed, with the objective of providing the basis for the information included in a stator rewind specification. Annex D contains a more detailed discussion of the construction and materials found in a generator stator. The inclusion of Annex D in this guide is for information only and is not an official part of this guide.

5.2 Winding design considerations

There are a few possibilities for the choice of the winding design. The objective of this clause is only to give short descriptions of different aspects.

During the generator planning stage, the most suitable winding configuration for the application should be selected. Two stator winding design types are commonly used in synchronous generators, either multi-turn coils or Roebel bars (single turn half-coils). If the original stator winding design was made with one design type, for example, with multi-turn coils, in some cases, to achieve the desired operational and/or output improvement(s) of the machine, it might be possible (mainly for hydro-generators) to convert the winding to the other design type (Roebel bars) and alternatively, Roebel bars to multi-turn coils.

These particular cases should be well justified in technical and economic terms. For this reason, at least (but not limited to) the following factors should be considered prior to the winding conversion:

- a) Technical: existing stator configuration (winding, core, frame), rated voltage, harmonics, armature current density, magnetic balance, winding balance, winding losses, excitation, etc.
- b) The outcome of a generator winding(s) feasibility study.
- c) Commercial: overall cost and duration of the new winding manufacturing and installation
- d) Ease of installation, maintenance, and potential repair.

The generator Owner should consult the OEM or other suitable qualified vendor to analyze the advantages and disadvantages of this aspect, particularly for a large generator.

For more information on stator winding design, see Annex D.

5.3 Stator coil/bar construction

The copper used in coil/bar construction is either electrolytic tough pitch copper (ETPC) or oxygen-free copper (OFC). Generally, oxygen-free copper is not used on air-cooled machines. The physical and electrical properties of each are essentially the same. There is a cost premium when OFC is selected over ETPC. Since OFC has no oxygen present, it is better when brazing applications are specified and the chance of hydrogen embrittlement of the copper (during torch brazing) is lessened. The copper wire (strand) is rectangular in shape and has rounded corners.

The strand insulation in all coil/bar designs should be reliable and capable of withstanding design operating temperature. Today, Class 155 (F) material is typically used. Since the voltage between individual strands is small (less than one volt), this insulation can be thin.

Direct water-cooled windings will have either 100% hollow strands or a mix of solid strands and hollow strands. The hollow strands are relatively large to allow for water passage, while the solid strands are thin

to reduce eddy-current losses. The hollow strands are typically copper, but other alloy materials are often used on some water-cooled windings to reduce corrosion problems.

Crucial considerations in stator coil/bar construction include the following:

- a) No strand or turn shorts.
- b) Adequate voltage surge-resistant turn insulation on multi-turn coils.
- c) Adequate thickness of the coil/bar groundwall to achieve designed voltage stress.
- d) Good coil/bar shape control (be of the correct geometry regarding edge radius, coil/bar shape and dimensions).
- e) Well-bonded and well-consolidated coil/bar for mechanical stability.
- f) On water-cooled bars, a strand header is brazed to the strands with a system that reduces the risk of initial leaks and no leaks develop over the life of the winding.

On higher voltage, the coils or bars are insulated with mica tape over which are applied the semiconducting slot armor paint or tape and the stress control paint or tape on the end arms. These materials should bond well to the bar to a reasonable extent to reduce voids. Generator design voltages are attained by the designer through the variation of the following physical factors: the number of winding turns in series, the length of the core, the winding pitch, the unit speed, etc.

5.4 Winding groundwall insulation

The groundwall insulation is the main high voltage electrical insulation that separates the copper conductors from the grounded stator core in generator stator windings. The groundwall insulation is designed for a steady-state phase-to-ground voltage that establishes the kV-per-mm [volts-per-mil] stress on the insulation. In the event of a ground fault (phase-to-ground), the temporary overvoltage will increase by a factor of $\sqrt{3}$ (the phase-to-phase voltage) as the neutral is isolated or connected to the ground by a very high impedance. This also reduces homopolar currents to very low values. The opposite will appear in the case of low impedances between the neutral and the ground. Low-voltage circuit breakers and associated cables between the generators and the step-up transformer can create transient overvoltages. Fortunately, generator winding groundwall insulation has very high impulse insulation strength ratings; but this is not true for turn-to-turn insulation. Thus, on multi-turn type windings, surge capacitors and arrestors are usually required.

In the rewind process, care should be taken to include an adequate safety margin for kV/mm [V/mil] to account for the potential of the phase-to-phase voltage as well as moderate transient overvoltages. The thickness of the dedicated taped turn insulation in a multi-turn coil can be added to the groundwall insulation thickness when calculating the operating electrical stress (expressed as kV/mm [V/mil]) of a coil.

Surge capacitors and arrestors are sometimes used to protect the line end turn-to-turn insulation from incoming surges. Surge capacitors were originally installed on many generators, but in the early 1980s, many of the generator manufacturers recommended the removal of capacitors on all units that were single-turn (coils or bars) and directly connected to the electrical system. Therefore, many generators today may not be equipped with surge capacitors. If the generator is equipped with the old-style silicon carbide arrestors, they should be removed and, if arresters are still needed, replaced with metal oxide arrestors.

Asphalt-impregnated windings were typically designed with voltage stress levels in the range of 1.76 kV/mm [45 V/mil], and as resin-based systems became popular stress levels were increased. Polyester-based resin systems that were initially used were increased to 2 kV/mm [51 V/mil], and later epoxy systems increased to 2.54 kV/mm [65 V/mil]. Today, there have been multiple factors leading to increased electrical field stress levels, sometimes above 3.6 kV/mm [90 V/mil]. These factors include market forces driving increased power output with smaller machines, desired improvements in efficiency, improvements in insulating materials, and a statistical trend toward low groundwall failure rates of modern

systems. Thinner groundwall insulation allows for more copper in the coil (slot), which reduces the copper losses (I^2R) and allows for better heat transfer from the copper to the cooling system. The Owner may desire to reduce the voltage stress level in modern winding groundwall insulation to theoretically extend the service life of the winding; however, with that, the Owner may observe decreased output ratings for windings with existing designs that use higher electrical stress levels. Note that an appropriate calculation of stress level should include the thickness of the insulating materials in the system only. Semi-conductive materials used to make up shields and stress-smoothing layers in the insulation should not be counted when assessing the groundwall insulation thickness for stress purposes. A discussion of historical practice and the development of insulation systems can be found in Maughan [B38] and Stone et.al.[B47].¹³

The groundwall insulation of stator windings is usually comprised of mica, glass, or organic reinforcing material, and a bonding/impregnating resin. Windings manufactured today will typically be manufactured using thermosetting epoxy resins.

Some smaller windings are made today with thermoplastic polyester resins. Generally speaking, polyester resins are relatively inexpensive and characterized by good electrical properties and good resistance to heat and mechanical impact. However, some polyester resins are sensitive to chemical reactions with moisture that can cause both electrical and mechanical degradation. While windings manufactured with polyester resins have given good operating service at moderate design demands, other more sophisticated thermosetting epoxy resins are often selected because of improved physical properties. The Owner is advised to explore the service performance records accumulated with the less expensive polyester system before using this insulation.

Groundwall insulation may be applied to the coil/bar using either of two common insulation systems: a) a “resin-rich”, with the application of resin-loaded insulation tapes, or b) vacuum pressure impregnation (VPI), where the insulation tape is dry or contains only a minimal amount of resin, or other resin catalyst agent. With the resin-rich system, all the impregnating resin is applied to the coil/bar before it is processed. The process is either a vacuum-pressure autoclave cycle, or a hot-pressing process. With the VPI insulation system, most of the impregnating resin is applied to the coil/bar after it enters a vacuum-pressure autoclave. Both systems have performed well in service.

