



IEEE Guide for Abnormal Frequency Protection for Power Generating Plants

STANDARDS

IEEE Power and Energy Society

Developed by the
Power System Relaying and Control Committee

IEEE Std C37.106™-2022

IEEE Guide for Abnormal Frequency Protection for Power Generating Plants

Developed by the

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

Approved 16 June 2022

IEEE SA Standards Board

Abstract: This guide has been prepared to assist the protection engineer in applying relays for the protection of generating plant equipment from damage caused by operation at abnormal frequencies including overexcitation.

Keywords: combined-cycle, combustion, excitation control system, fuse failure, governor control system, hydraulic, IEEE C37.106™, limiter, load shedding, nuclear, overexcitation, overfrequency, resonance, self-excitation, steam, torsional, turbine, underfrequency, voltage regulator, volts per hertz

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

Copyright © 2023 by The Institute of Electrical and Electronics Engineers, Inc.
All rights reserved. Published 5 May 2023. Printed in the United States of America.

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

PDF: ISBN 978-1-5044-8879-2 STD25538
Print: ISBN 978-1-5044-8880-8 STDPD25538

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 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 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 this standard, including but not limited to the warranties of merchantability, fitness for a particular purpose and non-infringement. 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 his or her own independent judgment in the exercise of reasonable care in any given circumstances or, as appropriate, seek the advice of a competent professional in determining the appropriateness of a given IEEE standard.

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

Official statements

A statement, written or oral, that is not processed in accordance with the IEEE SA Standards Board Operations Manual shall not be considered or inferred to be the official position of IEEE or any of its committees and shall not be considered to be, nor be relied upon as, a formal position of IEEE. At lectures, symposia, seminars, or educational courses, an individual presenting information on IEEE standards shall make it clear that 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).

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 in revisions to an IEEE standard is welcome to join the relevant IEEE 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 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 US 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

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

²Available at: <https://standards.ieee.org/content/ieee-standards/en/about/contact/index.html>.

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 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/>. 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.

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

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

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

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

IEEE Standards do not guarantee or ensure safety, security, health, or environmental protection, or ensure against interference with or from other devices or networks. IEEE Standards development activities consider research and information presented to the standards development group in developing any safety recommendations. 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, and interference protection practices and all applicable laws and regulations.

Participants

At the time this IEEE guide was completed, the J19 Working Group had the following membership:

Ritwik Chowdhury, *Chair*
Jason Eruneo, *Vice Chair*

Matchyaraju Alla
Kelvin Barner
Zeeky Bukhala
Ryan Carlson
Stephen Conrad
Manish Das
William English
Dale Finney
Normann Fischer

Derrick Haas
Sungsoo Kim
Gary Kobet
Mike Kockott
Daniel Lebeau
James Mearns
Bracy Nesbit
Molson Parvin
Manish Patel

Robert Pettigrew
Michael Thompson
Dennis Tierney
Steven Turner
Onur Usmen
Douglas L. Weisz
Tamatha Womack
Murty V.V. S. Yalla
Vinod Yedidi

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

Michael Basler
Thomas Beckwith
Martin Best
Steven Bezner
Jens Boemer
Brian Boysen
Gustavo Brunello
Koti Reddy Butukuri
Paul Cardinal
Sean Carr
Suresh Channarasappa
Ritwik Chowdhury
Manish Das
Neal Dowling
William English
Carl Fredericks
Fredric Friend
Kamal Garg
Shubhanker Garg

Jalal Gohari
Stephen Grier
Michael Higginson
Werner Hoelzl
Ali Hooshyar
Richard Jackson
Innocent Kamwa
Boris Kogan
Mikhail Lagoda
Don Lukach
John Martin
Daleep Mohla
Rhonda Netzel
Arthur Neubauer
James O'Brien
P. Sivaraman
Lorraine Padden
Bansi Patel
Manish Patel
Pathik Patel

