

IEEE Std C37.106™-2003
(Revision of
ANSI/IEEE C37.106-1987)

C37.106™

IEEE Guide for Abnormal Frequency Protection for Power Generating Plants

IEEE Power Engineering Society

Sponsored by the
Power System Relaying Committee



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

27 February 2004

Print: SH95150
PDF: SS95150

IEEE Guide for Abnormal Frequency Protection for Power Generating Plants

Sponsor

Power System Relaying Committee
of the
IEEE Power Engineering Society

Approved 16 June 2003
Reaffirmed 19 March 2009

IEEE-SA Standards Board

IEEE thanks the International Electrotechnical Commission (IEC) for permission to reproduce: Figure 1 on page 44 from its International Standard IEC 60034-3 “Rotating electrical machines—Part 3: Specific requirements for turbine-type synchronous machines,” 4th Ed. 1988-08. 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 by the author; nor is IEC in any way responsible for the other content or accuracy therein.

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: load shedding, overexcitation, overfrequency, underfrequency

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

Copyright © 2004 by the Institute of Electrical and Electronics Engineers, Inc.
All rights reserved. Published 27 February 2004. Printed in the United States of America.

Print: ISBN 0-7381-3732-4 SH95150
PDF: ISBN 0-7381-3733-2 SS95150

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.

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

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

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

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

In publishing and making this document available, the IEEE is not suggesting or rendering professional or other services for, or on behalf of, any person or entity. Nor is the IEEE undertaking to perform any duty owed by any other person or entity to another. Any person utilizing this, and any other IEEE Standards document, should rely upon the advice of a competent professional in determining the exercise of reasonable care in any given circumstances.

Interpretations: Occasionally questions may arise regarding the meaning of portions of standards as they relate to specific applications. When the need for interpretations is brought to the attention of IEEE, the Institute will initiate action to prepare appropriate responses. Since IEEE Standards represent a consensus of concerned interests, it is important to ensure that any interpretation has also received the concurrence of a balance of interests. For this reason, IEEE and the members of its societies and Standards Coordinating Committees are not able to provide an instant response to interpretation requests except in those cases where the matter has previously received formal consideration.

Comments for revision of IEEE Standards are welcome from any interested party, regardless of membership affiliation with IEEE. Suggestions for changes in documents should be in the form of a proposed change of text, together with appropriate supporting comments. Comments on standards and requests for interpretations should be addressed to:

Secretary, IEEE-SA Standards Board
445 Hoes Lane
P.O. Box 1331
Piscataway, NJ 08855-1331
USA

Note: 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 with respect to the existence or validity of any patent rights in connection therewith. The IEEE shall not be responsible for identifying patents for which a license may be required by an IEEE standard or for conducting inquiries into the legal validity or scope of those patents that are brought to its attention.

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

Introduction

[This introduction is not part of IEEE Std C37.106-2003, IEEE Guide for Abnormal Frequency Protection for Power Generating Plants.]

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

- 1) Protection of equipment from damage that could result from operation at abnormal frequency, and
- 2) 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 C37.106-1987):

- a) Addition of a definitions clause (Clause 3).
- b) Reference to the IEC standards (IEC 60034-1:1999 and IEC 60034-3:1996)^a and their impact on the frequency operation of generators in particular when they are applicable.
- c) Addition of a word of caution in subclause 1.1 (“Scope”) about the application of any time-frequency characteristic supplied in the guide.
- d) Addition of a word of caution in subclause 1.1 (“Scope”) about the interpretation or application of any clause originating from the referenced international standards.
- e) Removal of two turbine underfrequency relay schemes that have been evaluated as obsolete and replacement by a protection philosophy based on the use of modern multifunction generator packages.
- f) Addition of a new clause (Clause 8) on “System Wide Issues.”
- g) Addition of an informative annex (Annex B) on regional criteria.

Participants

At the time this guide was completed, the working group had the following membership:

Gabriel Benmouyal, *Chair*
E. C. Fennell, *Vice Chair*

Munnu Bajpai
M. P. Baldwin
L. Bize
H. J. Candia
J. D. Gardell
Bob Haas
J. W. Ingleson

P. Kumar
C. J. Mozina
Mukesh Nagpal
Robert Newton
Subhash Patel
Al Pierce
P. W. Powell

M. S. Sachdev
M. N. Satyanarayan
Pete Solanics
Sahib Usman
David Viers
L. C. Wang
W. P. Waudby

^aInformation on references can be found in Clause 2.

