



IEEE Guide for the Application of Protective Relays Used for Abnormal Frequency Load Shedding and Restoration

IEEE Power Engineering Society

Sponsored by the
Power Systems Relaying Committee

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

24 August 2007

IEEE Std C37.117™-2007

IEEE Guide for the Application of Protective Relays Used for Abnormal Frequency Load Shedding and Restoration

Sponsor

**Power Systems Relaying Committee
of the
IEEE Power Engineering Society**

Approved 8 March 2007

IEEE-SA Standards Board

Abstract: Information on the application of underfrequency load shedding and restoration to ac power systems is compiled in this guide. Various system conditions that may require the use of underfrequency load shedding and the application of protective relays to various methods of performing underfrequency load shedding are described in this guide. Some practical examples of underfrequency load shedding applications are also provided.

Keywords: protective relaying, relay applications, relaying, underfrequency

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

Copyright © 2007 by the Institute of Electrical and Electronics Engineers, Inc.
All rights reserved. Published 24 August 2007. 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.

Print: ISBN 0-7381-5539-X SH95634
PDF: ISBN 0-7381-5540-3 SS95634

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. At lectures, symposia, seminars, or educational courses, an individual presenting information on IEEE standards shall make it clear that his or her views should be considered the personal views of that individual rather than the formal position, explanation, or interpretation of the IEEE.

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
Piscataway, NJ 08854
USA

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 C37.117-2007, IEEE Guide for the Application of Protective Relays Used for Abnormal Frequency Load Shedding and Restoration.

This is a new guide that addresses the application of protective relays used for load shedding and restoration during electric power system abnormal frequency conditions. It presents background information, bibliography, and recommendations. It discusses abnormal frequency power system behavior, existing load shedding and restoration practices, the abnormal frequency function of typical protective relays, and possible new methods for improved load shedding and restoration. This guide is limited to electric power system applications and does not include abnormal frequency protection for power generating plants.

Notice to users

Errata

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

Interpretations

Current interpretations can be accessed at the following URL: <http://standards.ieee.org/reading/ieee/interp/index.html>.

Patents

Attention is called to the possibility that implementation of this guide may require use of subject matter covered by patent rights. By publication of this guide, 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 or patent applications for which a license may be required to implement an IEEE standard or for conducting inquiries into the legal validity or scope of those patents that are brought to its attention.

Participants

At the time this guide was submitted to the IEEE-SA Standards Board for approval, the C9 Under-frequency Load Shedding and Restoration Working Group had the following membership:

Alexander Apostolov, *Chair*
Kenneth C. Behrendt, *Vice Chair*

Ron Beazer	Wayne Hartmann	Mukesh Nagpal
Miroslav Begovic	Rich Hunt	Damir Novosel
Gabriel Bennmouyal	Mohamed Ibrahim	Murari Saha
Kenneth A. Birt	Gerald F. Johnson	Hong Ming Shuh
Brent Brobak	Dan Karlsson	Tarlocham Sidhu
Arvind Chaudhary	Ali Kazemi	Michael J. Thompson
Al Darlington	Ljubomir Kojovic	Demetrios A. Tziouvaras
Mike DeCesaris	Marc Lacroix	Eric Udren
Tom Domin	Tom Lanigan	Benton Vandiver
David Emigh	David Leonhardt	Don Ware
John Ferraro	Vahid Madani	Ray Young
Bill Feero	Dean H. Miller	Richard C. Young
	Pratap Mysore	

