

IEEE Recommended Practice for Voltage Sag and Short Interruption Ride- Through Testing for End-Use Electrical Equipment Rated Less than 1 000 V

IEEE Industry Applications Society

Sponsored by the
Power Systems Engineering Committee



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

IEEE Std 1668™-2017
(Revision of IEEE Std 1668-2014)

IEEE Recommended Practice for Voltage Sag and Short Interruption Ride- Through Testing for End-Use Electrical Equipment Rated Less than 1000 V

Sponsor

**Power Systems Engineering Committee
of the
IEEE Industry Applications Society**

Approved 14 June 2017

IEEE-SA Standards Board

This is a Redline Document produced by Techstreet, a business of Clarivate Analytics

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

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

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

Redline Processing Notes:

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

Abstract: A non-industry-specific recommended practice for voltage sag and short interruption ride-through performance and compliance testing for all electrical and electronic equipment connected to low-voltage power systems that can experience malfunction or shutdown as a result of reductions in supply voltage lasting less than one minute is detailed in this document. Testing procedures and requirements for test equipment are clearly defined within this document to reflect this electrical environment, including single-phase, two-phase, and three-phase balanced and unbalanced voltage sags. Requirements for certification and test reporting, including characterization of voltage-sag ride-through equipment are also defined.

Keywords: equipment testing, IEEE 1668™, immunity, power quality, ride-through, voltage dip, voltage sag, voltage-sag characteristics

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

Copyright © 2017 by The Institute of Electrical and Electronics Engineers, Inc.
All rights reserved. Published 27 November 2017. 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.

The National Electrical Code, NEC, and NFPA 70E are registered trademarks of the National Fire Protection Association.

PDF: ISBN 978-1-5044-4389-0 STD22823
Print: ISBN 978-1-5044-4390-6 STDPD22823

IEEE prohibits discrimination, harassment, and bullying.

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

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

Important Notices and Disclaimers Concerning IEEE Standards Documents

IEEE documents are made available for use subject to important notices and legal disclaimers. These notices and disclaimers, or a reference to this page, appear in all standards and may be found under the heading “Important Notices and Disclaimers Concerning IEEE Standards Documents.” They can also be obtained on request from IEEE or viewed at <http://standards.ieee.org/IPR/disclaimers.html>.

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

IEEE Standards documents (standards, recommended practices, and guides), both full-use and trial-use, are developed within IEEE Societies and the Standards Coordinating Committees of the IEEE Standards Association (“IEEE-SA”) Standards Board. IEEE (“the Institute”) develops its standards through a consensus development process, approved by the American National Standards Institute (“ANSI”), which brings together volunteers representing varied viewpoints and interests to achieve the final product. IEEE Standards are documents developed through scientific, academic, and industry-based technical working groups. Volunteers in IEEE working groups are not necessarily members of the Institute 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 Standards do not guarantee or ensure safety, security, health, or environmental protection, or ensure against interference with or from other devices or networks. 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.

IEEE does not warrant or represent the accuracy or content of the material contained in its standards, and expressly disclaims all warranties (express, implied and statutory) not included in this or any other document relating to the standard, including, but not limited to, the warranties of: merchantability; fitness for a particular purpose; non-infringement; and quality, accuracy, effectiveness, currency, or completeness of material. In addition, IEEE disclaims any and all conditions relating to: results; and workmanlike effort. 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: PROCUREMENT OF 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 should be considered the approved IEEE standard.

Official statements

A statement, written or oral, that is not processed in accordance with the IEEE-SA Standards Board Operations Manual shall not be considered 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. At lectures, symposia, seminars, or educational courses, an individual presenting information on IEEE standards shall make it clear that his or her views should be considered the personal views of that individual rather than the formal position of IEEE.

Comments on standards

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

Comments on standards should be submitted to the following address:

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

Laws and regulations

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

Copyrights

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 by public authorities and private users, IEEE does not waive any rights in copyright to the documents.

Photocopies

Subject to payment of the appropriate fee, 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. 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 the IEEE Xplore at <http://ieeexplore.ieee.org/> or contact IEEE at the address listed previously. For more information about the IEEE-SA or IEEE's standards development process, visit the IEEE-SA Website at <http://standards.ieee.org>.

Errata

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

Patents

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

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

Participants

At the time this IEEE recommended practice was completed, the Voltage Sag Ride-through Working Group had the following membership:

Doug Dorr, *Chair*
Scott Anderson, *Vice Chair*

Yves Allard	Gary Malhoit	James Rossman
William Brumsickle	Brad Martin	Mark Rucker
Math Bollen	John Mentzer	Salman Sabbah
Jack Caufield	Mark Minzloff	Mark Stephens
John Coffman	Melinda Norris	Rick Temple
Sasa Djokic	Gregory Olson	Chuck Thomas
Brian Fortenbery	Greg Rieder	Alden Wright
Robert Gettier		John-Carl Zarella

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

Mihaela Albu	Stephen Grier	Christopher Petrola
Dwight Alexander	Randall Groves	K. James Phillips
Roy Alexander	Robert Hanna	Iulian Profir
Mohammed Ashraf Ali	Lee Herron	John Rama
Saleman Alibhay	Werner Hoelzl	Charles Rogers
Curtis Ashton	Philip Hopkinson	James Rossman
Thomas Barnes	Richard Jackson	Thomas Rozek
Frank Basciano	Laszlo Kadar	Don Russell
Thomas Bishop	Yuri Khersonsky	Ryandi Ryandi
William Bloethe	James Kinney	Donald Sabin
Math Bollen	Jim Kulchisky	Steven Sano
Kenneth Bow	Mikhail Lagoda	Bartien Sayogo
Gustavo Brunello	Thomas La Rose	Robert Schuerger
William Bush	Theo Laughner	Kenneth Sedziol
William Byrd	Albert Livshitz	Xu She
Paul Cardinal	Walter McCannon	Veselin Skendzic
Wen-Kung Chang	Thomas McCarthy	Jerry Smith
Stephen Conrad	James Michalec	Gary Smullin
Dieter Dohnal	C. Michael Miller	Wayne Stec
Gary Donner	William Moylan	Mark Stephens
Douglas Dorr	Jerry Murphy	K. Stump
Neal Dowling	R. Murphy	David Tepen
Robert Durham	Bruce Muschlitz	James Van De Ligt
Rostyslaw Fostiak	Michael Newman	James Vergis
Carl Fredericks	Joe Nims	William Walter
Dale Frederickson	Gearold O. H. Eidhin	Daniel Ward
Mietek Glinkowski	Carl Orde	Kenneth White
Jalal Gohari	Lorraine Padden	Jian Yu
Edwin Goodwin	Bansi Patel	David Zech