Some generator manufacturers are using a global vacuum pressure impregnation (VPI) process in the factory for ratings up to at least 400 MW. For this method, low resin content tapes are applied to the coils/bars, which are then installed in the stator; the end windings are braced; the slot wedges installed, and windings connected; and then the entire stator core and winding assembly is subjected to the global VPI process in a large tank. Generator windings of this type are much more difficult to repair and the global VPI process cannot be repeated in the field. But regardless of the manufacturing method used, an appropriate stator winding design, high-quality materials, and careful control of the manufacturing process are essential for a satisfactory winding.

Regardless of the high voltage (typically above 4 kV) winding insulation system, all Vendors generally use slot surface semi-conductive grounding tape/paint, and an end-arm voltage grading system. Especially for Roebel-bar windings, some Vendors could propose a winding design where most of the winding overhang is treated with grading material. In this particular case, the grading material may have electrical contact with the bare copper at the ends of the bars. The Owner should be aware that with this type of stress grading system, the measurement of the winding insulation resistance and the polarization index test will have limited usefulness for the winding condition assessment during routine inspections. The Owner should determine in the technical specification whether complete stator winding overhang treated with grading material is acceptable or not.

Important considerations in the application of the groundwall insulation include the following:

- a) The bare coil/bar should be clean and of correct overall geometry, regarding shape and size.
- b) All groundwall materials should be of proven performance.

¹³ The numbers in brackets correspond to those of the bibliography in Annex A.

- c) Groundwall tape application should be in accordance with design specification.
- d) Coil processing performance on each coil/bar should be verified to comply with process specifications. (Application of temperature and pressure should be optimized.) It may be desirable to monitor the insulation capacitance to verify that proper curing has occurred.
- e) Finished coil/bar surfaces should be clean and free of contaminants.
- f) Slot-semiconducting paint or tape and end-arm-grading paint or tape should be applied to correct areas, stable mechanically and of correct resistances.
- g) On liquid-cooled windings, the strand liquid header should be free of contamination.
- h) There should be satisfactory completion of all proof tests: overpotential, power factor, partial discharge, and strand and turn testing.

5.5 Stator coil/bar testing

If the Owner desires to discuss the testing of the stator coils for prototype or production testing, a general plan is described in Annex M. Annex M. lays out a plan for stator coil/bar testing of hydro-generators. For turbo-generators, this can be used as a base plan but it is recommended to involve turbo-generator specialists in compiling an appropriate stator bar/coil test plan. The main point is a discussion between the Owner and the Vendor should occur to work out the details.

5.6 Stator coil/bar fit

There have been cases of stator coils not fitting properly in the core while in the winding process. This leads to additional outage time and costs to address the issue. For a rewind, it is highly advised that a process be implemented to check that the manufactured and tested coils will properly fit in the core with all the proper clearances. Some companies that provide rewinds build a mockup of the core at the manufacturing facility and physically check that the coils/bars will fit properly into the stator slot with all the proper clearances. An alternative method is to use a highly accurate measurement (meets the drawing tolerance for the many features of the coil/bar), which verifies its shape and fit within the winding. This is recommended to be done at the manufacturing and/or test facility before the coils/bars are sent to the site for the rewind.

Any anomalies in the coils not fitting the mock-up or design tolerances need to be addressed during the initial manufacture of coils/bars and certainly before shipping.

At installation, if anomalies in the original construction are identified that inhibit design clearances, additional discussion with the manufacturer is recommended on the best course of corrective action for proper installation of the new winding.

5.7 Generator end winding and connection rings support

The design of the end winding support and connection rings vary between manufacturers considerably in rating and speeds of the generator. The end windings should be designed to withstand very high forces associated with possible short circuits as well as vibrational forces and thermal expansion associated with normal operation. Large generators have support systems for the end winding and winding connections. Smaller generators may operate satisfactorily with designs that only rely on cord-tie support systems. Generally, ties that are reinforced with a cured resin have been found necessary on all but the smallest, low-duty machines. Some Vendors may provide other means of clamping the coils to the blocking components. If the Owner wants ties, they should be written in the technical specification. Because there are many system variations that have been found reasonably satisfactory, it is difficult to define details of end winding specifications in this document.

It is possible to rewind some generator stators while reusing the existing end winding bracing system. This introduces the issue of reusing the phase rings. Note that this is an important decision point because

handling baskets and phase rings is labor-intensive and can add several days to the schedule. In many instances, the circular rings do not have the same voltage stress as the coils in the slot. This will significantly reduce the aging of these components. This may allow the phase or connection rings to be reused, saving installation time and costs.¹⁴

Important considerations for the end winding support systems include the following:

- a) The system should be of a laboratory test and/or service-proven design.
- b) If consideration is being given to re-using the old bracing system, it should be determined that the old materials meet the new design requirements.
- c) If the system is fully cured and bonded, allowance should be made for thermal expansion of the coils/bars in the slot, when energized.
- d) All non-cured ties should be tight.
- e) Supports should keep the coils/bars firmly seated within the full length of the slot.
- f) There should be no voids between the blocks and the bars.
- g) On vertical windings, such as in vertical shaft hydro-generators, there should be a provision for restraining the downward movement of the winding and wedge system components.

Vibration forces in the end winding should be kept under control so that there is no fatigue of the copper conductors or wear of the blocking and support components. At very high levels of end winding vibration, copper fatigue can occur very quickly depending on the OEM design and needs to be mitigated appropriately. Thermal cycling and shrinkage effects can also promote advanced loosening leading to increased vibration. The electrical forcing function frequency is equal to the rotor speed (revolutions per second) times the number of poles of the rotor, which calculates to twice the line frequency. The structure should not have excitable natural frequencies near this frequency. A bump test performed according to IEC 60034-32 can be used to determine these natural frequencies. The end winding components should not have $N=2$ (four node, elliptical mode) global natural frequencies for two pole turbine generators or $N=4$ (eight node, 4 lobe) global natural frequencies for 4 pole generators near twice the line frequency.¹⁵

Local modes of end winding components may also be a concern at twice-line frequency. If the core is flexibly mounted, generally line frequency is not a concern. The OEM should be consulted for frequency exclusion zones (typically -5 Hz to $+15$ Hz from double line frequency). Adjustment of these values should take damping, thermal shift and aging into account. Winding natural frequency will decrease as the temperature increases when the unit goes into operation.

For turbine generators, a “bump” or “shaker” modal test should be performed to determine if the stator winding is susceptible to high vibration. When doing these tests, the methods described in IEC 60034-32 should be followed and proper conditions applied. It should be verified that all winding and support system blocking, and ties are fully settled, and their resin binders cured. For water cooled windings, the mass of water in the coils needs to be considered. The modal test can be done with the stator filled with water or accounted for in the frequency exclusion zone. The winding filled with water will add mass and drop the measured frequency as much as 3 Hz. This more closely matches the operating condition of the winding. Bump or shaker tests have limited applicability to stators with large numbers of poles, such as is common on hydro-generators, as there are a large number of localized response modes and frequencies. Acceptable response levels and frequency exclusion zones should be agreed upon with the Bidder, based on measured performance for the subject end-winding support system.

¹⁴ There are other factors to be considered as well. For example, non-OEM's are unlikely to have the data to pre-manufacture connection rings, so at best, for non-OEM rewinds, the connections rings can be removed, reinsulated and then re-installed. For water cooled generators, in some cases there are brazed joints in the connection rings that have some propensity to leaks. Not addressing this issue during the rewind may result in an unwanted leak later.