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

William J. Ackerman	Gary R. Engmann	Mark F. McGranaghan
Steven C. Alexanderson	Fredric A. Friend	Gary L. Michel
Ali Al Awazi	Frank J. Gerleve	Dean H. Miller
Munnu Bajpai	Jeffrey G. Gilbert	Joydeep Mitra
Thomas M. Barnes	Manuel M. Gonzalez	Charles A. Morse
G. J. Bartok	Stephen E. Grier	Karl N. Mortensen
Michael J. Basler	Randall C. Groves	George R. Nail
David L. Bassett	Roger A. Hedding	Michael S. Newman
Kenneth C. Behrendt	Gary A. Heuston	Gary L. Nissen
Wallace B. Binder, Jr.	Jerry W. Hohn	James M. O'Brien
Kenneth A. Birt	Dennis Horwitz	Robert D. Pettigrew
Oscar E. Bolado	James D. Huddleston, III	Charles W. Rogers
Stuart H. Bouchey	Gerald F. Johnson	M. S. Sachdev
Steven R. Brockschink	Hermann Koch	Steven Sano
Chris Brooks	David W. Krause	Bogdan Seliger
Gustavo A. Brunello	Edward Krizauskas	Paul B. Sullivan
Tommy P. Cooper	Jim Kulchisky	Richard P. Taylor
James R. Cornelison	Federico Lopez	S. Thamilarasan
Luis M. Coronado	William G. Lowe	Michael J. Thompson
Randall P. Crellin	William Lumpkins	Demetrios A. Tziouvaras
J. P. Disciullo	G. L. Luri	Joe D. Watson
Michael J. Dood	Vahid Madani	William P. Waudby
Randall L. Dotson	Keith N. Malmedal	Kenneth D. White
Paul R. Drum	Omar S. Mazzoni	James W. Wilson, Jr.
Donald G. Dunn	Walter P. McCannon	Richard C. Young
Paul R. Elkin		Luis E. Zambrano

When the IEEE-SA Standards Board approved this guide on 8 March 2007, it had the following membership:

Steve M. Mills, *Chair*
Robert M. Grow, *Vice Chair*
Don Wright, *Past Chair*
Judith Gorman, *Secretary*

Richard DeBlasio
Alex Gelman
William R. Goldbach
Arnold M. Greenspan
Joanna N. Guenin
Julian Forster*
Kenneth S. Hanus
William B. Hopf

Richard H. Hulett
Hermann Koch
Joseph L. Koepfinger*
John Kulick
David J. Law
Glenn Parsons
Ronald C. Petersen
Tom A. Prevost

Narayanan Ramachandran
Greg Ratta
Robby Robson
Anne-Marie Sahazizian
Virginia C. Sulzberger*
Malcolm V. Thaden
Richard L. Townsend
Howard L. Wolfman

*Member Emeritus

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

Satish K. Aggarwal, *NRC Representative*
Alan H. Cookson, *NIST Representative*
Virginia C. Sulzberger, *Member/TAB Representative*

Jennie Steinhagen
IEEE Standards Program Manager, Document Development

Matthew J. Ceglia
IEEE Standards Program Manager, Technical Program Development

Contents

1. Overview	1
1.1 Scope	1
1.2 Purpose	1
2. Normative References	1
3. Description of system conditions addressed in this guide	2
4. Normal and abnormal frequency operation of electrical power systems and its effect on equipment in the system	3
4.1 Power system dynamic	3
4.2 Abnormal frequency operation of power systems	4
5. Underfrequency load shedding and restoration philosophy	6
6. Underfrequency load shedding methods	8
6.1 Manual/SCADA load shedding	8
6.2 Automatic load shedding	8
6.3 Local	9
6.4 Wide area underfrequency load shedding	11
7. Load restoration methods	12
8. Frequency relays, measuring principles, and characteristics	13
8.1 Electromechanical relays	13
8.2 Solid-state (static) relays	13
8.3 Microprocessor (digital) relays	14
9. Operating principles	14
9.1 Fixed frequency	14
9.2 Rate of change of frequency df/dt	15
9.3 Average rate of change $\Delta f/\Delta t$	18

10. Scheme design.....	19
10.1 Dependability and security	19
10.2 Redundant frequency relays sensing multiple voltage sources	19
10.3 Current and voltage supervision	19
10.4 Directional power supervision.....	22
10.5 Rate-of-frequency-change supervision.....	22
11. Effects of voltage change on frequency load shedding	23
12. Existing frequency load shedding and restoration practices	24
12.1 NERC: 2003 underfrequency load shed criteria.....	24
12.2 Nordel underfrequency load shed criteria	26
12.3 France, Electricité de France underfrequency load shedding.....	26
12.4 Ireland, Electricity Supply Board underfrequency load shedding and automatic frequency restoration	27
12.5 Industrial applications	28
13. Setting and performance criteria	29
13.1 Performance criteria	29
13.2 Setting guidelines for abnormal frequency load shedding	30
14. Maintenance, testing, and reliability.....	31
14.1 Frequency protection elements	32
14.2 Rate-of-change elements	32
14.3 Average rate-of-change elements	33
14.4 Testing of load shedding schemes	34
14.5 Testing of load restoration schemes	34
15. Examples	34
15.1 Practical application of load shedding.....	34
15.2 Historical examples of underfrequency load shedding during system disturbances	36
Annex A (informative) Bibliography	40

IEEE Guide for the Application of Protective Relays Used for Abnormal Frequency Load Shedding and Restoration

1. Overview

1.1 Scope

This document serves as a guide for the application of protective relays used for load shedding and restoration during electric power system abnormal frequency conditions. It presents background information, a bibliography, and recommendations. It discusses abnormal frequency power system behavior, existing load shedding and restoration practices, the abnormal frequency function of typical protective relays, and possible new methods for improved load shedding and restoration. This guide is limited to electric power system applications and does not include abnormal frequency protection for power generating plants.