When the IEEE-SA Standards Board approved this recommended practice on 14 June 2017, it had the following membership:

Jean-Philippe Faure, *Chair*
Gary Hoffman, *Vice Chair*
John D. Kulick, *Past Chair*
Konstantinos Karachalios, *Secretary*

Chuck Adams
Masayuki Ariyoshi
Ted Burse
Stephen Dukes
Doug Edwards
J. Travis Griffith
Michael Janezic

Thomas Koshy
Joseph L. Koepfinger*
Kevin Lu
Daleep Mohla
Damir Novosel
Ronald C. Petersen
Annette D. Reilly

Robby Robson
Dorothy Stanley
Adrian Stephens
Mehmet Ulema
Phil Wennblom
Howard Wolfman
Yu Yuan

*Member Emeritus

Introduction

This introduction is not part of IEEE Std 1668-2017, IEEE Recommended Practice for Voltage Sag and Short Interruption Ride-Through Testing for End-Use Electrical Equipment Rated Less than 1000 V.

IEEE Std 1668-2017 is a non-industry-specific recommended practice for voltage-sag ride-through performance and compliance testing for all electrical and electronic equipment connected to low-voltage power systems that can experience malfunction or shutdown as a result of reductions in supply voltage lasting less than one minute. The recommended practice includes defining minimum voltage-sag immunity requirements based on actual voltage-sag data. A clause dedicated to the detailed analysis of voltage sags experienced by end users provides insight into real-world voltage sags. Testing procedures and test equipment requirements are clearly defined within this document to reflect this electrical environment, including single-phase, two-phase, and three-phase balanced and unbalanced voltage sags. This recommended practice also defines certification and test reporting requirements, including voltage-sag ride-through equipment characterization.

Grateful acknowledgment

The following material from CIGRE Working Group C4.1 10 Final Report, Voltage Dip Immunity of Equipment and Installations, April 2010 is reprinted with permission:

- [Table 7](#) adapted from Table 6-5 page on 185 of CIGRE report
- [Figure 19](#) adapted from 6-6 page 145 and Figure 6-35 on page 160 of CIGRE report
- [Table 8](#) adapted from Figure 2-17 page 40, and from Table 4.1 on page 101 of CIGRE report
- [Table 9](#) from un-numbered table on page 35 of CIGRE report
- [Figure 20](#) adapted from Table 4.2 on page 102 of CIGRE report
- [Figure 21](#) adapted from Table 4.1 on page 101 of CIGRE report and Table 4.2 and Table 4.3 on page 104 of CIGRE report
- [Table A.1](#) adapted from Table 4.1 on page 101 of CIGRE report and Table 4.2 and Table 4.3 on page 104 of CIGRE report

Contents

1. Overview	14
1.1 Scope	14
1.2 Purpose	14
1.3 Limitations	15
2. Normative references	15
3. Definitions, acronyms, and abbreviations	15
3.1 Definitions	15
3.2 Acronyms and abbreviations	17
4. Primer on voltage sags	18
4.1 Background on voltage sags	18
4.2 The basics of voltage sags	19
4.3 Other key voltage-sag characteristics	21
4.4 Faults and voltage sags	25
4.5 Voltage sags and current relationships	35
4.6 How common are voltage sags?	35
4.7 Other causes and effects of voltage sags	41
5. Recommended voltage-sag test requirements	42
5.1 Background on test requirements	42
5.2 Classification of voltage-sag types in three-phase systems	43
5.3 Recommended voltage-sag immunity levels	45
Annex A (informative) Test procedures and guidelines	51
Annex B (normative) Test equipment requirements	79
Annex C (normative) Certification and test reports	80
Annex D (informative) Bibliography	82

List of Figures

Figure 1—Single-phase voltage sag (instantaneous voltage rms plot)	19
Figure 2—Simplified voltage-sag magnitude duration scatter plot with an example of a 24-V dc power-supply sensitivity overlay.....	21
Figure 3—Waveforms of two voltage sags illustrating point-on-wave.....	22
Figure 4—Example of point-on-wave of voltage-sag initiation influencing the trip level of an ac contactor [B11].....	23
Figure 5—Two-phase voltage sag with positive and negative phase shift.....	24
Figure 6—Balanced voltage-sag simulation	25
Figure 7—Unbalanced voltage-sag simulation	25
Figure 8—Example of voltage sags and fault clearing times for distribution and transmission lines	26
Figure 9—Voltage recovery after fault is cleared (simulation)	27
Figure 10—Slow voltage recovery after fault is cleared (simulation)	27
Figure 11—Voltage sag at 480 Vrms utilization voltage from a transmission-system fault (A-G) simulation	29
Figure 12—Example fault scenario and timing diagram	31
Figure 13—Voltage sag at 480-Vrms utilization voltage from a single-phase fault on the distribution system (Phase A to ground, simulation).....	32
Figure 14—Voltage sag at 480-Vrms utilization voltage from a fault within a facility (simulation).....	34
Figure 15—Single-line diagram of a typical electrical system	36
Figure 16—Sag and interruption rate magnitude histogram [B6].....	38
Figure 17—Number of affected phases (i.e., voltage-sag types) for voltage sags with at least one remaining voltage below 85% of nominal [B6].....	39
Figure 18—Percent residual voltage by type of sag [B6]	40
Figure 19—Three-phase (Type III) voltage-sag contour charts [B1].....	41
Figure 20—Recommended Type I test vector where E represents the nominal phase-to-neutral voltage, V represents the residual voltage or “Dip magnitude”, and X represents the residual phase-to-neutral voltage [B1]	44
Figure 21—Recommended and alternative Type II test vectors where E represents the nominal voltage and V represents the residual voltage [B1].....	45
Figure 22—Recommended Type I and Type II test levels	46
Figure 23—Recommended Type III test levels	47
Figure A.1—Example EUT power distribution [computerized numerical controller (CNC) machine]	55
Figure A.2—Test setup (single-phase test setup shown for clarity)	57