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

William Ackerman
Munnu Bajpai
George Bartok
Farouk Baxter
Gabriel Benmouyal
Kenneth Birt
Daniel Brosnan
Gustavo Brunello
Simon R. Chano
Stephen Conrad
Ratan Das
Robert Dempsey
Thomas Domin
Clifford Downs
Paul Drum
Walter Elmore

Ahmed Elneweih
A. T. Giuliant
Stephen Grier
Roger Hedding
James D. Huddleston, III
J. W. Ingleson
Joseph L. Koepfinger
Daniel Love
Gregory Luri
Jesus Martinez
Thomas McCaffrey
Jeff McElray
Gary Michel
William Mindick
George Nail

George Parr
Subhash Patel
Robert Pettigrew
Radhakrishna Rebbap-
ragada
Charles Rogers
James Ruggieri
M. S. Sachdev
Tarlochan Sidhu
James Stoner
John Tengdin
S. Thamilaras
Demetrios Tziouvaras
Gerald Vaughn
Charles Wagner
W. P. Waudby

When the IEEE-SA Standards Board approved this guide on 16 June 2003, it had the following membership:

Don Wright, *Chair*

Howard M. Frazier, *Vice Chair*

Judith Gorman, *Secretary*

H. Stephen Berger
Joe Bruder
Bob Davis
Richard DeBlasio
Julian Forster*
Toshio Fukuda
Arnold M. Greenspan
Raymond Hapeman

Donald M. Heirman
Laura Hitchcock
Richard H. Hulett
Anant Jain
Lowell G. Johnson
Joseph L. Koepfinger*
Tom McGean
Steve Mills

Daleep C. Mohla
William J. Moylan
Paul Nikolich
Gary Robinson
Malcolm V. Thaden
Geoffrey O. Thompson
Doug Topping
Howard L. Wolfman

*Member Emeritus

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

Alan Cookson, *NIST Representative*
Satish K. Aggarwal, *NRC Representative*

Andrew Ickowicz
IEEE Standards Project Editor

Contents

1. Overview	1
1.1 Scope	1
2. References	2
3. Definitions	2
4. Generator-transformer abnormal frequency capabilities and protection	3
4.1 General background	3
4.2 Generator over/underfrequency capability	4
4.3 Generator and transformer overexcitation capability	6
4.4 Generator-transformer volts per Hertz protection	10
5. Turbine abnormal frequency capabilities	13
5.1 Turbine over/underfrequency capability	13
5.2 Steam turbine over/underfrequency capabilities	14
5.3 Combustion turbine over/underfrequency capabilities	15
5.4 Over/underfrequency capabilities of combined cycle units	16
5.5 Hydraulic turbine over/underfrequency capabilities	17
5.6 Over/underfrequency operational limits for a steam turbine	17
6. Turbine abnormal frequency protection	18
6.1 Underfrequency protection methods for steam turbines	18
6.2 Load-shedding based underfrequency protection	19
6.3 Protective system philosophy and criteria	19
6.4 Turbine underfrequency protection relay schemes	20
6.5 Combustion turbine underfrequency protection philosophy, relay settings, and guidelines	21
6.6 Underfrequency protection considerations for combined-cycle generating units	22
7. Impact of abnormal frequencies on power plant auxiliaries	22
7.1 Power plant auxiliaries—underfrequency considerations	22
7.2 Bus transfer issues	23
7.3 Nuclear plants—general background	23
8. System-wide issues	25
8.1 System natural response	25
8.2 Automatic generation control	26
8.3 Islanding and underfrequency load shedding	26
8.4 Generator underfrequency tripping	27
8.5 Regional criteria	27
Annex A (informative) Bibliography	28
Annex B (informative) Regional criteria	31

IEEE Guide for Abnormal Frequency Protection for Power Generating Plants

1. Overview

1.1 Scope

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. Emphasis is placed on the protection of the major generating station components at fossil steam generating stations, nuclear stations, and on combustion turbine installations. Consideration is also 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 either load shedding or a discrete under-frequency protective function. If both load shedding and a discrete protective function are used, then they must be coordinated.

It should be borne in mind that much of the information concerning the operation of turbines and generators at off-nominal frequency, very often, do not belong to the public domain and may vary from one manufacturer to another. In view of that situation, it is recommended that any piece of data presented in the guide as fictitious, example or typical should be discussed with the equipment supplier in order to obtain the relevant and detailed information for a particular equipment or installation.

Furthermore, when specifications or clauses originating from international standards are presented and discussed, it is by no means meant that these specifications are automatically applicable. Verification should be made with the manufacturer about which standards the equipment has been designed to comply with.

When reference is made in the text to rated frequency, it is meant as 60 Hz or 50 Hz. When examples are provided at the specific frequency of 60 Hz, they are also applicable to 50 Hz.