Subhash Patel
Charles Rogers
Christopher Ruckman
Thomas Rudolph
Steven Sano
Bartien Sayogo
Gary Smullin
Michael Thompson
Onur Usmen
James van de Ligt
Benton Vandiver
John Vergis
Quintin Verzosa
Kenneth White
Philip Winston
Tamatha Womack
Rachel Wood
Sergio Zimath
Nicholas Zagrodnik

When the IEEE SA Standards Board approved this guide on 16 June 2022, it had the following membership:

David J. Law, *Chair*
Ted Burse, *Vice Chair*
Gary Hoffman, *Past Chair*
Konstantinos Karachalios, *Secretary*

Edward A. Addy
Ramy Ahmed Fathy
J. Travis Griffith
Guido R. Hiertz
Yousef Kimiagar
Joseph L. Koepfinger*
Thomas Koshy
John D. Kulick

Johnny Daozhuang Lin
Kevin Lu
Daleep C. Mohla
Andrew Myles
Damir Novosel
Annette D. Reilly
Robby Robson
Jon Walter Rosdahl

Mark Siira
Dorothy V. Stanley
Lei Wang
F. Keith Waters
Karl Weber
Sha Wei
Philip B. Winston
Daidi Zhong

*Member Emeritus

Introduction

This introduction is not part of IEEE Std C37.106-2022, IEEE Guide for Abnormal Frequency Protection for Power Generating Plants.

There are two major considerations associated with operating generating stations at abnormal frequency:

- Protection of equipment from damage that could result from operation at abnormal frequency, and
- Prevention of a cascading effect that leads to a complete plant shutdown as long as limiting conditions are not reached during abnormal frequency operation.

The major components of a plant that are affected by abnormal frequency operation are the generator and unit step-up transformer, the turbine and/or compressor, and the station auxiliaries. The following major modifications have been brought up to the previous version of the guide (IEEE Std C37.106-2003):

- a) Updates in [Clause 4](#) to improve application guidance for volts per hertz protection supervision, tripping practices, and applications with voltage transformers (VTs) at the generator voltage level.
- b) Updates in [Clause 5](#) including torsional resonance considerations for steam turbine generators (STGs) and applications of hydraulic turbine generators.
- c) Updates in [Clause 6](#) for the different frequency protection methods, supervision, tripping practices, and considerations, such as self-excitation in hydraulic turbine generating plants.
- d) Much of the content in [Clause 8](#) was deleted to reduce repetition.
- e) Addition of [Annex A](#) to aid application engineers configure protection in steam and combustion turbine generating plants.
- f) Addition of [Annex B](#) to aid engineers apply protection in hydraulic turbine generating plants.
- g) Addition of [Annex C](#) for considerations when applying user-defined volts per hertz curves in microprocessor-based relays.
- h) Removal of annex that provided examples of regional criteria because it was out of scope; relevant references have been added instead.

Acknowledgements

IEEE thanks the International Electrotechnical Commission (IEC) for permission to reproduce Figure 1 from IEC 60034-3:2020. All such extracts are copyright of IEC Geneva, Switzerland. All rights reserved. Further information on the IEC is available from www.iec.ch. IEC has no responsibility for the placement and context in which the extracts and contents are reproduced, nor is IEC in any way responsible for the other content or accuracy therein.