1.2 Purpose

There is currently no IEEE guide for the application of protective relays used for load shedding and restoration during electric power system abnormal frequency conditions. This guide complements IEEE Std C37.106™-2003 [B35].¹ It provides information to assist in the application of load shedding and restoration schemes. Methods and examples are provided.

2. Normative references

The following referenced documents are indispensable for the application of this document. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments or corrigenda) applies.

¹ The numbers in brackets correspond to those of the bibliography in Annex A.

Arrilaga, J., and Harker, B. J., *Computer Modelling of Electrical Power Systems*, 1st ed. New York: John Wiley and Sons, 1983, pp. 220–222.

Bjerg, G. J., “System and load behavior following loss of generation” *IEE Proceedings*, vol. 119, no. 10, Oct. 1972.

Fink, L. H., et al., “Emergency control practices,” *IEEE Transactions on Power Apparatus and Systems*, vol. PAS-104, no. 9, pp. 2336–2341, Sept. 1985.

Mandozzi, M., et al., “Recent improvements of emergency control of ENEL power system in interconnected and isolated operation,” *Proceedings of the CIGRE Conference*, Paris, France, 1992, Paper 39-302.

Ohura, Y., et al., “Microprocessor based stabilizing control equipment for survival of isolated mid-city power system,” *IEEE Transactions on Power Delivery*, vol. PWRD-1, Oct. 1986, pp. 99–104.^{2,3}

Working Group on Methods of System Preservation During Underfrequency Conditions, “A status report on methods used for system preservation during underfrequency conditions,” *IEEE Transactions on Power Apparatus and Systems*, vol. PAS-94, no. 2, Mar./Apr. 1975, pp. 360–366.

3. Description of system conditions addressed in this guide

The predominant system condition addressed in this guide involves the use of protective relays for underfrequency shedding of connected load in the event of insufficient generation or transmission capacity within a power system. When load and supply for an isolated portion of the power system are unequal, the generators in that area will speed up if there is a surplus of generation or slow down if there is a deficit. When the load in a power system significantly exceeds generation, the system can survive only if enough load is separated from the system with a shortage in generation to cause generator output to be equal to or slightly above the connected load. The generation deficiency most often results from the loss of a major transmission line or transformer that is involved in a large transfer of power within the power system or between interconnected systems. Unplanned loss of a major generation source may also cause the deficiency. Frequency is a reliable indicator that such a deficiency condition exists on the power system.

Underfrequency load shedding is performed in order to minimize the risk of a further uncontrolled system separation, loss of generation, or system shutdown. If sufficient load is shed to preserve interconnections and keep generators online, the system can be restored rapidly. If the system collapses, a prolonged outage will result.

Underfrequency load shedding plans are based on studies of a system’s dynamic performance, given the greatest probable imbalance between load and generation. Plans should be coordinated between interconnected power systems as well as with underfrequency isolation of generating units, tripping of shunt capacitors, and other automatic actions that occur in the system under abnormal frequency, voltage, or power flow conditions.

In the case of ties to industrial and commercial customers that have local generation, underfrequency load shedding can be used to quickly remove non-essential industrial load in an effort to match essential industrial load to the available generation in the event the utility supply is lost.

Underfrequency relaying can also be utilized to sense disturbances and separate power systems by opening system ties. This requires close coordination between interconnected power systems. Similar relaying can

² IEEE publications are available from the Institute of Electrical and Electronics Engineers, 445 Hoes Lane, Piscataway, NJ 08855-1331, USA (<http://standards.ieee.org/>).

³ The IEEE standards or products referred to in this clause are trademarks of the Institute of Electrical and Electronics Engineers, Inc.

be utilized to separate non-utility generation from the utility power system during system disturbances, but this must be closely coordinated with the underfrequency load shedding schemes utilized on the host system.