¹⁵ Note that some refer to the elliptical mode for two-pole generators as $N=2$, and $N=4$ for four-pole generators.

Vibration monitoring of the end windings may be an important option if recommended for larger turbo-generators, or any generator that is observed to have high end winding vibration, evidenced by dusting, greasing, and insulation abrasion. The primary function of online vibration monitoring equipment is to track changes in vibration over time to allow predictive maintenance. Some OEM's may set absolute limits on the vibration. This can be a function of end winding design features or location of the sensors. Fiber optic sensors that can be mounted on high-voltage components are preferred and should be placed on coil ends, phase leads or main leads to provide the most sensitivity.

Different OEM's have different philosophies for where to place end winding vibration sensors and acceptable limits (radial or tangential) based on the sensor locations and Vendors specific design. It is easy to see that vibration sensors placed on coils near the end of a stator core will normally see much lower values than vibration sensors placed on the stator coils farther away from the core. Normal values of vibration sensors placed on coils near the end of the core can be 50 μm to 75 μm [2 mils to 3 mils] p-p displacement where sensors placed on the end of the stator coils farthest from the core can be 75 – 254 μm [3 mils to 10 mils] p-p displacement.

The limits of acceptable vibration levels for the end-winding support system, based on in-service performance, should be agreed upon with the Vendor.

5.8 Slot support systems

Numerous types of slot wedging (support) systems have been used on generators. On smaller generators, a flat wedge with slot fillers to apply pressure on the coil/bar has been found satisfactory, if properly assembled. On larger units, currently, most manufacturers use proven systems based on a radial spring, compressed (as prescribed by the Supplier) with either flat wedges or some variation of a “piggyback” tapered double-wedge system. This spring will help prevent the rebound of a coil/bar off the bottom of the slot and reduces the possibility of vibration if the coil/bar is bottomed in the slot. Some manufacturers include arrangements for measuring the amount of ripple remaining in the radial spring. For higher voltage machines, some sort of side packing is typically used. Side ripple springs are a common method for assuring pressure. Hard-side packing or conformable slot support systems, often based on silicone rubber or other elastomers, are sometimes used as an alternative to side ripple springs. All of these systems can adequately support the coils/bars in the slot if they are properly installed and oil is not allowed into the machine. Oil contamination will result in a reduction of the coefficient of friction between the groundwall and side ripple springs. As a result, coil movement occurs, as well as abrasion of the groundwall insulation. Liquid-cooled coils should be supported by conformable layers at the bottom of the slot to dampen and help prevent internal strand cracking. Regardless of the type of slot support system, the windings should be carefully fitted to the stator slot in order to provide proper contact for the slot grounding paint or tape, to help prevent vibration and to conduct heat. Inadequate fitting in the slot may lead to significant slot discharge activity.

Important considerations in winding slot support systems include the following:

- a) All wedges should be tight, as confirmed and documented by measurement and test according to OEM specifications and procedures.
- b) All wedges should be aligned to ventilation ducts as required.
- c) Correct wedge materials should be used, per design requirements.
- d) There should be no damage done to the core laminations.
- e) Use of adequate side-packing

5.9 Series/phase electrical connections and insulation

Adequacy of the electrical connections is vital to the successful operation of the generator. Several methods of making this connection at the series and phase leads are used. Usually, the electrical connection is made by brazing or soldering. The brazing process typically uses a silver alloy and is performed at a higher temperature than solder, which results in a much stronger bond. However, bolted connections are also used on some designs by some manufacturers. On liquid-cooled generators, the electrical connection may also incorporate the liquid cooling circuit.

Some important considerations for electrical connection methods include the following:

- a) Use of a proven design with capable workmanship.
- b) On brazed connections, all components should be clean before brazing. (Water-soaked material used to protect the insulation during brazing can wick into the insulation system and cause failures later in the winding life cycle, and thus should be avoided or used with caution.) The use of chill blocks is preferred.
- c) On bolted designs, dimensions should be absolutely correct, all fits should be proper, all hardware should be locked, and all bolts should meet design requirements.
- d) Electrical resistance of the winding copper should meet the specification at completion of winding installation.

Three basic approaches are used in insulating the electrical connections: taped, potted, and electrical clearance (spacing). Some designs will use potting at the series connections, and tape at the phase connections. Similarly, where clearance is used for the isolation of voltage, the clearance may be made greater at the phase locations. Overlap of the potting with the insulation is a critical dimension and should be given serious thought. In all cases, only a service-proven design should be accepted by specification.

When spacing in an air atmosphere supplies a significant portion of the dielectric strength, it is extremely important to consider the atmospheric conditions and altitude where the generator is operating.

On large units, it is a good practice to bring the end of the phase and neutral connection of each parallel circuit out to intermediate circuits that terminate at the main bus or the neutral bus. If the electrical clearance is sufficient, the designer may choose to not insulate the connections.

6. Generator rotor considerations

Clause 6 is divided into two main subclauses. Subclause 6.1 addresses cylindrical rotors, and 6.2 addresses salient-pole rotors. Annex E contains a more detailed discussion of the construction and materials found in a cylindrical generator rotor. Annex E is included in this guide for information only and is not an official part of the standard.

6.1 Cylindrical rotors

6.1.1 Rotor forging

In general, the existing forging is reused during a rotor rewind. Otherwise, a new rotor is ordered. The new rotor may be a duplicate or an upgrade/uprate. If a new forging is required, the forging should be of the highest quality and vacuum degassed, because rotors are designed to operate at high mechanical duty.

During a rewind, the existing forging should be given thorough NDE since cracks may be developing in the forging. In addition, forgings made prior to 1960 were generally not made with vacuum de-gassed ingots and, therefore are subject to internal voids or occlusions. Typically, if there are cracks, they will be found

under the retaining ring shrink-fit area of the rotor forging, at the top of rotor teeth, at the bore surface, or at the rotor body axial centerline.

6.1.2 Rotor winding

There are three basic options for a rotor rewind: 1) re-insulate with the original conductors (usually copper), 2) rewind in kind but with new conductors, and 3) install a new winding design, with possible increased capacity. Each is briefly considered here:

- a) Re-insulating with original conductors is typically the lowest-cost route, although there may be a considerable cost involved in cleaning, straightening, and perhaps re-annealing the conductor. Also, distortion and cracks may be found and must be corrected.
- b) Rewind in-kind with new conductors could be the quicker route if new conductor material is ordered in advance. Furthermore, this reduces the risk that fatigue life of the conductor has been consumed. It should be kept in mind that mechanical duty on some areas of the conductors can be high, particularly on high-speed (2-pole) rotors.
- c) A new winding design may be a preferred route if rotor winding reliability problems have been experienced and/or an uprate in output may be desirable.

Regardless of the option taken, the conductors should be of correct shape, hardness, and surface conditions.

There are some rotors that have conductors made from materials other than copper. Aluminum alloys, such as “Condol,” were used in the 1950s instead of copper. These special alloys may not be readily available today for repairs to the conductors. Also, it may be difficult to redesign a rotor using copper conductors, instead of an aluminum alloy, because copper—which is heavier—may produce additional angular and radial forces.

6.1.3 Rotor coil winding prototype and or production testing

If the Owner desires to discuss the testing of the rotor coils for prototype or production testing, a general plan is described in Annex N. Annex N lays out a plan for rotor coil testing of hydro-generators. For turbo-generators, this can be used as a base plan but it is recommended to involve turbo-generator specialists in compiling an appropriate rotor coil test plan. The main point is a discussion between the Owner and the Vendor should occur to work out the details.