Contents

1. Overview	11
1.1 Scope	11
1.2 Purpose	11
1.3 Word usage	11
2. Normative references	12
3. Definitions, acronyms, and abbreviations	12
3.1 Definitions	12
3.2 Acronyms and abbreviations	14
4. Generator-transformer abnormal frequency capabilities and protection	15
4.1 General background	15
4.2 Generator overfrequency and underfrequency capabilities	15
4.3 Generator and transformer overexcitation capabilities	17
4.4 Generator and transformer V/Hz protection	21
5. Turbine abnormal frequency capabilities	26
5.1 Turbine overfrequency and underfrequency capabilities	26
5.2 Steam turbine overfrequency and underfrequency capabilities	26
5.3 Combustion turbine overfrequency and underfrequency capabilities	30
5.4 Combined-cycle unit overfrequency and underfrequency capabilities	31
5.5 Hydraulic turbine overfrequency, underfrequency, and overvoltage capabilities	32
6. Turbine abnormal frequency protection	32
6.1 Frequency protection methods	32
6.2 Load-shedding based underfrequency protection	34
6.3 Steam turbine underfrequency protection	34
6.4 Combustion turbine underfrequency protection	36
6.5 Combined-cycle installation underfrequency protection considerations	37
6.6 Hydraulic turbine underfrequency protection	37
7. Impact of abnormal frequencies on power plant auxiliaries	37
7.1 Power plant auxiliaries—underfrequency considerations	37
7.2 Auxiliary bus transfer issues	38
7.3 Nuclear plants—general background	38
8. System-wide issues	40
Annex A (informative) Steam/combustion turbine generator application example	42
Annex B (informative) Hydraulic turbine generator application example	50
Annex C (informative) Applying a user-defined curve for V/Hz protection	51
Annex D (informative) Bibliography	52

IEEE Guide for Abnormal Frequency Protection for Power Generating Plants

1. Overview

1.1 Scope

This application guide assists the protection engineer in applying relays for the protection of synchronous generating plant⁶ equipment from damage caused by operation at abnormal frequencies including overexcitation. Consideration is given to the effect of abnormal frequency operation on those associated station auxiliaries whose response can affect plant output. The guide also presents background information regarding the hazards caused by operating generation equipment at abnormal frequencies. It documents typical equipment capabilities and describes acceptable protective schemes. Underfrequency protection can be provided by load shedding and/or a discrete underfrequency protection scheme.

Guidance is provided to help meet requirements from regulatory bodies. The protective functions discussed in this guide may be implemented with a multifunction microprocessor-based protection system.

1.2 Purpose

This guide summarizes the use of relays and devices such that the reader may select the necessary equipment to provide adequate protection for ac generators from abnormal frequency conditions.

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*).^{7,8}

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*).

⁶This document does not provide guidance on inverter-based resources which are covered in IEEE Std 2800 Standard for Interconnection and Interoperability of Inverter-Based Resources Interconnecting with Associated Transmission Systems [B29].

⁷The use of the word *must* is deprecated and cannot be used when stating mandatory requirements, *must* is used only to describe unavoidable situations.

⁸The use of *will* is deprecated and cannot be used when stating mandatory requirements, *will* is only used in statements of fact.

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

2. Normative references

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

IEC 60034-3:2020, Rotating Electrical Machines—Part 3: Specific Requirements for synchronous generators driven by steam turbines or combustion gas turbines.⁹

IEEE Std C50.13™-2014, IEEE Standard for Cylindrical-Rotor 50 Hz and 60 Hz Synchronous Generators Rated 10 MVA and Above.^{10,11}

IEEE Std C57.12.00™-2015, IEEE Standard General Requirements for Liquid-Immersed Distribution, Power, and Regulating Transformers.

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* should be consulted for terms not defined in this clause.¹²

automatic control: In excitation control system usage, automatic control refers to maintaining synchronous machine terminal voltage at a predetermined level without operator action, over the operating range of the synchronous machine. (IEEE Std 421.1™-2007 [B30])

automatic voltage regulator (AVR): A term often used to designate either the voltage regulator alone or the complete control system comprised of limiters, etc. (IEEE Std 421.1™-2007 [B30])

boiling water reactor (BWR): A nuclear steam supply in which the primary reactor coolant is piped, as steam, directly to the turbine. After being condensed, the water is returned to the reactor as feedwater that is subsequently transformed back to steam as it absorbs thermal energy from the nuclear reaction.

combined-cycle power plant: A power plant that incorporates combustion turbine and steam turbine prime movers driving generators. Exhaust gases from the combustion turbine raises steam temperature in heat recovery generators. The steam generated drives the steam turbine.

combustion turbine: An internal combustion engine consisting of compressor, combustor, and turbine sections. Gas (normally air) from the compressor is mixed with combusted fuel and expands in the turbine resulting in mechanical (rotational) energy.

excitation control system: The feedback control system that includes the synchronous machine and its excitation system. The term is used to distinguish the performance of the synchronous machine

⁹IEC publications are available from the International Electrotechnical Commission (<https://www.iec.ch>) and the American National Standards Institute (<https://www.ansi.org/>).