After an underfrequency load shedding event, frequency relays can be utilized to automatically restore or supervise the restoration of load to a power system. Sufficient time delay should be employed to assure that the power system is stable prior to initiating load restoration.

In areas where isolation of a large surplus of generation relative to connected load can be anticipated, automatic overfrequency tripping of generation may be considered to prevent excessive high frequency and resultant uncontrolled generator tripping and equipment damage.

4. Normal and abnormal frequency operation of electrical power systems and its effect on equipment in the system

4.1 Power system dynamic

An electric power system behaves like a mechanical system in rotation. Figure 4-1 shows a simplified power system. Mechanical power is produced from water or steam and causes mechanical torque T_{mech} on the shaft that joins the turbine to the generator. The generator transforms the mechanical power into electrical power. The load connected to the generator causes an electrical torque T_{elec} on the shaft. As shown in Figure 4-1, a change in power demand or in production causes a fluctuation of the speed of the turbine-generator, resulting in fluctuation of the frequency of the power system.

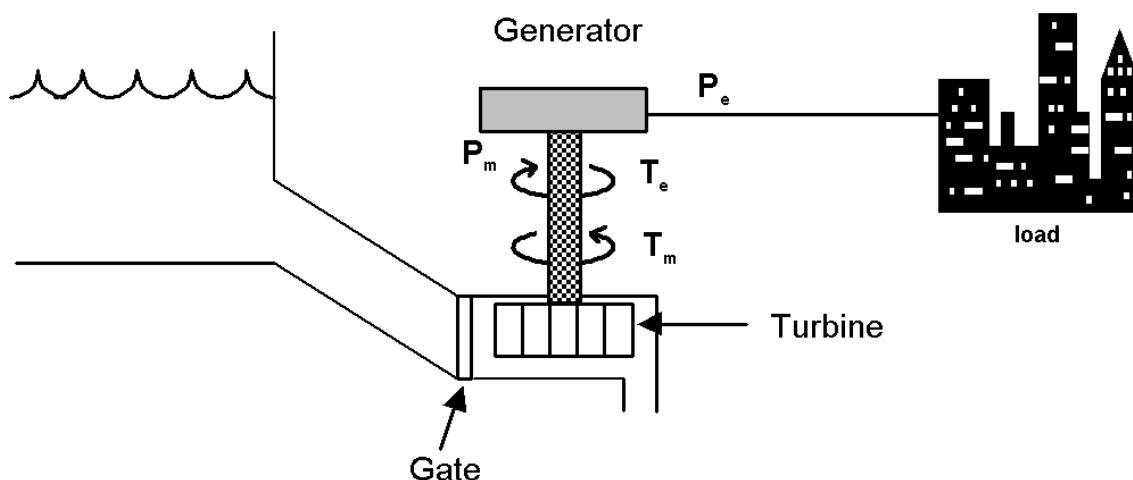


Figure 4-1—Power system model

A difference between the electrical torque and the mechanical torque creates an accelerating torque T_a , given in Equation (1) as follows:

$$T_a = T_{\text{mech}} - T_{\text{elec}} \quad (1)$$

The equation of motion shows the relation between the accelerating torque and the resulting angular acceleration of the turbine, given in Equation (2) as follows:

$$T_a = T_{\text{mech}} - T_{\text{elec}} = J \frac{\partial \omega}{\partial t} \quad (2)$$

where

J is the moment of inertia (kg-m²)

ω is the angular velocity (rad/s)

$\frac{\partial \omega}{\partial t}$ is the angular acceleration (rad/s²)

T_a is the resulting torque (N-m or J/rad)

For small variations:

$$P_{\text{mech}} \approx T_{\text{mech}}$$

and

$$P_{\text{elec}} \approx T_{\text{elec}}$$

Then:

$$P_{\text{mech}} - P_{\text{elec}} = J \frac{\partial \omega}{\partial t} \quad (3)$$

where

P_{mech} is mechanical power

P_{elec} is electrical power

From Equation (3), any variation in P_{elec} or P_{mech} affects the frequency of the power system.

4.2 Abnormal frequency operation of power systems

Subclause 4.1 described how the frequency fluctuates when there is a change in the production of, or in the demand for, energy. If a generator trips, the frequency will decline. Depending on the prime mover and spinning reserve, the frequency will eventually go back to its desired value (Figure 4-2). However, if frequency drops too low, underfrequency relays may initiate load shedding to stop frequency decline and begin frequency recovery.