6.1.4 Rotor winding turn insulation

Three general approaches are taken to insulate the copper turns: 1) all taped turns, 2) insulating separator strips in the slots, and 3) insulating strips throughout the winding. Continuous taping offers more protection from contamination but is relatively uncommon. When used, alternate turns may be taped in order to reduce the amount of insulation buildup.

The more common approach is to use only insulating strips. It is essential that the strips be permanently bonded so that they do not migrate out of position, and the insulation commonly is bonded only to one side of each turn.

6.1.5 Rotor winding slot insulation

Two approaches are used for insulating copper from the ground: 1) a total enclosure of the coil copper by applying insulation overall (for indirect cooling), and 2) slot cells (for direct cooling). Indirect cooling is commonly used only on smaller rotors because the insulation does not permit the removal of heat from the conductor. A direct-cooled winding is more vulnerable to contamination than an indirect-cooled winding because clean, dry creepage paths are used throughout the winding to support the rotor voltage. However,

because cooling gas is in direct contact with the copper winding, a much higher capacity can be obtained from the rotor. As a result, direct cooling is common on all but smaller rotors.

It is common that cooling gas is discharged radially through holes in the wedge and a top-of-slot creepage block. In these designs, care should be taken to verify that all holes are in correct alignment when installing the winding and that the insulation system's design will not permit axial movements that lose this alignment.

It is important that the underside of the top-of-slot insulation that contacts the copper turns have the correct surface friction coefficient, to allow for thermal expansion and contraction of the winding.

6.1.6 Slot damper bars

Rotor winding damper circuits are used to address negative sequence current in the rotor forging and reduce the resultant heating. Configurations vary, including copper strips under the slot wedge, thicker bars under the wedge and bars in the pole face. The damper and pole face bars are connected to both retaining rings in turbo-generators to create a negative sequence current path known as a damping circuit. During a rewind, these bars should receive a full inspection for cracks and other deficiencies, using visual, NDE, or other agreed-upon inspection techniques. Any cracks or deficiencies must be addressed if these components are considered for re-use in the rewind.

6.1.7 Slot wedges

Slot wedges operate at very high mechanical stress. Generally, wedges are made of steel, although aluminum is sometimes used, as well as other alloys. In some rotor designs, magnetic wedges are used in the slots next to the poles for flux shaping. Because mechanical duty is high, the wedges should receive a full NDE for cracks and other deficiencies. It is not uncommon during disassembly of the rotor coil slots to find electrical arc damage on the wedges, due to negative sequence currents. It is very important that any arc damage be blended out since it would act as a stress riser for future crack initiation. In some cases, the arc damage is so severe that a large number of the wedges have to be replaced.

It is essential that wedge patterns be symmetrical axially and circumferentially. Where a flux probe is installed in the stator to detect shorted turns in the rotor, all wedges in the probe's axial position have to be non-magnetic. Otherwise the sensitivity of the probe to shorted turns is lost.

6.1.8 End winding blocking and insulation

Design and assembly of end winding blocking is a critical issue on high-speed 2 or 4-pole rotors. The block fit shall be symmetrical circumferentially to help ensure that all coils are restrained equally. Also, axial fit shall be sufficiently close, in order to hold the coils in proper position and help prevent turn distortion. Deviation from the original manufacturer's basic design approach to blocking is sometimes necessary because when changing from a retaining ring with ventilation holes, a different ventilation system has to be used. Also, in the case of distorted turns, a design change may be required to correct the inherent problem.

CAUTION

Use caution when reusing any blocking material manufactured prior to 1988, because it may contain asbestos.

In those designs where the axial position of the top-of-slot creepage block is held by the retaining ring insulation, assembly tolerances for the blocking shall be held precisely.

The retaining ring insulation shall be of correct thickness and surface dimensions. In addition, the surface shall contain a slip layer to reduce the friction coefficient between the retaining ring insulation and the

copper coils. In some of the spindle-mounted retaining ring designs, the original design did not allow sufficient freedom of movement between the coil and the insulation, resulting in uneven growth of the coil and subsequent vibration. As a remedy, the addition of a fluoropolymer resin slip layer can provide the necessary freedom of movement.¹⁶

6.1.9 Retaining rings

The most highly stressed component in the generator is the retaining ring. (This is sometimes referred to as a “rotor end cap”.) Its purpose is to restrain the angular and radial acceleration forces of the rotor winding end-turns. Its strength determines rotor diameter limits. Non-magnetic steel retaining rings have been in general use in almost all large generators since the 1950s. The non-magnetic alloy (18Mn-5Cr) used by most manufacturers between the 1950s and 1980s is subject to stress corrosion cracking. Replacing the retaining rings with a new alloy ring (18Mn-18Cr) will significantly reduce the risk of severe failure and unscheduled outages. Annex E has a detailed description of retaining rings, and their inherent risks.

6.1.10 Collector rings and bore copper

The insulation systems for the collector rings, terminal studs, and bore copper are not subject to the same wear as the coils’ insulation systems, and typically last much longer. For this reason, they typically are not automatically included as part of a rotor rewind. But they should be evaluated for unexpected wear, and good surface film condition (also known as patina). Uneven wear on the collector rings can be corrected by machining of the rotor. If the wear is too great, they can be replaced. If the rings are machined, or replaced, a proper film shall be established, after the generator is returned to service. A proper film is a result of a combination of adequate moisture in the air, carbon from the brushes, and adequate current density on the face of the brushes. The radial lead seals should also be tested and replaced, if necessary, on hydrogen-cooled generators.

In large machines, a helical groove is made in the collector ring to reduce the operating temperature and optimize brush performance. This groove may have a small radius at the bottom and the edges may be chamfered to help prevent sharp edges.

6.1.11 Miscellaneous rotor components

The entire rotor should be evaluated if taken apart for a rewind. It may be desirable to upgrade pole cross-over straps to a flexible design, or to replace old end-turn blocking material with a new glass type blocking material.

Pole-to-pole crossovers on certain generators have been known to fail in as little as 350 starts. A rigid design is more prone to failure, due to low cycle fatigue from start and stop operation. Two examples of rigid type designs that have failed prematurely are shown in Figure 1 and Figure 2.

¹⁶A commonly known name for fluoropolymer resin coating is Teflon®. Teflon® is a registered trademark of E. I. du Pont de Nemours and Company. This information is given for the convenience of users of this standard and does not constitute an endorsement by the IEEE of these products. Equivalent products may be used if they can be shown to lead to the same results.



Figure 1—Pole-to-pole “T” type solid copper connector



Figure 2—Straight solid copper connector

Examples of flexible pole connector designs, typically of the Greek letter omega shape (Ω) are shown in Figure 3 and Figure 4. Omega shaped connectors with multiple layers of copper typically provide better life than rigid structures and, also, may enable earlier visual detection before failure. Figure 3 is an example of a non-laminated copper omega connector and Figure 4 is an example of a laminated copper omega connector.