¹⁰The IEEE standards or products referred to in [Clause 2](#) are trademarks owned by The Institute of Electrical and Electronics Engineers, Incorporated.

¹¹IEEE publications are available from The Institute of Electrical and Electronics Engineers (<https://standards.ieee.org/>).

¹²*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.

and excitation system in conjunction with the power system from that of the excitation system alone. (IEEE Std 421.1™-2007 [B30])

NOTE—See Figure 1.¹³

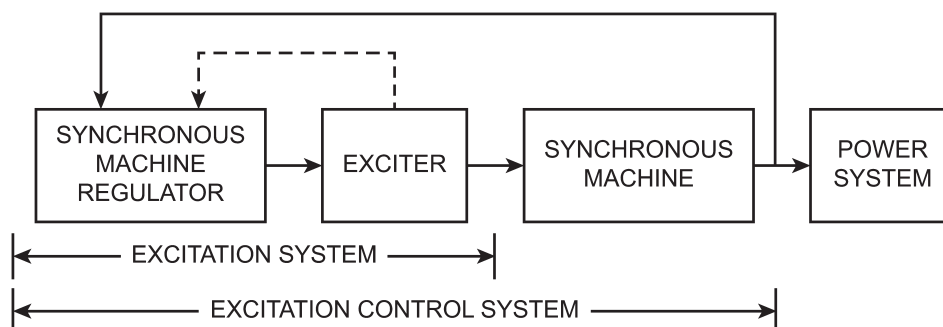


Figure 1—Block diagram of excitation control system

excitation system: The equipment providing field current for a synchronous machine, including all power, regulating, control, and protective elements. (IEEE Std 421.1™-2007 [B30])

exciter: The equipment that provides the field current for the excitation of a synchronous machine. (IEEE Std 421.1™-2007 [B30])

field current/voltage limiter: A control function that acts to prevent the field current or voltage from exceeding a preset value. (IEEE Std 421.1™-2007 [B30]) *See also:* **overexcitation limiter.**

frequency: In a waveform, the number of crests of the same sign that occur per unit of time.

hydraulic turbine: A machine that develops mechanical energy (rotational) from the injection of a quantity of fluid (normally water) at a pressure (head).

inverse-time relay: A protective relay with operating characteristic which produces a combination of a fast operation at high multiples of pickup values and slow operations at low multiples of pickup values, hence an inverse-time characteristic.

load: A device to which power (watts) is delivered or consumed.

load rejection: Loss of load at the generator output.

load shedding: The intentional and automatic disconnection of a portion of load in an overload condition.

overexcitation: An overfluxing condition which occurs whenever a generator or transformer ratio of the voltage to frequency (volts per hertz) applied to the terminal of the equipment exceeds design limits (typically greater than 1.05 volts per hertz for generators on a continuous basis). *See also:* **volts per hertz.**

overexcitation limiter (OEL): A control function that limits the field current of the synchronous machine or excitation equipment to permissible values with regard to thermal overload. Action may be immediate or time delayed. Also called a maximum excitation limiter. (IEEE Std 421.1™-2007 [B30]) *See also:* **field current/voltage limiter.**

¹³Notes in text, tables, and figures are given for information only and do not contain requirements needed to implement the standard.

overfrequency: A condition that occurs when the system frequency increases above its nominal value as a result of the connected generation exceeding the system load.