If the loss of generation is greater than the spinning reserve, the frequency could eventually stabilize at a new value lower than the desired one (Figure 4-3). However, in practice, underfrequency relaying is used to reestablish the balance between power demand and the available production. Underfrequency load shedding will prevent frequency from staying too low for too long. If the frequency decline is excessive, generating units can be automatically tripped off causing an additional decline of frequency, and possible

collapse of the system. It is very important to coordinate system underfrequency load shedding with underfrequency protection of the generator. Premature generator tripping, before system load shedding is complete, can lead to unnecessary system collapse.

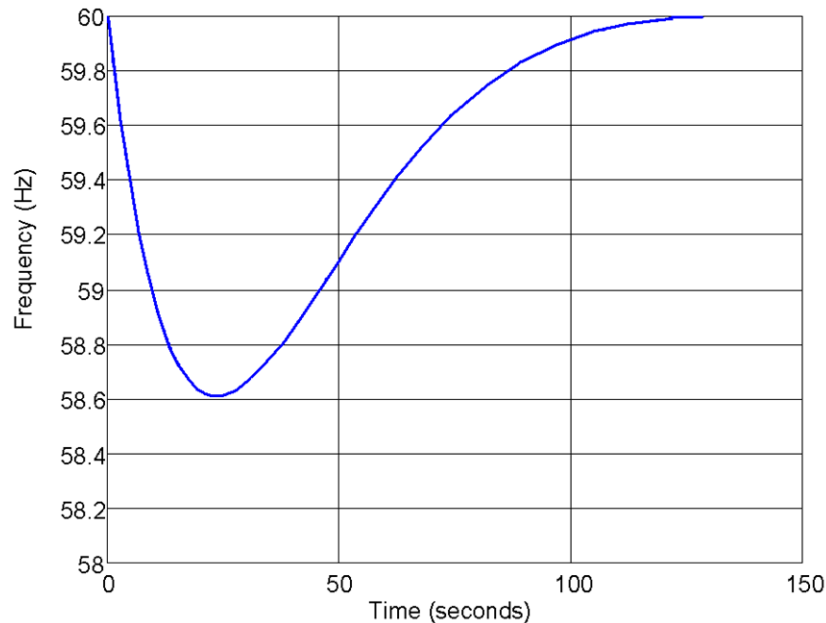


Figure 4-2—Frequency changes with sufficient spinning reserve

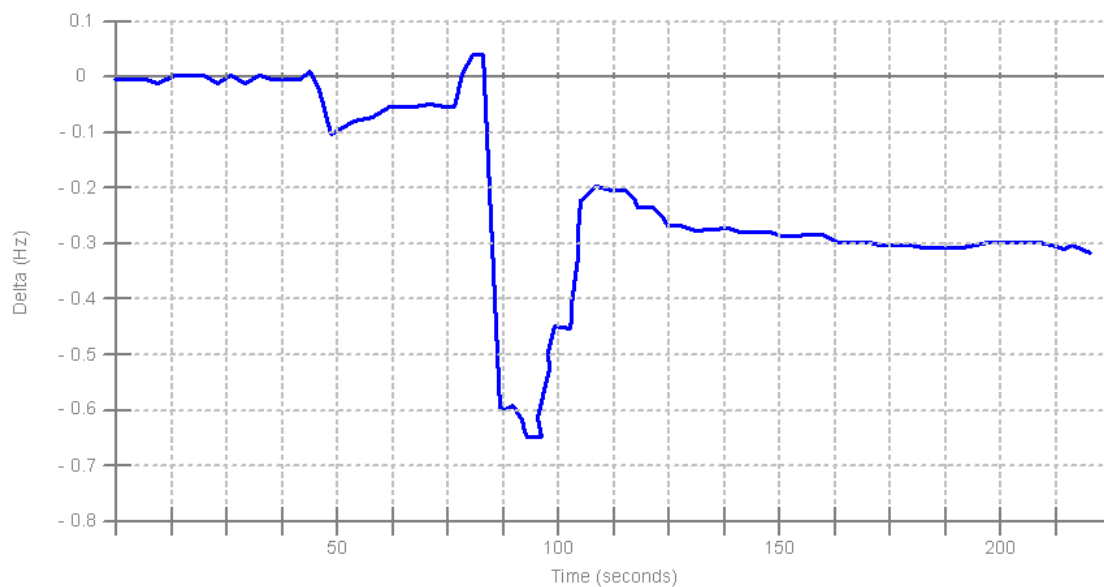


Figure 4-3—Frequency oscillation with insufficient spinning reserve

Looking again at the relation developed in Equation (3), Equation (4) follows:

$$\Delta P = J \frac{\partial \omega}{\partial t} \quad (4)$$

The rate of change of frequency is proportional to the power imbalance, ΔP .