Figure A.3—Ideal vector magnitudes for Type II, Type II.A1, and Type II.A2 voltage-sag compliance test points	59
Figure A.4—Example voltage-sag tolerance curve of an EUT	61
Figure A.5—Example EUT voltage-sag tolerance curve with PQ data overlay	62
Figure A.6—Top-down voltage-sag characterization test flow chart.....	65
Figure A.7—Top-down voltage-sag characterization method	66
Figure A.8—Left-right voltage-sag characterization test method flow chart.....	69
Figure A.9—Illustration of left-right voltage-sag characterization test method	70
Figure A.10—Box-in voltage-sag characterization test method flow chart	73
Figure A.11—Illustration of box-in voltage-sag characterization test method	74
Figure A.12—Example of a three-phase voltage sag characterization procedure.....	78

List of Tables

Table 1—Example of simplification of voltage-sag events in data analysis, rms voltage variation events (7.56-kV base voltage)	20
Table 2—Secondary transformer voltages (pu) and phase angles from a transmission-system fault (A-G) ...	30
Table 3—Four representative recloser schemes	31
Table 4—Secondary transformer voltages (pu) and phase angle from distribution system fault (A-G)	33
Table 5—Annual average SARFI rate of voltage sags (DPQ II—all sites) [B6].....	37
Table 6—Yearly SARFI rates(60-s aggregate period, DPQ I, DPQ II, and DPQ II Group 1 sites) [B6]	38
Table 7—Breakout of voltage-sag types [B1].....	40
Table 8—Recommended Type I, Type II, and Type III voltage-sag classifications [B1]	43
Table 9—Fault propagation as described by Type I, Type II, and Type III voltage-sag type classifications [B1]	43
Table 10—Recommended test points for Type I and Type II voltage sags.....	45
Table 11—Recommended test points for Type III voltage sags	47
Table 12—Voltage-sag equipment-immunity specification sheet (for use with three-phase equipment)	48
Table 13—Voltage-sag equipment-immunity single-specification sheet (for use with single-phase equipment)	49
Table A.1—Recommended and allowed voltage-sag test vectors and considerations [B1] (where E represents the nominal voltage, V represents the residual voltage, X represents the residual phase to neutral voltage).....	51
Table A.2—Test method guidance matrix for various equipment and devices	52
Table A.3—Example DAS monitoring points (three-phase test).....	56
Table A.4—Type I single-phase equipment compliance test matrix	58
Table A.5—Type I three-phase system with neutral compliance test matrix	58
Table A.6—Type II compliance testing test matrix.....	59
Table A.7—Type II.A1 (Alternative 1) compliance testing matrix.....	60
Table A.8—Type II.A2 (Alternative 2) compliance testing matrix.....	60
Table A.9—Type III compliance testing test matrix	61
Table A.10—Top-down method equipment characterization test matrix, 50 Hz example.....	66
Table A.11—Top-down method equipment characterization test matrix, 60 Hz example	67
Table A.12—Left-right method equipment characterization test matrix, 50 Hz example.....	70
Table A.13—Left-right method equipment characterization test matrix, 60 Hz example.....	71
Table A.14—Box-in method equipment characterization test matrix, 50 Hz example	74

Table A.15—Box-in method equipment characterization test matrix, 60 Hz example	75
Table A.16—Source requirements for full characterization	77

IEEE ~~Trial-Use~~ Recommended Practice for Voltage Sag and Short Interruption Ride-Through Testing for End-Use Electrical Equipment Rated Less than 1000 V

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

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

1. Overview

1.1 Scope

This document is a non-industry-specific recommended practice for voltage-sag ride-through performance and compliance testing for all electrical and electronic equipment connected to low-voltage power systems (with nominal/rated voltage less than 1000 V) that can experience malfunction or shutdown as a result of reductions in supply voltage lasting less than one minute. The recommended practice includes defining minimum voltage-sag immunity requirements based on actual voltage-sag data. A clause dedicated to the detailed analysis of voltage sags experienced by end users provides insight into real-world voltage sags. Testing procedures and requirements for test equipment are clearly defined within this document to reflect the electrical environment, including single-phase, two-phase, and three-phase, balanced and unbalanced voltage sags. The recommended practice also defines requirements for certification and test reporting, including characterization of voltage-sag ride-through equipment.

1.2 Purpose

The purpose of this recommended practice is to clearly define test methods and ride-through performance for determining the sensitivity of electrical and electronic equipment to voltage sags. Analysis of real-world sags provides the foundation for both test methods and performance criteria, aligning themselves as closely as possible to the end user's electrical environment. The recommended practice will define the characteristics in terms of the depths/magnitudes, durations, phase angles, and vectors of voltage sags required to relate to real-world voltage sags. The recommended practice will show how different voltage-sag testing methods can be used to simulate real-world sags. End users will be able to use the recommended practice in their purchase specifications to [help](#) ensure the required level of equipment performance. In addition, end users can use the voltage-sag criteria as a performance benchmark for existing equipment. This recommended practice can be used to provide a benchmark that can be used to identify equipment that has enhanced ride-through characteristics.

1.3 Limitations

This recommended practice is limited to the testing of equipment to voltage sags. Other power disturbances—including swells and harmonic and high-frequency impulsive transient events—are not within the scope of this document.

This recommended practice assumes a baseline electrical environment in compliance with ANSI C84.1-[2011](#) ~~2006~~ Range A for steady-state utilization voltage and IEEE Std 519TM-~~1992~~[2014](#) for harmonics.¹

Proper application of this recommended practice does not require any filtering of the harmonics during the testing or analysis to achieve accurate quantification of ride-through performance.