pressurized water reactor (PWR): A nuclear steam supply in which the primary reactor coolant is recirculated through in a closed loop through the tube side of a shell and tube heat exchanger (steam generator) while feedwater is pumped into the shell side of the exchanger and transformed to steam that is piped to and drives the turbine.

relays: Devices that operate when the inputs provided to it meet some predefined and specified conditions.

self-excitation: A condition of increasing flux and voltage that occurs when the shunt capacitive reactance at a rotating machine's terminals is smaller than its synchronous reactance.

steam turbine: An engine in which the steam thermal energy is converted to kinetic energy as it passes over fixed vanes and to mechanical energy as it passes over blades affixed to a rotor.

synchronous machine regulator: A general term applied to a regulator that couples the output variables of a synchronous machine to control the exciter output through forward and feedback elements for the purpose of regulating the synchronous machine output variables. (IEEE Std 421.1™-2007 [B30]) *See also:* **automatic voltage regulator**.

system frequency: The frequency at which electricity is generated and distributed throughout an interconnected system (i.e., 50 Hz or 60 Hz).

underfrequency: A condition that occurs when the system frequency drops below its nominal value as a result of the system load exceeding the connected generation.

underfrequency load shedding (UFLS): A scheme using frequency and time-delay elements to detect an underfrequency condition and to selectively disconnect loads from the system.

voltage regulator: A synchronous machine regulator that functions to maintain the terminal voltage of a synchronous machine at a predetermined value, or to vary it according to a predetermined plan. (IEEE Std 421.1™-2007 [B30])

volts per hertz (V/Hz): The unit of measure for generator and transformer excitation is defined as voltage divided by frequency. Conventionally, it is expressed in per unit or percentage. *See also:* **overexcitation**.

volts per hertz (V/Hz) limiter: A function that acts to prevent the ratio of terminal voltage to frequency from exceeding a preset level. The purpose is to prevent excessive magnetic flux in the synchronous machine and connected transformers. (IEEE Std 421.1™-2007 [B30])

3.2 Acronyms and abbreviations

AVR	automatic voltage regulator
BWR	boiling water reactor
CTG	combustion turbine generator
DNBR	departure from nucleate boiling ratio
GSU	generator step-up
HRSG	heat recovery steam generator
HV	high-voltage
kVA	kilovolt-amperes

LV	low-voltage
MG	motor-generator
OEL	overexcitation limiter
pf	power factor
PWR	pressurized water reactor
STG	steam turbine generator
UAT	unit auxiliary transformer
UFLS	underfrequency load shedding
V/Hz	volts per hertz
VT	voltage transformer

4. Generator-transformer abnormal frequency capabilities and protection

4.1 General background

Generators, transformers, and turbines all have operational frequency limitations. Turbine capabilities are generally more restrictive than those of generators and transformers. Turbine capabilities are discussed in [Clause 5](#). Operation of generators at low frequencies can result in overheating due to reduced ventilation. Operation of generators and their associated transformers at reduced frequencies while at rated voltages can also result in exceeding overexcitation limits as flux within these devices is inversely proportional to frequency. This clause discusses abnormal frequency capabilities of generators and transformers.

4.2 Generator overfrequency and underfrequency capabilities

4.2.1 General considerations

There are two principal considerations associated with operation of synchronous generators outside of the standard frequency range:

- Accelerated aging of mechanical components, which happens during both underfrequency and overfrequency, and
- Thermal considerations, which are of principal interest for underfrequency operation.

It is recognized that reduced frequency results in reduced speed of rotation, causing reduced ventilation; therefore, operation at reduced frequency may be at reduced kilovolt-amperes (kVA) in synchronous generators. [Figure 2](#) shows recommended maximum continuous loading at various frequencies for 2-pole or 4-pole cylindrical rotor generators as published by two manufacturers (MFRs).

In view of reduced generator capability and expected increased loading during underfrequency conditions, the short-time thermal capability of a generator could be exceeded. Operating precautions may be taken to stay within the short-time thermal rating of the generator rotor and stator. The permissible short-time operating levels for both the stator and rotor for cylindrical rotor synchronous generators are specified in IEEE Std C50.13-2014 and are shown in [Figure 3](#).