Figure 4-4 illustrates the theoretical relationship between percentage of loss of generation and the resulting rate of change of frequency. The rate of change of frequency is an instantaneous indicator of power deficiency. In actual power systems, rate of change of frequency has an oscillatory nature due to the oscillatory nature of the change in machine speed. The frequency oscillations vary with the response of the generators and interaction between the generators, and will differ by location and the power system condition that has prompted the response. The instantaneous system frequency, and the rate of frequency change will differ between the center of inertia of the power system, and individual buses on the power system.

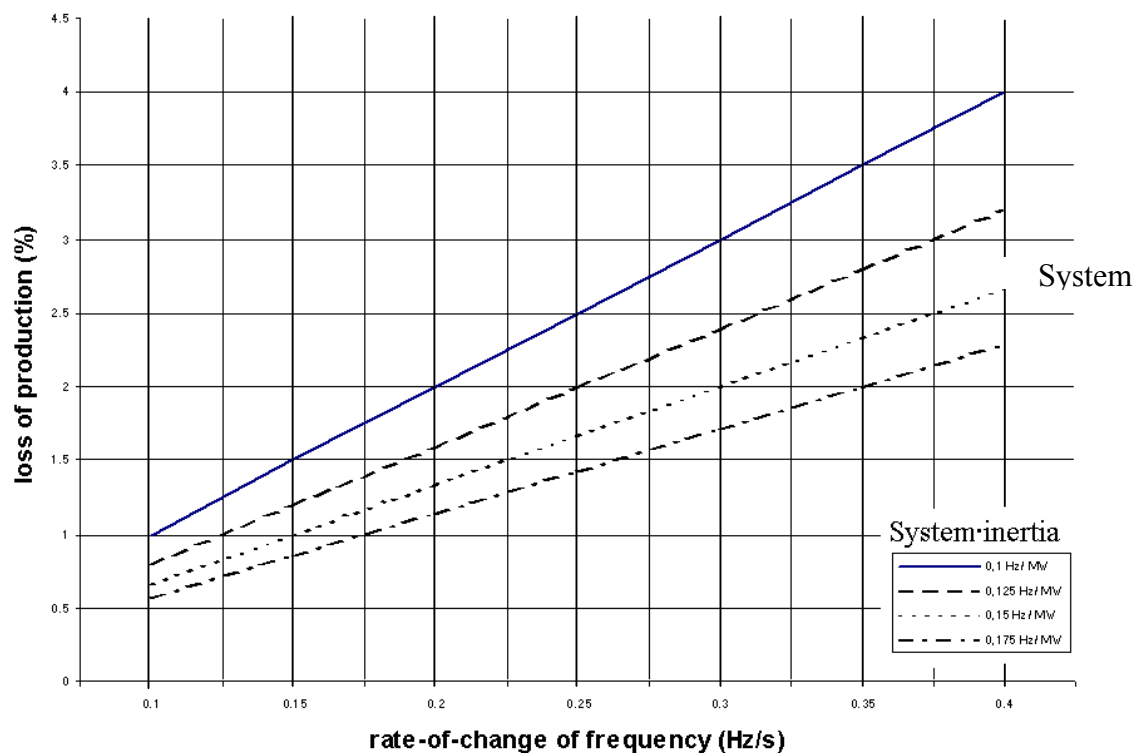


Figure 4-4—Rate-of-change of frequency versus loss of generation

5. Underfrequency load shedding and restoration philosophy

An automatic underfrequency load shedding program is applied to restore the system frequency to an acceptable level following a major system emergency that can cause a generation deficiency. In addition, automatic underfrequency load shedding can prevent a total system collapse and can help achieve fast restoration of all affected loads. The North American Electric Reliability Council (NERC) following the 1965 northeast blackout recommended the implementation of underfrequency load shedding in the U.S.