2. References

ANSI C50.13-1989, American National Standard Requirements for Cylindrical-Rotor Synchronous Generators.¹

IEC 60034-1:1999, Rotating Electrical Machines—Part 1: Rating and Performance.²

IEC 60034-3:1996, Rotating Electrical Machines—Part 3: Specific Requirements for Turbine-Type Synchronous Machines.

IEEE C37.102™ -1995 (R2001), IEEE Guide for AC Generator Protection.^{3, 4}

IEEE C57.12.00™ -2000, IEEE Standard General Requirements for Liquid-Immersed Distribution, Power, and Regulating Transformers.

3. Definitions

For the purpose of this standard, the following terms and definitions apply. IEEE 100, *The Authoritative Dictionary of IEEE Standards Terms* [B22], should be referenced for terms and definitions not defined in this clause.

3.1 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.

3.2 combined-cycle power plant: A power plant that incorporates combustion 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.

3.3 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.

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

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

3.6 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.

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

¹ANSI publications are available from the Sales Department, American National Standards Institute, 25 West 43rd Street, 4th Floor, New York, NY 10036, USA (<http://www.ansi.org/>).

²IEC publications are available from the Sales Department of the International Electrotechnical Commission, Case Postale 131, 3, rue de Varembe, CH-1211, Genève 20, Switzerland/Suisse (<http://www.iec.ch/>). IEC publications are also available in the United States from the Sales Department, American National Standards Institute, 11 West 42nd Street, 13th Floor, New York, NY 10036, USA.

³IEEE publications are available from the Institute of Electrical and Electronics Engineers, 445 Hoes Lane, P.O. Box 1331, Piscataway, NJ 08855-1331, USA (<http://standards.ieee.org/>).

⁴The IEEE standards and products referred to in Clause 2 are trademarks belonging to the Institute of Electrical and Electronics Engineers, Inc.

3.8 load rejection: Loss of load at the generator output.

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

3.10 overexcitation: A condition which occurs whenever a generator or transformer ratio of the voltage and 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).

3.11 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.

3.12 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.

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

3.14 steam turbine (ST): 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.

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

3.16 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.

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

3.18 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.

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 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 over/underfrequency capability

4.2.1 General considerations

There are two principal considerations associated with operation of synchronous generators outside of the standard frequency range: 1) accelerated aging of mechanical components, which happens during both underfrequency and overfrequency, and 2) 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 should be at reduced kilovoltamperes (kVA) in synchronous generators. Figure 1 shows typical recommended maximum continuous loading at various frequencies for 2-pole or 4-pole cylindrical rotor generators as published by two manufacturers.

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 should 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 ANSI C50.13-1989⁵ and are shown in Figure 2.

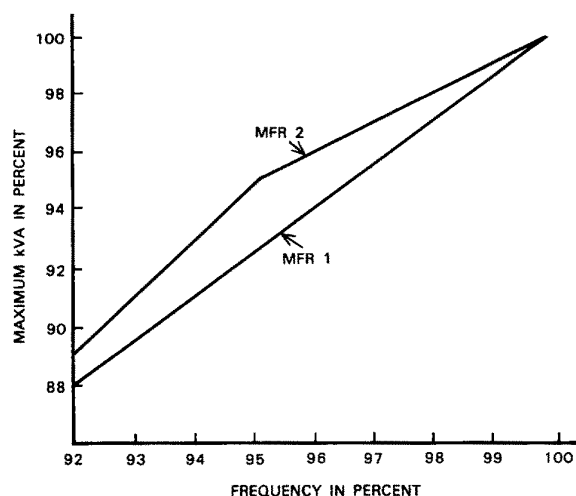


Figure 1—Generator capability versus frequency

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% or less of rated voltage.

⁵Information on references can be found in Clause 2.