Overfrequency is usually the result of a sudden reduction in load, such as a unit full load rejection and, therefore, corresponds to light-load or no-load operation of a generator. During overfrequency operation, machine ventilation is improved, and the flux density required for a given terminal voltage is reduced. Therefore, operation within the allowable overfrequency limits of the turbine will not produce generator overheating as long as operation is within rated kVA and 105% of rated voltage.

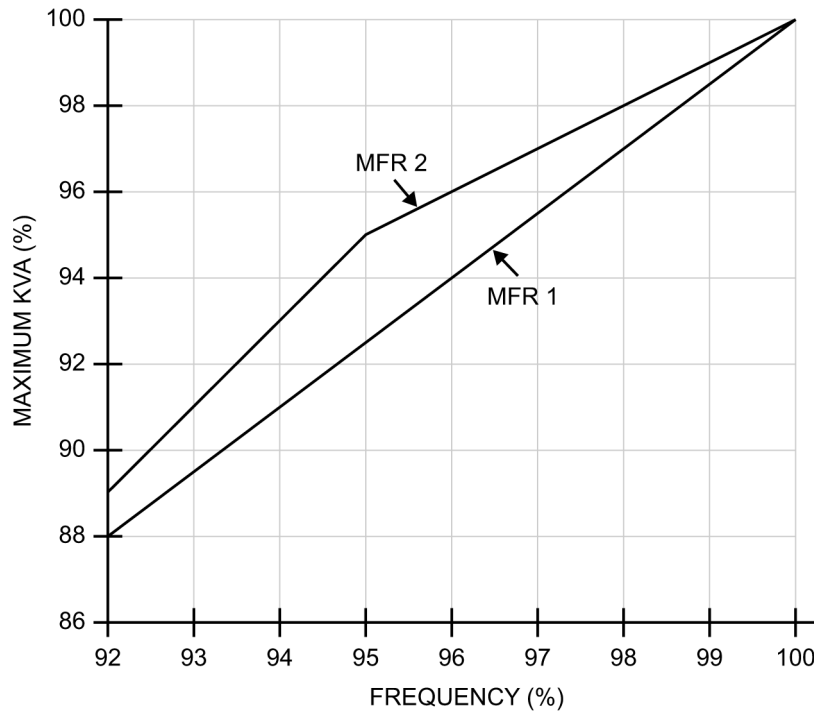


Figure 2—Generator capability versus frequency

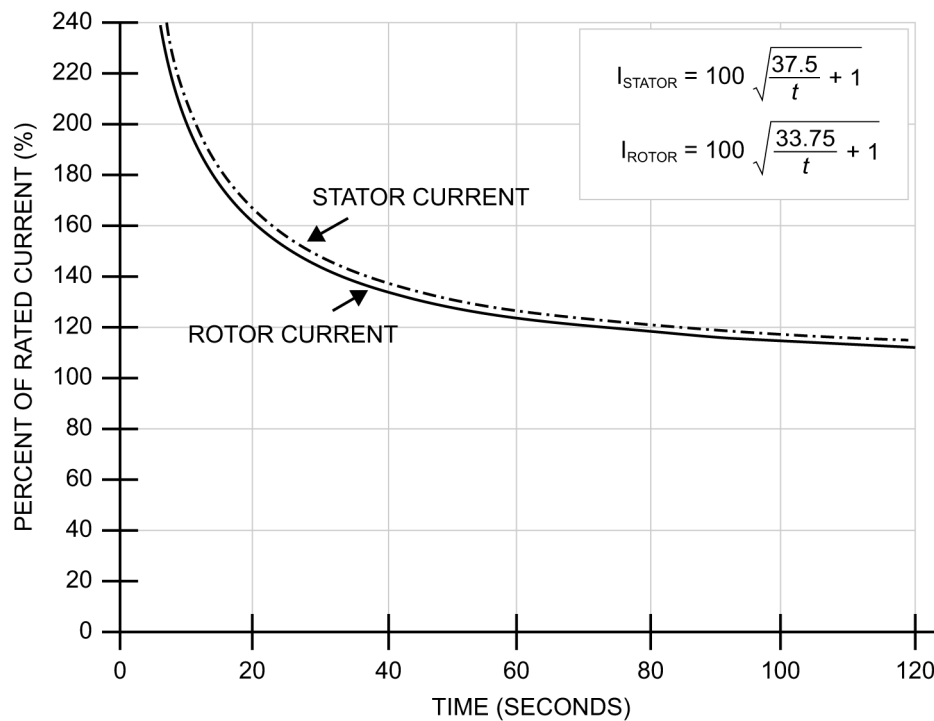
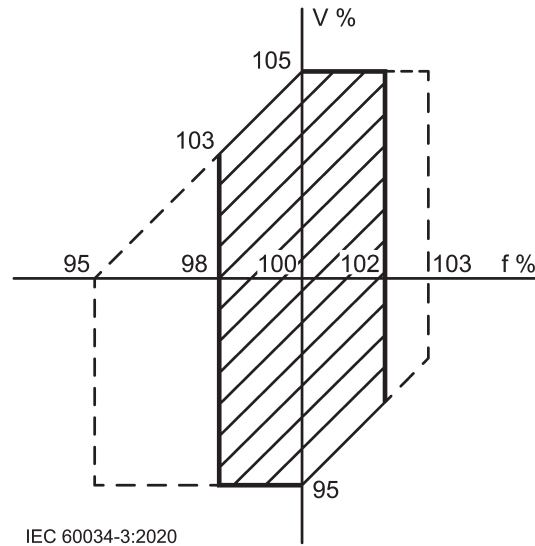


Figure 3—Cylindrical rotor generator short-time thermal capability

4.2.2 Conformance to IEC 60034-3:2020

Some turbine generators are designed to accommodate the IEC 60034-3:2020 frequency-voltage characteristics. IEC 60034-3:2020 requires generators to deliver continuously rated output at the rated power factor (pf) over the ranges of $\pm 5\%$ in voltage and $\pm 2\%$ in frequency, as shown by the shaded area in Figure 4.



Reprinted with permission from IEC 60034-3 ed.7.0. Copyright © 2020 IEC Geneva, Switzerland. www.iec.ch

Figure 4—Operation over ranges of voltage and frequency

IEC 60034-3:2020 recommends that operation outside the shaded area “be limited in extent, duration and frequency of occurrence.”