This recommended practice is a performance specification and does not address safety issues. It should not supersede any safety requirements.

¹Information on references can be found in Clause 2

This recommended practice does not override applicable international, national, and local codes.

This recommended practice does not address product quality that may or may not result in the application of the required immunity test levels.

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.

ANSI C84.1-~~2006~~, [2011](#), American National Standard for Electric Power Systems and Equipment—Voltage Ratings (60 Hertz).²

IEC 61000-4-34, Electromagnetic compatibility (EMC)—Part 4-34: Testing and measurement techniques— Voltage dips, short interruptions and voltage variations immunity tests for equipment with mains current more than 16 A per phase.³

IEEE Std 519™-~~1992~~[2014](#), IEEE Recommended Practices and Requirements for Harmonic Control in Electrical Power Systems.^{4,5}

²ANSI 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/>).

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

⁴The IEEE standards or products referred to in this clause [in](#) are trademarks ~~of~~ [owned by](#) the Institute of Electrical and Electronics Engineers, ~~Inc.~~ [Incorporated](#).

⁵IEEE publications are available from the Institute of Electrical and Electronics Engineers ~~445 Hoos Lane, Piscataway, NJ 08854, USA~~ (<http://standards.ieee.org/>).

SEMI F47-0706, Specification for Semiconductor Processing Equipment Voltage-Sag Immunity.⁶

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.⁷

calibration: The checking of a measuring instrument against an accurate standard to determine any variation of measured from actual values.

equipment under test (EUT): The electrical or electronics equipment being tested for voltage-sag ride- through performance.

galloping conductor: A transmission or distribution line that is moving unpredictably, typically due to heavy loading of ice and high winds.

immunity: The ability of equipment under test ([EUT](#)) to continuously operate (as intended) in the presence of an electromagnetic disturbance, such as voltage sags.

impulsive transient: A sudden non-power frequency change in the steady-state condition of voltage or current that is unidirectional in polarity (primarily either positive or negative) disturbance in the ac waveform typically evidenced by a sharp, brief waveform discontinuity.

interruption: *See: voltage interruption.*

⁶This standard may be obtained from the Semiconductor Equipment and Materials International (SEMI) organization at www.semi.org.

⁷*IEEE Standards Dictionary Online* ~~subscription is available at:~~
~~http://www.ieee.org/portal/innovate/products/standard/standards_dictionary.html~~ is available at: <http://dictionary.ieee.org/>.

malfunction: The failure of the equipment under test ([EUT](#)) to maintain continuous operation (as intended) in the presence of a voltage sag or momentary interruption.

momentary interruption: A type of short duration variation. The complete loss of voltage (< 0.1 pu) on one or more phase conductors for a time period between 0.5 cycles and 3 s.

nominal voltage: The voltage by which a portion of the system is designated and to which certain operating characteristics of the system are related. Each system voltage pertains to a portion of the system bounded by transformers or utilization equipment. Nominal voltage as referenced throughout the text of this document refers to nominal system voltage. All voltage values are given as root-mean-square (rms) values unless stated otherwise.

original equipment manufacturer (OEM): A company that supplies equipment to other companies for use in their manufacturing process or to incorporate into another product.

per unit (pu): ~~The A per-unit quantity pu refers to per unit, which is dimensionless. the ratio of the actual value of a quantity 1.0 pu corresponds to 100%. The nominal condition is often considered to be 1.0 pu to the base value of the same quantity.~~

phase under test (PUT): The selected phase or combination of phases during a voltage-sag test of equipment under test ([EUT](#)).

residual/remaining voltage: Minimum voltage during a voltage sag expressed in volts, as a percentage of nominal voltage, or in per unit. All residual voltage values are root-mean-square (rms) unless stated otherwise.

ride-through capability: The ability of the equipment under test ([EUT](#)) to withstand voltage sags and momentary interruptions to specified durations and magnitudes without malfunctioning.

sag: *See: voltage sag.*

sag generator: A test apparatus capable of reducing the voltage supplied to equipment under test ([EUT](#)) with specified magnitudes and phase angles for a specific duration in order to accurately reproduce different types of voltage sags and momentary interruptions.

sustained interruption: A type of long-duration root-mean-square (rms) voltage variation where the complete loss of voltage (< 0.1 pu) on one or more phase conductors is for a time greater than 1 min.

System Average Interruption Frequency Index (SAIFI-X): Indicates how often the average customer experiences a sustained interruption over a predefined period of time.

System Average rms Variation Frequency Index (SARFI-X): For X less than 100, the system average rms variation frequency index (SARFI) is a the count of short duration root mean square (rms) variations of the voltage below (for $X < 100\%$) or voltage above (for $X > 100\%$) a set percentage (X)sags at a given location site, or in a given system, per year with a magnitude less than X percent. For X more than 100: the count of voltage swells at a given site, or system over a set monitoring period (typically normalized per year), in a given system, per year with a magnitude greater than X percent. For X a predefined curve: the count of voltage sags at a given site, or in a given system, per year more severe than the curve limits

NOTE—See Sabin [B20].⁸

system integrator: A company that integrates equipment, components, and subsystems into a whole and ~~ensures~~ verifies that they all function together.

temporary interruption: A type of short duration variation. The complete loss of voltage (< 0.1 pu) on one or more phase conductors for a time period between 3 s and 1 min.

uninterruptible power supply (UPS): An electrical apparatus that provides reliable power to a load when the input power source, typically from the utility, fails.

voltage dip: *See: voltage sag.*

voltage interruption: The disappearance of the supply voltage on one or more phases. An additional qualifying term (i.e., momentary, sustained, or temporary) indicates the relative duration of the interruption.

⁸The numbers in brackets correspond to those of the bibliography in Annex D.

voltage sag: A reduction in any or all phases of supply voltage to between 0.1 pu and 0.9 pu in rms voltage or current at the power frequency for durations of 0.5 cycle to 1 min.

voltage swell: An increase in any or all phases of supply voltage or current at the power frequency for durations from 0.5 cycles to 1 min. Typical values are 1.1 pu to 1.8 pu.