Figure 3—Omega-type solid copper connector

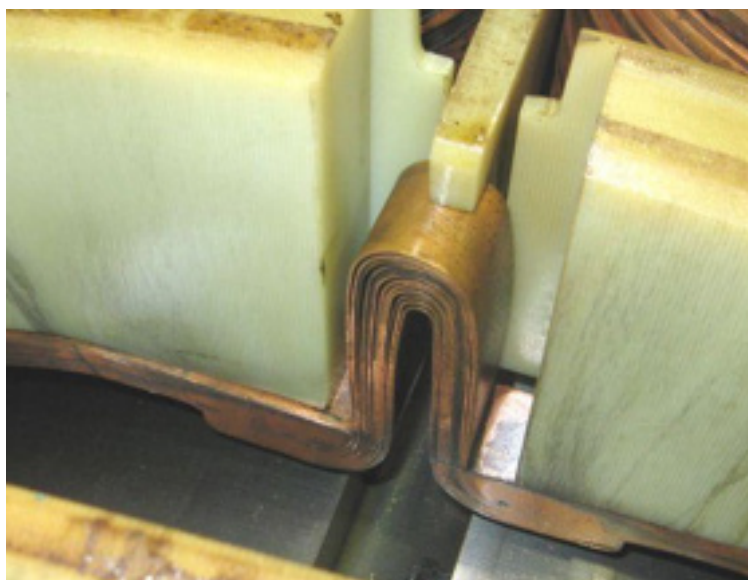


Figure 4—Omega-type laminated copper connector

6.2 Salient-pole rotors

6.2.1.1 Rotor categories

Salient-pole machines fall under three principal rotor categories: integral-pole rotor, shaft rotor, and shaft-and-spider. Annex F has a detailed description of salient-pole rotors. The inclusion of Annex F in this guide is for information only and is not an official part of this guide.

6.2.1.2 Integral-pole rotors

Integral-pole rotors are found in high-speed (4-pole and 6-pole) units. In this construction, the poles, pole tips, and shaft are usually machined from a single forging to produce superior mechanical properties. Integral poles do not have laminations, and they usually do not employ circuit elements such as shorting segments or amortisseur bars (also known as damper windings). Some integral-pole rotors have separate pole tips that are bolted into the pole body. Pole faces on integral-pole rotors may be machined in such a way as to simulate a lamination stacking, in order to reduce the pole face losses.

6.2.1.3 Shaft rotors

Shaft rotor constructions are also used in high-speed units or units where very high acceleration forces act on the poles. The poles are comprised of laminations stacked in the axial direction of the rotor and held together under compression by endplates and rivets. These dovetail designs use sets of long tapered keys driven between the side of the pole dovetail and the matching dovetail of the rotor shaft. These keys usually extend the length of the pole. The body of the rotor (or shaft) is typically made from a machine forging or constructed from steel plates or laminations. The poles can be attached to the rotor by means of dovetails, T-shaped keys, or bolts.

6.2.1.4 Shaft-and-spider rotors

Shaft-and-spider rotors are typically found in low-speed generators. They have a straight shaft to which a central hub and radial arms (the spider) are keyed, bolted, or shrunk-fit. In some hydro-generators, the spider and the rim can be made of cast steel. In large hydro-generators, the spider has radial arms against which a laminated rim is piled to form a solid cylinder-type component. The diameter of the spider is much larger than that of the straight shaft that carries it. The individual laminated wound poles are in turn bolted, or keyed with dovetails or T-shaped keys to the outer diameter of the rim. Bolts are typically removable from inside the rotor rim, to allow the possibility of removing one pole without removing the rotor. A fabricated hub with shaft extensions is also possible. These poles are often equipped with amortisseur (damper) bars and shorting segments.

6.2.2 Shaft, spider, and rim

These items are not a subject of this document, but it is prudent to conduct a rigid inspection of these items during any salient-pole rotor rewind. An engineering analysis should be performed on these components if an uprate is being considered.

6.2.3 Poles and damper windings

It is not usually necessary to remove damper windings during a rewind. On some older rotor designs, the damper winding and pole pieces have to be removed in order to gain access to the old rotor winding. If the damper winding is removed, the components of the damping circuit should receive a full NDE for cracks and other deficiencies or be replaced. If the damper winding is not removed, a detailed visual inspection should be performed. Any cracks or deficiencies must be addressed if these components are to be re-used for the rewind.

The poles are usually detached from the rotor by extracting the bolts or the dovetail keys. Some 4- and 6-pole designs have bolt-on-pole tips that have to be removed to access the field pole windings for repair. On high-speed generators, “V” blocks between the poles have to be dismantled prior to pole removal. (The function of these blocks is to support the rotor coils against the radial acceleration related forces due to rotation. Some of these blocks are made of metal with separate insulation components, while others are made from solid blocks of insulation material. Lifting and handling of the poles should be arranged in advance, prior to detaching the poles. After the old rotor coil windings are removed from the poles, the poles should be cleaned by suitable methods, such as glass bead blasting, and the damper winding should be inspected and/or tested for cracks.

6.2.4 Rotor coils

On salient-pole rotors, there are two types of rotor coils. There are: 1) wire wound coils (those made from rectangular insulated wire); and 2) strap or strip wound coils (those made with large rectangular straps or strips, which were edge bent or brazed into the coil form). Wire wound coils are constructed with several pre-insulated conductors wrapped around the pole body in multiple layers. This type of field winding cannot be economically re-insulated and must be replaced if the insulation is deemed unsuitable. Strap or strip wound coils need turn-to-turn insulation inserted between the turns prior to the consolidation of the coils. Old coils typically used asbestos for this turn insulation. Modern strap or strip wound coil designs should consider materials that have thermal, mechanical, and electrical properties that are adequate for this application. Traditional materials are synthetic aromatic polyamide insulation and glass composite materials¹⁷. Material choices should consider the hygroscopic properties of the insulating system.

Some strap or strip wound coil designs contain extended turns (such as a fin arrangement) to improve the cooling. Since there are large rotational mechanical forces acting on the coils, it is essential that they are well-bonded into a monolithic structure. The groundwall material can consist of insulation applied to the tops and inside surfaces of the coils or can be applied directly to the pole body. The outside copper surfaces of the field coil can be bare or painted with an insulating varnish. Top (closest to the air gap) and bottom (closest to the rim) insulating washers (or collars) are supplied to give additional creepage insulation surfaces to ground. There are machines that do not incorporate the bottom washer.

On some generators, the rotor coils are designed to carry the current in one direction on one pole, and in the other direction on the next pole. These are called open or crossed coils. On other generators, all the rotor coils are wound in the same direction and special connections are installed on top of the rotor rim to carry the current in one direction in one pole and in the other direction in the next pole.

The leads that interconnect the rotor poles to one another are a feature integral to the rotor pole coil design in salient pole machines. These leads, connections and supports take various forms that are design-specific. The connections between the poles come in many different styles including:

- a) Straight solid copper tabs that can be brazed, soldered or bolted with no flexibility. These may be found on small-diameter machines that are not regularly cycled, see Figure 5.
- b) Flexible style of connection, including thin laminated copper strips that are brazed to the pole coil, see Figure 6.
- c) Solid but flexible connector shaped like an omega (Ω) that can be brazed and bolted or just bolted to the coil, see Figure 7.
- d) Solid but flexible connector shaped like a “U,” also known as a “horseshoe,” see Figure 8.
- e) Braided style (shunt) that is bolted to the coil, see Figure 9.

This aspect of the machine design provides for withstanding the various magnetic, thermal, and mechanical stresses inherent to the rotor pole coils and the connecting leads under operation. This is critical to maintaining field current continuity under both normal and fault conditions.

The rewind materials should include the following: connecting material, top and bottom washers, tightening materials, pole brace insulation, and tapered keys if applicable. If the design contains springs, these should be re-qualified or replaced.

¹⁷ This term is also commonly known as Nomex. This information is given for the convenience of users of this standard and does not constitute an endorsement by the IEEE of these products or their suppliers. Equivalent products may be used if they can be shown to lead to the same results.