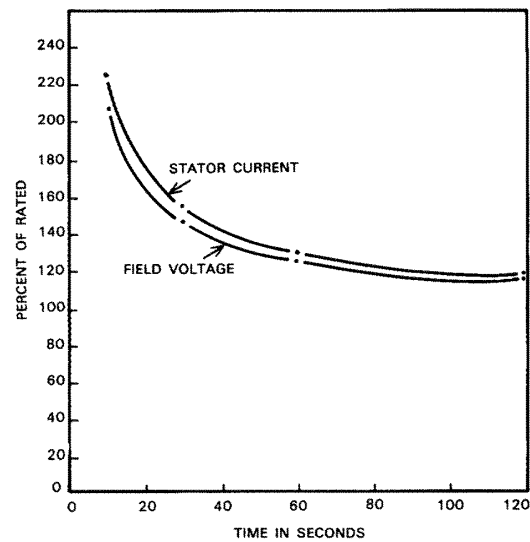


Figure 2—Generator short-time thermal capability

Another concern during extended underfrequency or overfrequency operation is excitation of mechanical resonances, particularly double-frequency torsional resonances of rotating components that are excited by operation at off-nominal frequencies coincident with high negative sequence levels within the local transmission system. System negative sequence may provide a forcing torque on the generator rotating components at twice the system frequency of quite high magnitude. For example, a system negative sequence voltage of 2.5% may result in a generator negative sequence current of roughly 8% (assuming a generator negative sequence reactance of 15% and a main transformer leakage reactance of 16%) and produce a torque at twice system frequency (120 Hz for a 60 Hz system) of roughly 8% of the generator steady state torque. If such a torque is applied when the generator rotor is operating at half of a torsional natural frequency, high cycle fatigue damage can be rapid, cumulative, and destructive. Some manufacturers may place total cumulative time limits (e.g. 2 hours lifetime, etc.) for operation within the IEC frequency bandwidth but outside of the continuous range (95–98% and 102–103% of nominal frequency).

Although the risk of simultaneous operation at frequencies other than nominal and high system negative sequence may seem unlikely, it is a possible condition that should be evaluated in the determination of the amount of time a unit should be allowed to operate beyond the continuous range. Consideration may be given to employing two sets of continuous negative sequence current relay settings: one for operation within the continuous frequency range and one for operation in the short term range described by IEC 60034-3:1996 (see 4.2.2).

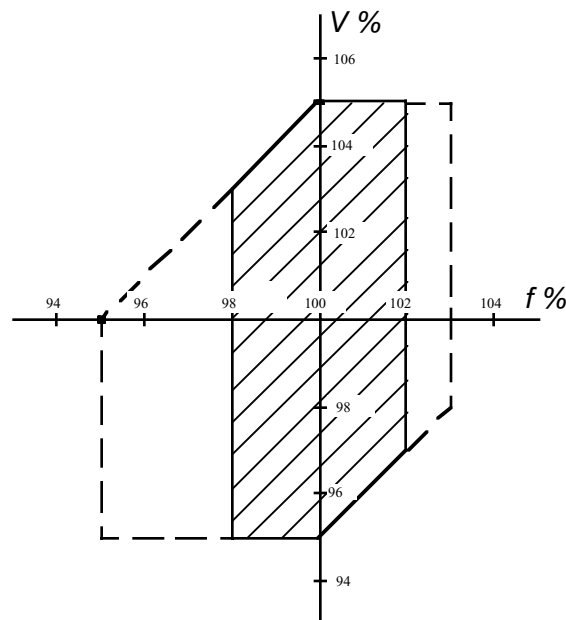
Occasionally, changes will be made to a synchronous machine or turbine after it goes into service that change the mechanical natural frequencies of the shaft system. While the changes may seem innocuous or beneficial for the thermal and electrical performance, they can greatly increase the risk exposure to operation at or near a torsional natural frequency during off-nominal frequency operation. For example, a rotating rectifier exciter may be replaced with collector rings of much smaller mass, increasing the torsional natural frequencies of the shaft system, perhaps into the continuous range, if the closest torsional natural frequency is below twice running speed. Similarly, changes in turbine blading, generator blower blading, retaining ring design (“long ring” vs. “short ring”, etc.) may have a significant impact (beneficial or detrimental) on operation at frequencies other than nominal. Any changes to the shaft system must be considered in the assessment of the frequency capability of a turbine generator.

4.2.2 Conformance to IEC 60034-3:1996

Some turbine generators are designed to accommodate the IEC 60034-3:1996 frequency-voltage characteristics. IEC 60034-3:1996 requires generators to deliver continuously rated output at the rated power factor over the ranges of $\pm 5\%$ in voltage and $\pm 2\%$ in frequency, as shown by the shaded area in Figure 3.

IEC 60034-3:1996 recommends that operation outside the shaded area “be limited in extent, duration and frequency of occurrence.” 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 98–102% 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 (98–102% of rated frequency) as soon as possible and to minimize operation outside of this range, both in extent and in duration, and in concert with load shedding practices.



SOURCE: IEC 60034-3:1996 (Figure 1)

Figure 3—Operation over ranges of voltage and frequency

4.3 Generator and transformer overexcitation capability

Overexcitation exists whenever the per unit V/Hz exceeds the design limits of the equipment.

Power transformers directly connected to generators may be subjected to overexcitation during generator run-up or run-down. Load shedding in systems supplied by overhead lines or cables can cause overvoltages and result in overexcitation of power transformers.