3.2 Acronyms and abbreviations

CNC computerized numerical controller

DAS data acquisition system

DEV device

DPQ distribution power quality

EUT equipment under test

IGBT insulated gate bipolar transistor

ITE information technology equipment

OEM original equipment manufacturer

PLC programmable logic controller

POC point of connection

PPE personal protective equipment

pu per unit

PUT phase under test

rms root-mean-square

SAIFI-X	System Average Interruption Frequency Index
SARFI-X	System Average rms Variation Frequency Index
SCR	silicon controlled rectifier
SEMI	Semiconductor Equipment Materials International
UPS	uninterruptible power supply

4. ~~A~~ Primer on voltage sags

4.1 Background on voltage sags

~~Electrification has been called the greatest engineering achievement of the 20th Century, even though most of us today view it as a basic necessity. With the flick of a switch, our quality of life dramatically improves.~~ While the electricity delivered today generally meets the demands of the average consumer, the power quality and reliability of delivered electrical energy can vary significantly over time and from one region to another. Interruptions in electrical service and voltage anomalies can be common and accepted in some areas of the world. However, in today's more highly developed industrial and digital economies, the manufacturing processes have more stringent power quality requirements. These requirements have resulted in customers expecting higher-quality and continuity of electrical power supply with significant reductions in interruptions, as well as other power quality disturbances. However, even in the most highly developed power systems, variations in voltage do occur from time to time, and these variations affect some customers more than others. Interruptions, voltage sags, swells, overvoltages, harmonics, switching transients, flicker, and many other power quality events and disturbances are realities of all electric power systems.

One of the more predominant power quality events is the voltage sag, which is a reduction in the rms voltage magnitude below a given threshold lasting typically from several cycles to several seconds.^{9,10} It is widely known that voltage sags can have a strong impact on high-tech industries. ~~EPRI~~ [One source \[B4\]](#) has reported that a single voltage sag can cost manufacturers from tens of thousands to as much as \$2M ~~[B2]~~ US. Electrical and electronics equipment connected to electrical networks have varying degrees of sensitivity to voltage sags. This sensitivity is determined by two major factors: the design of the equipment and the physical characteristics of the voltage sag.

The goal of this recommended practice is to present and recommend voltage-sag test levels and test methods that best represent actual voltage sags. The audiences for this recommended practice include [the following](#):

- The equipment owners who want to better understand the phenomena of voltage sags and specify voltage-sag immunity testing aimed at obtaining less sensitive electrical equipment resulting in improved ride-through for critical processes.
- System integrators or original equipment manufacturers (OEMs) who are designing and building electrical equipment and ~~must therefore~~ [should](#) understand the electrical environment and the test methods that will be used to determine the immunity of their equipment.
- The test engineers who want to properly evaluate individual electrical equipment, or processes involving a number of different equipment, against voltage sags to determine the immunity or robustness of the equipment under test (EUT).

⁹The most common value for a sag-magnitude threshold (including monitoring applications) is 90% of the nominal or declared voltage.

¹⁰The minimum duration for which voltage-sag magnitude based on rms voltage value could be calculated is one half of a cycle. The upper limit for voltage-sag duration is usually set to distinguish voltage sags from steady state undervoltages which may be as long as a few minutes.

To help the reader understand the recommended requirements for voltage-sag immunity presented in this document, it is important to provide a brief background on voltage-sag characteristics and to explain how voltage sags occur and then propagate through the electrical system. This clause also aims to help the reader understand the background statistics related to the types of voltage sags as they occur on the electrical network.

4.2 The basics of voltage sags

The two basic characteristics of a voltage sag are the reduction in rms voltage magnitude (depth) and the duration of the voltage reduction. These are the most common voltage-sag parameters used.

The terminology used to describe the magnitude of voltage sags varies and is often confusing. Most commonly, voltage-sag magnitudes are expressed in percentage of the remaining nominal voltage, also stated as residual or remaining voltage, during the disturbance. For example, if a 48-V reduction in voltage magnitude occurs as a result of a voltage sag on a system with 480-V nominal voltage, resulting in a remaining/residual voltage of 432 V, this would be referred to as a “sag to 90% of nominal voltage.” Expressing the magnitude of a voltage sag as a percentage of nominal voltage allows for easy comparison between different voltage levels. This is especially helpful when analyzing the effect of faults resulting in voltage sags across wide areas and at different voltage levels.

Per IEEE Std 1159™-2009 [B13], duration of the voltage sag is defined as the time from when the rms voltage decreased below 90% of the nominal steady-state voltage to when it returned above 90% of the nominal steady-state voltage, measured in milliseconds, seconds, or cycles. An example of a voltage sag as an rms plot to 46% of nominal for 5.4 cycles (60 Hz) is shown in Figure 1.