Figure 5—Straight solid copper tabs

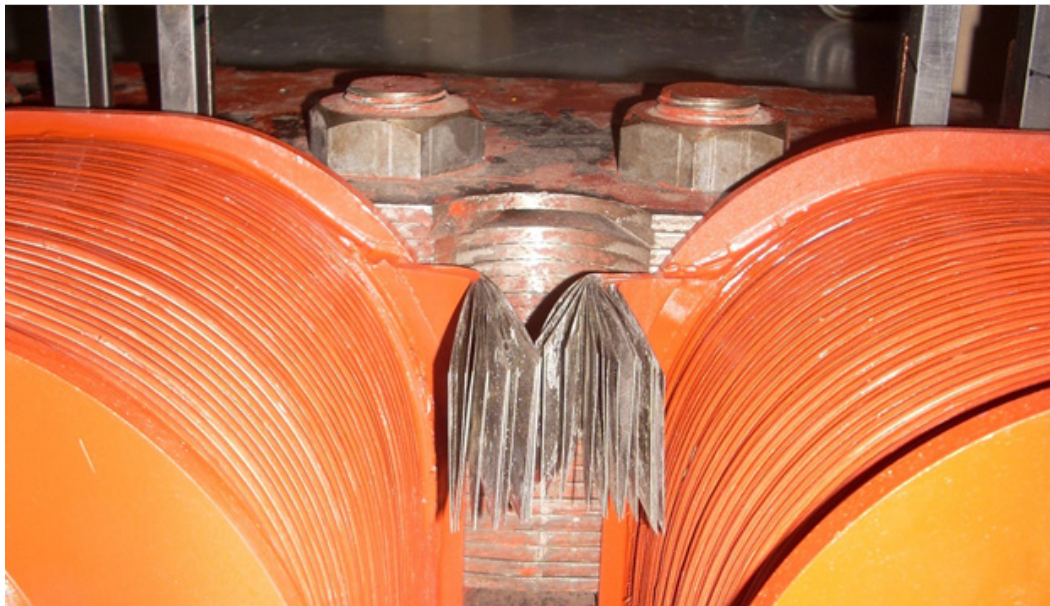


Figure 6—Thin laminated copper strips before connection



Figure 7—Solid but flexible connector shaped like an omega (Ω)

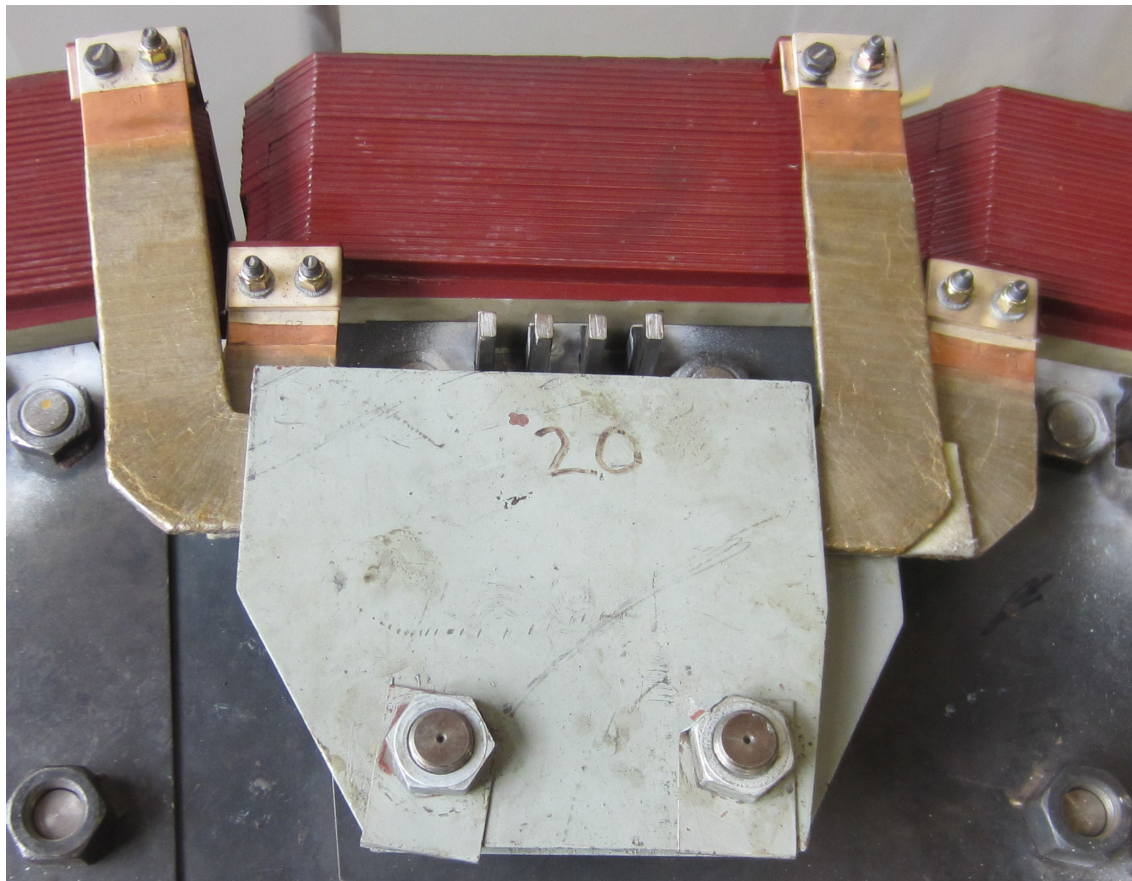


Figure 8—Solid but flexible connector shaped like a “U,” also known as a “horseshoe”



Figure 9—Braided style (shunt)

6.2.5 Rotor coil winding prototype and or production testing

If the Owner desires to discuss testing the rotor coils for prototype or production testing, a general plan is described in Annex N. Annex N lays out a plan for hydro-generator rotor coil testing, but this can be modified to work for salient pole turbo-generators. The main point is a discussion between the Owner and the Vendor should occur to work out the details.

6.2.6 Collector rings

During a salient-pole rotor rewind, it is important to inspect and address any issues with the collector ring insulation and the connecting straps or cables. Replacement or re-insulation may be necessary. The brush rigging should also be inspected, cleaned, and electrically tested. Related equipment should also be evaluated during a salient-pole rotor rewind. For example, it may be desirable to replace variable-pressure brush holders with constant-pressure brush holders.

In large machines, a helical groove is made in the collector ring to reduce the operating temperature and optimize brush performance. This groove needs to have a small radius at the bottom, and the edges may be chamfered to help prevent sharp edges.

7. Writing the technical specification

7.1 General

A technical specification can take on many forms, from simple to complex. A good specification, however, is one that has sufficient detail to enable the desired level of quality to be achieved, but not so extensive that it encumbers the Vendor's design effort. Vendors generally have a specific design standard, which usually provides the necessary level of quality and reliability that an Owner will want. However, during the production and assembly of the components, many things can go wrong. The technical specification is used to clarify the design requirement aspects of the equipment and the steps necessary during manufacture, to check and help ensure that quality is built in throughout the manufacturing process and can be referred to for acceptance criteria upon completion. Another important aspect is to be sure the calculations (mechanical, thermal, etc.) are accurately completed well before the proposal of a certain design by the Vendor and respond correctly to the specifications. The following annexes offer a description of the common components found in a typical specification.

- Annex G contains two useful tables of information that are typically supplied by the Owner, or by the Vendor.
- Annex H contains an extensive list of questions, which should be helpful in formulating the actual scope of the project.
- Annex I is a typical specification for the stator rewind of a turbo-generator.
- Annex J is a typical specification for the rotor rewind of a turbo-generator.
- Annex K is a typical specification for the stator rewind of a hydro-generator.
- Annex L is a typical specification for the rotor rewind of a hydro-generator.