¹⁴ A manufacturer could, therefore, impose severe time restrictions for the generator itself, particularly for operation below 95% of rated frequency or above 103% of rated frequency (respectively, 57 Hz or 61.8 Hz on a 60 Hz basis) and, to a lesser extent, for operation outside of the continuous range of 98% to 102% of rated frequency. Operation outside of the standard frequency range may result in accelerated aging of generator and prime mover mechanical components due to high-cycle fatigue of stationary and rotating components.

In view of these considerations, a manufacturer may require, for the generator only, frequency operational limits in the form of time-frequency characteristics. In such a situation, the principal goal of frequency protection schemes is to return the frequency to the continuous IEC operating frequency range (98% to 102% of rated frequency) as soon as possible and to limit operation outside of this range, both in extent and in duration, and in concert with load shedding practices.

4.3 Generator and transformer overexcitation capabilities

Overexcitation exists whenever the per unit volts per hertz exceeds the design limits of the equipment.

For a generator, there is a complex relationship between the exciter current and the terminal voltage because the excitation current creates the magnetic flux in the generator to produce the terminal voltage. However, this relationship is non-linear and depends on the saturation characteristics of the machine, the rotor speed, the load current, unit geometry, and possibly other factors.

¹⁴IEC 60034-3 ed.7.0. Copyright © 2020 IEC Geneva, Switzerland. www.iec.ch