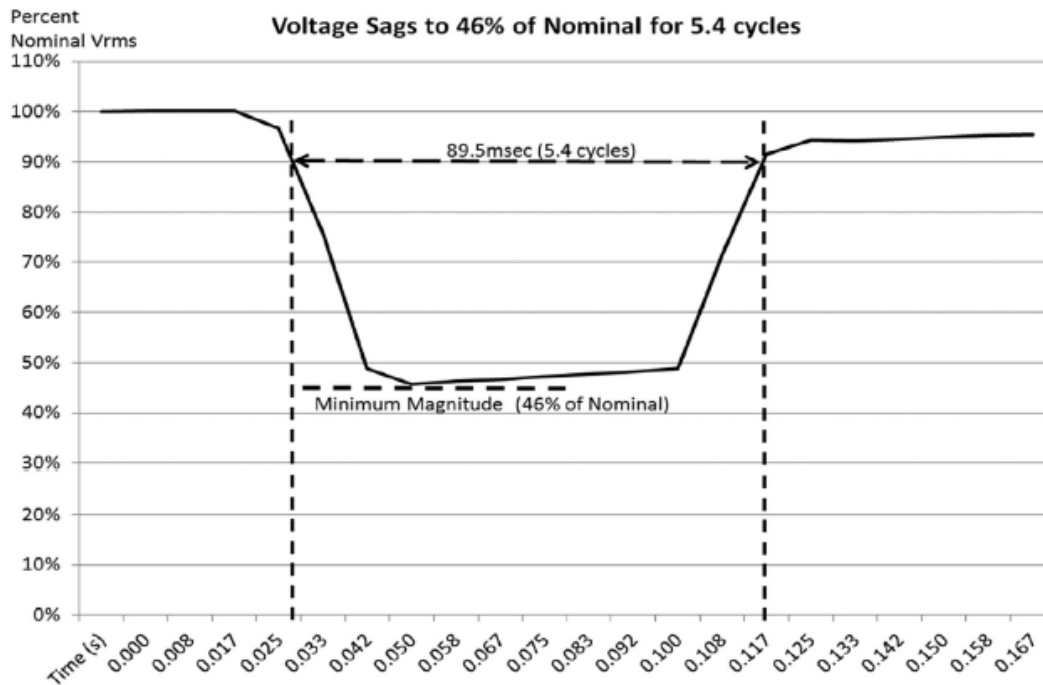


Figure 1 – Single-phase voltage sag (instantaneous voltage rms plot)

Consideration should also be given when doing voltage-sag analysis to other voltage-sag characteristics and waveform data that may be lost if the sag characterization is kept as only an rms voltage magnitude and duration. Characteristics such as phase-shift, point-on-wave of initiation, and recovery of the instantaneous voltage waveform during the sag may have an effect on equipment performance as well.

When considering three-phase systems, the magnitude and duration of three voltages ~~must~~ should be measured to obtain complete information about the voltage sag. This can be a set of three phase-to-neutral voltages or a set of three phase-to-phase voltages, or a set of three phase-to-ground voltages. Furthermore, in a three-phase system, voltage sags can be single-phase, two-phase, or three-phase in nature.

In order to simplify understanding of voltage sags, it is customary to represent a voltage sag by visualizing the worst-case voltage-sag magnitude and duration (i.e., the minimum voltage of all sagged phases and the total duration for which at least one phase is experiencing rms voltage reduction below 90% of the nominal voltage) to represent a voltage reduction event that has occurred on an electrical supply. These representations can omit the magnitude and duration of the readings that occurred on the other monitoring channels when polyphase voltage-sag events occur. The event summary shown in Table 1 is an example of the simplification that is often used to represent voltage sags. The data in the table includes the time and date of the event and the magnitude and duration information for the worst-case channel measurement from the power quality monitor.

Table 1— Example of simplification of voltage-sag events in data analysis, rms voltage variation events (7.56-kV base voltage)

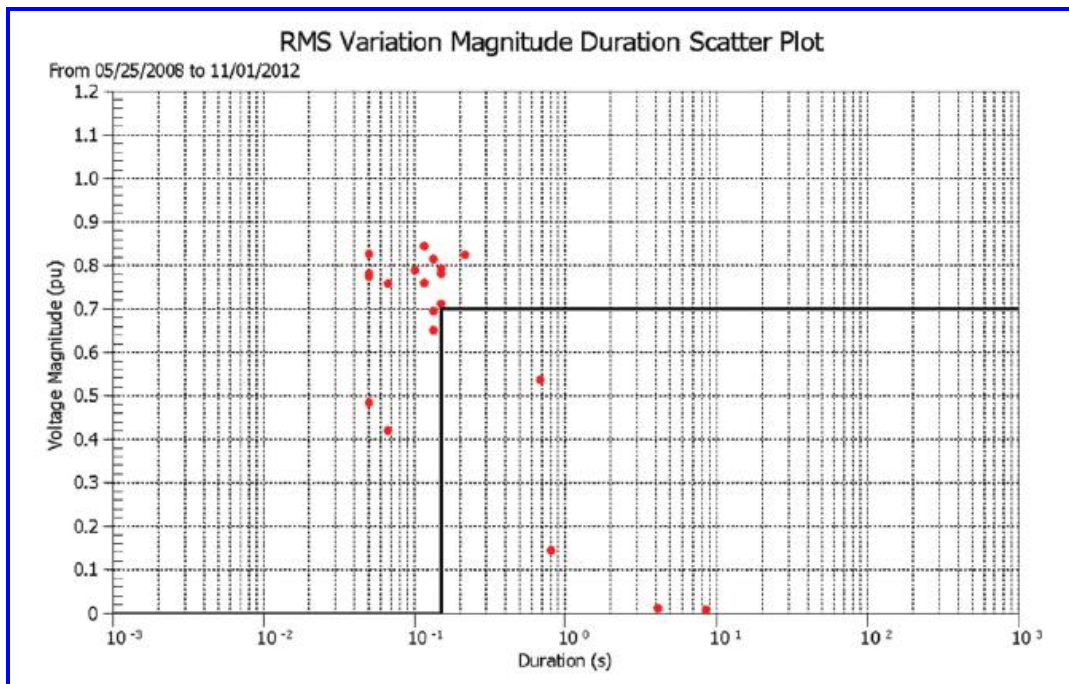
Time stamp	Phase	Magnitude (kV)	Magnitude (pu)	Duration (s)	Duration (cycles)
05/25/2008 14:41:13.0000	A	3.175	0.420	0.067	4.0
07/31/2009 07:58:49.3367	C	0.056	0.007	8.417	505.0
10/30/2009 11:16:47.0767	A	5.901	0.781	0.050	3.0
05/02/2010 13:03:12.2967	B	6.244	0.826	0.050	3.0
05/14/2010 14:47:09.5467	C	5.999	0.794	0.150	9.0
12/14/2010 07:05:20.5167	B	1.092	0.144	0.800	48.0
04/24/2011 06:57:56.8867	B	6.237	0.825	0.217	13.0
05/01/2011 06:14:52.4367	A	5.383	0.712	0.150	9.0
07/06/2011 08:13:52.5567	A	0.084	0.011	4.100	246.0
07/21/2011 16:11:18.0567	C	4.921	0.651	0.133	8.0
11/16/2011 02:15:05.4367	B	5.908	0.781	0.150	9.0
01/20/2012 22:24:57.1567	B	5.257	0.695	0.133	8.0
05/31/2012 17:14:26.9067	A	5.866	0.776	0.050	3.0
06/20/2012 22:26:02.3167	C	3.661	0.484	0.050	3.0
07/02/2012 17:58:48.7467	C	6.384	0.844	0.117	7.0
07/10/2012 16:09:16.7567	A	4.053	0.536	0.683	41.0
07/20/2012 05:07:58.7267	C	5.740	0.759	0.067	4.0
08/05/2012 12:06:24.4667	C	6.153	0.814	0.133	8.0
09/08/2012 00:00:43.3967	A	5.964	0.789	0.100	6.0
10/30/2012 14:05:18.0367	C	5.747	0.760	0.117	7.0