The tables and the sample specifications in the annexes are included for illustration only and are not an official part of the guide.

7.2 Objective

A typical specification begins with an objective, which is a clear statement of the Owner's intent. Does the Owner want a rewind in kind, or does the Owner want improvements? The plans for future operation should be clearly stated here.

7.3 Project description

The project description is a written document that should give the potential Vendor a verbal picture of the project, along with a description and location of the plant site. The expected outage schedule should be defined, and any other planned work identified, so that rules of shared equipment (such as cranes) are clearly understood. The generator's nameplate information is provided, along with a brief history of its maintenance and operation. Any manufacturer's bulletins or advisements should be identified, along with their status (whether or not they have been adopted). The unit history should particularly include commissioning and performance test results where available. An opportunity to read operational data such as temperatures and loads should be considered to reduce performance prediction risks. If there is an opportunity to pre-measure the generator, the contact personnel and time period can be provided here. The bid contact personnel and the bid return dates should also be included in the project description.

7.4 Definitions

A section on definitions is important to identify the terms that are used in the specification. Reference to industry standards can be included here, but care should be used so that they do not conflict with other requirements set forth in the specification. For example, if the Owner references IEEE Std C50.13, and then adds certain design requirements, thermal limits, or monitoring necessities, there then needs to be a clear statement showing an exception has been taken to the referenced standard.

7.5 Scope

In the scope, it is necessary for the Owner to clearly define the work scope as well as the technical requirements. The Owner should decide on how much design detail, if any, is to be contained in the specification. One option is to prepare a purely functional specification (or performance specification). In this case, the Owner focuses on the machine output and the operating conditions. Another approach is to specify certain design features or processing methods. The danger in this approach is that it may place unnecessary responsibility on the Owner and might preclude design features that would be better for the application. Unless the Owner has generator design experience, it may be advisable to have the prospective Bidders specify the details of their design, and materials. However, even the performance specification should identify any known design weaknesses, and a request for the Vendor's design solution.

The Owner should require enough detail in the Bidder's proposal so that it is clearly understood by both parties what is and is not included in the bid. For example, core and frame cleaning is something that has to be done on almost every rewind. The frame cleaning may necessitate the removal of stator hydrogen or air coolers. But the extent of required cleaning will vary by generator. The scope of work can require the Bidder to include the estimated hours for core cleaning in their base price, and an hourly rate for any extraordinary work. The scope can also require the Bidder to include an evaluation for core tightness, and an hourly rate for tightening the core, if necessary.

The scope should require the Vendor to have a good quality program and to present it in detail. The program should include material tests and installation inspections performed to meet quality requirements. Some tests, such as the accelerated endurance tests, may be waived to save time and money if the Vendor can produce acceptable test records from similarly sized windings for an identical insulation system.

The scope should require the Vendor to provide the safety data sheets (SDS) for all materials used on-site for a rewind. Any excess material brought in by the Vendor should be removed by the Vendor at completion of the rewind.

The addition of monitoring devices should be included in the scope. Thermal sensors [such as resistance temperature detectors (RTDs) and thermocouples (TCs)], and vibration sensors are not always part of the standard material requirements. For example, on direct-cooled coils, IEEE Std C50.13 does not require the manufacturer to install embedded temperature detectors (RTDs or TCs) in the stator slots. Instead, it only stipulates temperature detectors at the coolant discharge. Therefore, if the Owner of a turbo-generator wants temperature detectors embedded in the stator slot, they should be specified here in the scope.

For a discussion regarding suggested minimum number of RTDs see Table G.1 in Annex G.

7.6 Work conditions

This part of the specification should address issues such as site access, storage of materials, lay-down space, local labor agreements, safety practices, environmental requirements, housekeeping, and facilities (offices, lunchrooms, toilets, etc.) Information on the site utilities should also be provided to the Bidders. This includes the ampacity of local voltage service, lifting requirements, crane limitations, the capacity of house compressed air and house service water, and the connector types and sizes. In addition to the work conditions just mentioned, any hazardous materials should be identified, and methods of abatement and/or personnel protection required should be identified. Quality standards for assessing site conditions (ISO or others) should also be included here.

7.7 Foreign material exclusion

The specification should include the requirement for a foreign material exclusion (FME) program. A FME program is a set of procedures intended to reduce the possibility of intrusion into the machine of foreign material before, during, and after the inspection. In principle, the definition of foreign material is anything not normally present during the operation of the generator that may adversely affect its constituent components if left there. It is important not to inadvertently contaminate the generator with such things as water, corrosive liquids, and personal items like pens, keys, flashlights, and other metallic objects (which can short circuit lamination or particles that become magnetic termites). Sometimes these materials can be introduced by walking on them and then walking into the machine. Therefore, in situations where stringent FME rules are applied, paper or rubber booties are worn over the shoes to reduce this risk as well as protect the surfaces walked on in the machine. A lack of adequate access control can be the cause of serious damage to the stator or rotor of a large generator—in particular, the stator winding. Thus, it is critical to account for all tools and parts coming in and out of a generator during an outage. Klempner and Kerszenbaum [B33] provide additional examples of problems that can arise from inadequate FME practices.

A good FME program will include clearly written procedures addressing all aspects of training and implementation. Responsibilities should be clearly defined, as well as contingencies for the loss of FME control. A typical FME procedure may include FME signs, FME zones, appropriate clothing, tool control, and spare parts controls. The stringency of the FME program will affect cost and should be considered with respect to the value of the machine. This should be worked out between the Vendor and Owner.

7.8 Deliverables

This part specifies what is expected of the Bidder in their answers to the bid request. It may include requests for schedules, their quality program, the specifics of their design, the various breakouts of the pricing, specific answers to questions asked throughout the specification, and their experience list.

7.9 Commercial issues

Included in this section are the terms and conditions required by the Owner including their specific terms of payment.

7.10 Attachments

Included in this section can be the plant rules and safety guide, any drawings available, and the specific pricing sheet.

8. Testing

8.1 General

Testing is performed at various stages of a generator stator or rotor rewind. For hydro-generators, the testing that is performed during the manufacturing of the replacement stator winding and during the refurbishment of the rotor windings is addressed in Annex M and Annex N, respectively. This clause addresses those tests typically performed during the rewinding of the stator and rotor, and testing done on completed stator and rotor windings. Recommended tests are divided into two categories: in-process testing during assembly (rewinding), and final acceptance tests.

NOTE—The testing discussed in this guide is for testing associated with the generator rewind process and **NOT** on-site maintenance testing.

This guide does not discuss all the details of these tests or the pros and cons of each test. Where existing test standards are available, they should be used. This guide offers some recommendations on test values not already covered in existing standards. There are many variables and differences based on specific situations, conditions, and manufacturing techniques. All testing, type of test, test method, voltage level, duration, and acceptance criteria should be discussed and agreed upon between the Owner and Vendor before a rewind contract is signed. If an industry standard is not applicable, a detailed discussion should take place and a test protocol put in writing and approved.

8.2 Stator core

Often the core does not need significant repair work during a stator rewind. However, the stator core could have existing damage, or the core iron can be damaged during the rewind process. Visual inspection of the core and core testing are ways to determine if damage did or did not occur. A low flux or high flux loop test should be considered for all stator rewinds. Testing of the stator core is typically performed at the following points in the rewind process:

- a) Testing can be performed before removing the wedges and coils/bars. This will establish a baseline condition and is typically done with a low flux test.
- b) Testing can be performed after removing all wedges, coils/bars, and cleaning the core slots, prior to starting winding installation. This is sometimes done with either a low flux or a high flux test. Note that in this machine condition the slot bottoms are most accessible for inspection with a thermal camera during a high flux test. A low flux test does not apply the same stress level as a high flux test.
- c) Testing can be performed after installing all coils/bars and wedges, to confirm core integrity. This is generally done with a low flux test.