[\(New\)](#)

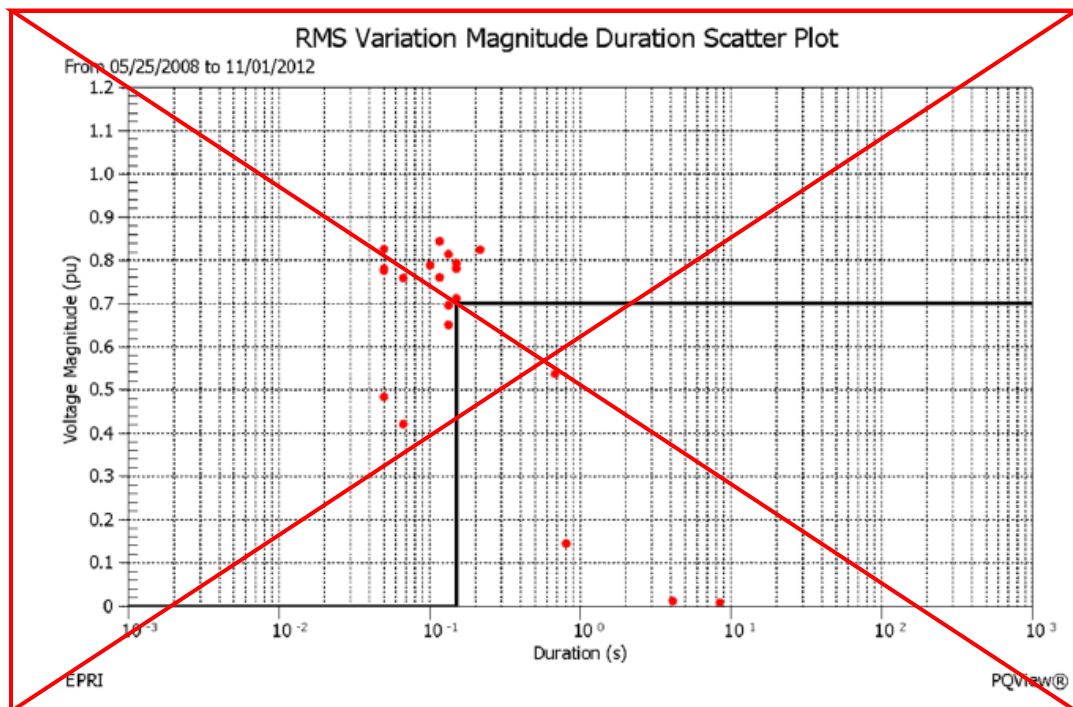
Time Stamp	Phase	Magnitude (kV)	Magnitude (pu)	Duration (s)	Duration (cyc)
05/25/2008 14:41:13.0000	A	3.175	0.420	0.067	4.0
07/31/2009 07:58:49.3367	C	0.056	0.007	8.417	505.0
10/30/2009 11:16:47.0767	A	5.901	0.781	0.050	3.0
05/02/2010 13:03:12.2967	B	6.244	0.826	0.050	3.0
05/14/2010 14:47:09.5467	C	5.999	0.794	0.150	9.0
12/14/2010 07:05:20.5167	B	1.092	0.144	0.800	48.0
04/24/2011 06:57:56.8867	B	6.237	0.825	0.217	13.0
05/01/2011 06:14:52.4367	A	5.383	0.712	0.150	9.0
07/06/2011 08:13:52.5567	A	0.084	0.011	4.100	246.0
07/21/2011 16:11:18.0567	C	4.921	0.651	0.133	8.0
11/16/2011 02:15:05.4367	B	5.908	0.781	0.150	9.0
01/20/2012 22:24:57.1567	B	5.257	0.695	0.133	8.0
05/31/2012 17:14:26.9067	A	5.866	0.776	0.050	3.0
06/20/2012 22:26:02.3167	C	3.661	0.484	0.050	3.0
07/02/2012 17:58:48.7467	C	6.384	0.844	0.117	7.0
07/10/2012 16:09:16.7567	A	4.053	0.536	0.683	41.0
07/20/2012 05:07:58.7267	C	5.740	0.759	0.067	4.0
08/05/2012 12:06:24.4667	C	6.153	0.814	0.133	8.0
09/08/2012 00:00:43.3967	A	5.964	0.789	0.100	6.0
10/30/2012 14:05:18.0367	C	5.747	0.760	0.117	7.0

(Deleted)

A “one-point” representation of the voltage-sag data shown in Table 1 is typically graphed as depicted in Figure 2. The per unit voltage-sag minimum data in the chart (dots) are plotted against voltage-sag duration time. The solid line shows the sensitivity limit for an example 24-V dc power supply.