The point of core testing is to detect interlaminar shorts. This can be difficult if it is intended to detect shorts that only occur under conditions of vibration and thermal expansion. No tests used today will completely simulate operating conditions. High flux loop tests can induce more vibration and temperature rise than low flux tests.

High flux loop tests which use thermal cameras to evaluate the core can only see the surface of the core that is in the line-of-sight. Low flux tests, such as EL CID, that use magnetic measurements of the core effectively scan the full surface of the core including those areas inside the slots that are normally obscured from the line-of-sight by the coils and wedges (if performed with the winding in place).

If the core is in good condition and the low flux test shows no indications, a high flux loop test may not be necessary. If all or a section of core is replaced or moved as part of a rewind, then a high flux test is recommended to test the core at interlaminar electrical stresses similar to operating stress levels. Also, it is recommended to perform a high flux test of cores with splits as well as older cores if there is any doubt about core integrity. If a high flux loop test cannot be performed (due to physical construction, machine configuration, etc.), a low flux test is recommended.

For some types of machines and stator constructions, such as large hydro-generators, loop test flux levels or durations should be lowered, if required, due to compressive hoop stress between the core and the frame. The differential temperature between the core and the frame should not exceed 25°C in order to help prevent buckling in the core. See IEEE P1719™ [B15] for more information.

The original equipment manufacturer, or other suitable qualified entity, may need to be consulted for recommendations on high flux testing. Refer to IEEE Std 62.2 [B27], IEEE Std 56™ [B26], and IEEE P1719 [B15] for additional information on high flux testing.

Before the core test, an inspection should be performed to remove any foreign material close to the stator iron.

Appropriate core tightness should be established prior to any core testing. There are a variety of core construction techniques that require evaluation to establish if a core is tight. This may require analysis of the overall system or information from the OEM to establish the intended tightness of various clamping features. This can include but is not limited to the following:

- a) Through-bolts/Studs: Studs that pass through the yoke of the stator core, are connected at each end via the clamping feature, and are insulated to help prevent interlaminar shorts.
- b) Studs at the back of the core: One type is a stud welded to the stator frame shelf, which uses the stator frame as support for compressing the core at each end via the clamping feature. Another type is a free-standing core stud/rod that does not attach to the frame but is attached to the clamping feature by washers and nuts, thus independently providing compression of the core without the use of the stator frame shelves as support.
- c) Bands around the core (compression bands/belly bands): This construction is more specific to two pole turbo generators. The compression band serves to keep the frame and core tightly connected thus reducing the possibility of vibration. This compression band does not contribute to lamination compression in the axial direction.

Clamping features should not be overtightened as this can lead to yielding of the clamping feature and/or frame. Further, it can lead to unnecessarily high core pressure that can crush and compromise some types of core insulation and can cause droop of the stator laminations around the vent spacer reducing the air flow through this area and potential permanent core deformation.

The clamping feature bolts can be checked for tightness either by checking tension or torque, depending on the style of bolt as previously discussed. For a bolt that is welded to the frame shelf, a torque measurement is required to determine if the design core pressure is applied when properly tightened. This may require initial loosening of the nut and then re-tightening. Consult the OEM or suitable qualified entity for the proper torque value and if the bolt threads should be lubricated or not during this activity. For a bolt that is free standing, using a hydraulic mechanical device to stretch the bolt and measuring the stretch determines if the correct design pressure is applied. When the correct stretch is achieved on the bolt, the nut is turned tight (not torqued) onto the bolt and the mechanical device released to achieve the correct core design pressure. Consult the OEM or suitable qualified entity for the value of bolt stretch and tightening procedure that satisfies the design core pressure.

On hydro-generators having split cores, check that the frame-split section flange bolts are tightened properly before performing a loop test. These frame-split section flange bolts can have a very high specified torque/tension value. Should a bolt be loose, consult the OEM or suitable qualified entity for the correct torque/tension. Designs may have various bolts at different tightness values such as a split opening bolt, which limits compression of the split. Consult the OEM or suitable qualified entity for your particular design. See C.2.1 for additional details.

If there has been a history of core tightening during previous maintenance outages, consideration should be given to evaluating the mechanical structure for hard stops so that planning can be made regarding mechanical alterations, new core bolts, or the addition of iron to the core prior to the rewind. The potential addition of material can occur on older, longer cores. If core tightening is a necessary and persistent task, consult the OEM or a suitable qualified entity for possible next steps.

Since deteriorated bolt insulation may need to be replaced during the rewind, it would be preferable to measure the insulation resistance of all core clamping bolt insulation. Typically, this can be done using 500 V dc prior to finalizing the rewind specification. Normally, core clamping bolt insulation that is older than 40 years should be replaced during a rewind, because the insulation is typically only accessible during a rewind with all the coils removed.

Low flux core tests on cores with splits require special evaluation techniques. See IEEE P1719 [B15] and Ridley, G.K. [B43] for more information.

Some cores are built with insulation at the back. In this case, there is no return path for the current. Therefore, low and high flux tests on these types of cores can have difficulty detecting shorted laminations because the usual shorting path offered by the keybar or building bolt along the back of the core is now insulated. It may be possible to detect some thermal stress due to eddy currents at the surface at the shorting. If a return current is created by shorted laminations in the back of the core, circulating currents will develop and flux tests will be able to detect the faults.

When replacing cores and uprating a machine, the Vendor may change machine reactances and even rated core flux levels. The Owner should be made aware of the possible changes.

8.3 Stator winding

To detect potential damage to the machine during the installation, and to offer a certain level of assurance for future operation, 8.3.1, 8.3.2 and 8.3.3 contain recommended tests and test levels for stator windings. Installation techniques and processes vary throughout the industry, and hence it is often difficult to cover all the issues with existing specifications. Therefore, a discussion between the Owner and Vendor is recommended to achieve an agreement regarding the testing requirements.

8.3.1 Rewind assembly tests

Various tests should be performed throughout the process of winding stator coils or bars into the machine. The order of testing and test levels is important since some aspects of the winding can only be verified during the winding process.

Progressive electrical testing is recommended during the rewind to identify issues earlier in the process, and to provide a reasonable assurance that the winding will successfully pass the final test as per 8.3.2. This can be achieved by applying the tests at higher voltages earlier in the rewind process. There is a possibility that a coil or coils can fail the progressive electrical testing. As a result of this possibility, it is recommended that spare top and bottom bars or coils be on-site during the rewind. The details of this can be worked out between the Owner and the Vendor prior to the rewind commencing. An example list of tests and test levels is shown in Table 1. Other test voltages may be chosen for specific machines based on rated voltage or Vendor recommendations. These tests are made to verify that the Vendor will meet the final test required by the contract. Vendor quality testing requirements may vary. Vendor specific information on quality tests can be requested of the Vendor by the Owner if desired.

The Owner should make it clear, in the rewind specification, that whenever a coil or bar is rejected for obvious mechanical damage or fails electrical testing, whether the Vendor would be allowed to address the failed coil or bar using any of the following:

- a) In place repair for areas outside the grounded region; or
- b) Remove, strip, re-insulate, and re-use the coil or bar; or
- c) Coil splicing to replace the faulted leg/side

Please note that if the bar or coil is repaired instead of a full replacement, the Owner should have a discussion with the Vendor considering possible paths for addressing a bar/coil repair.