(New)



(Deleted)

Figure 2—Simplified voltage-sag magnitude duration scatter plot with an example of a 24-V dc power-supply sensitivity overlay

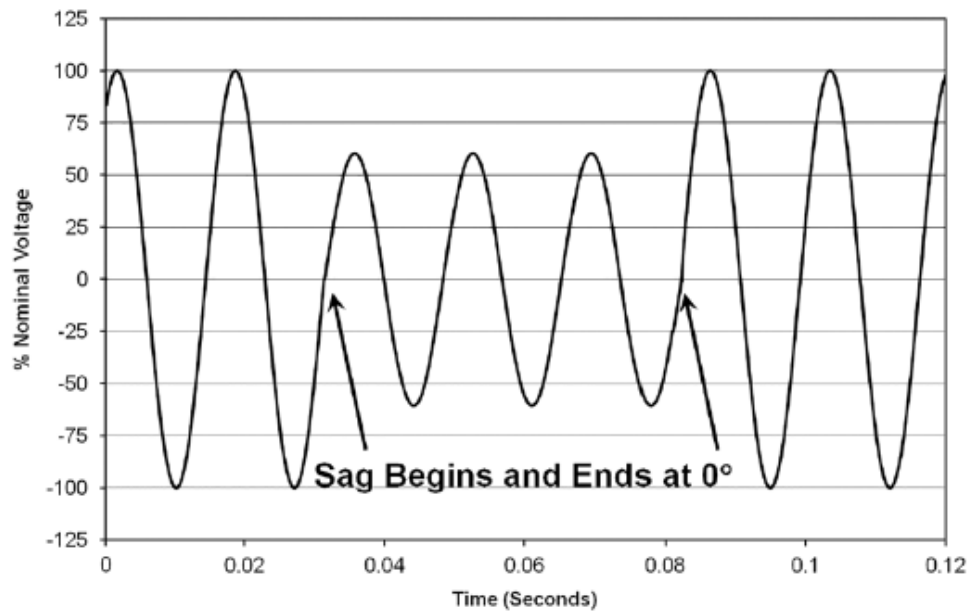
These data-visualization methods and representations are useful to quickly review the information. They are especially useful in looking at events occurring at a site over an extended time period. This approach is widely adopted, and often equipment sensitivity curves are also displayed with the voltage-sag data as shown in Figure 2. The solid line represents an example voltage-sag level where a control component may shut down. As the legend states, of the 20 events seen over the study period, there were four events that were below the voltage-sag sensitivity limit for this device.

The simplified approach (worse phase only, max duration) does not help the end user to understand the true mechanics of the event. Such a simplified view can lead to misunderstanding regarding why one event of a certain magnitude and duration can cause an industrial process to shut down, where another of a similar magnitude and duration does not. Therefore, a more detailed understanding of voltage-sag characteristics, as well as how these events occur, is required.

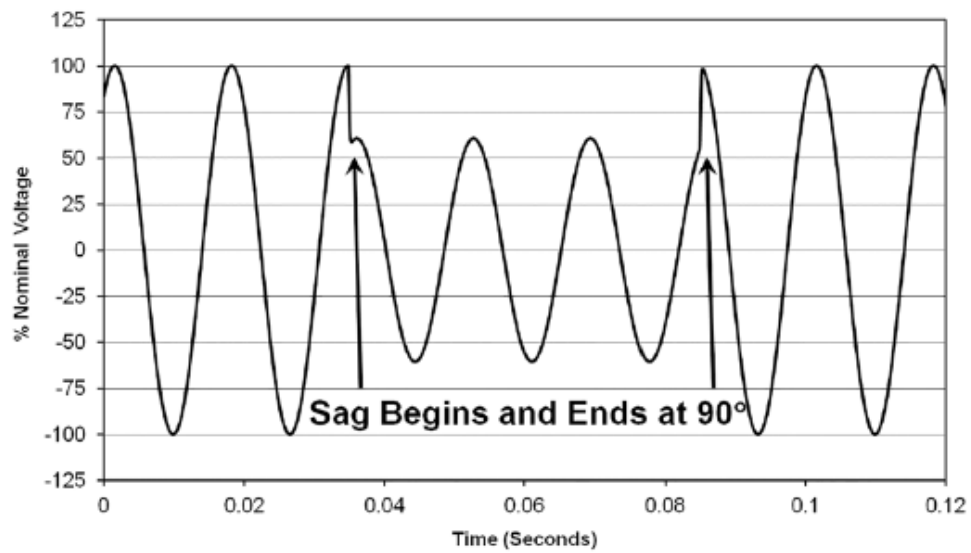
4.3 Other key voltage-sag characteristics

In order to characterize voltage sags representative of the real-world electrical environment, it is important to understand some additional characteristics: the point on the sine wave of the instantaneous voltage where the voltage sag occurs, how the voltage phase angle can change during the voltage sag, and the difference between balanced and unbalanced voltage sags. In 4.4, the relation between fault clearing time and duration of a fault-caused voltage sag will be discussed, as well as how voltage recovers after the fault is cleared.

Although it can seem logical that voltage sags usually occur at or near the peak of the sine wave, because there is more energy at that instant, research shows that the sag initiation is not partial to voltage peaks; in fact, it is generally random (~~EPRI TR-112692 [B6]~~). [according to one source \[B8\]](#). In the event where a voltage sag occurs at the zero crossing, the sine wave will maintain its symmetry during the voltage reduction. When a voltage sag occurs elsewhere on the sine wave, there is an abrupt change in voltage leaving a portion of the sine wave present. Figure 3 shows how point-on-wave can influence the shape of the sine wave. Here, we see two voltage sags to 60% of nominal lasting three cycles (60 Hz). The waveform shown in Figure 3 [part a\)](#) shows the voltage sag occurring at the zero crossing. Note how there is little change in shape of the sine wave. Figure 3 [part b\)](#) shows the resulting change in the waveform when the voltage sag occurs at the peak of the sine wave, or 90°. The actual values of points on wave of sag initiation or ending can influence performance of equipment during or after a voltage sag. For example, in the case of a switch-mode power supply, the point-on-wave of initiation of the voltage sag will determine the energy available for ride-through in the dc link capacitor. Subsequently, the point-on-wave at the end of the voltage sag will determine inrush current at the end of the event.



a.



b.

Figure 3—Waveforms of two voltage sags illustrating point-on-wave

Equipment and devices in many industrial processes sometimes malfunction when subjected to shallow sags and yet do not malfunction during deeper sags. Even though this can seem counterintuitive, devices such as contactors—electromechanical devices used for on/off switching and control/protection of electrical equipment—are extremely sensitive to the point-on-wave at which the sag is initiated. Figure 4 shows the voltage required to keep the contactor operational in reference to the point-on-wave of where the voltage sag is initiated. If the voltage falls below the curve during the sag event, the contactor will malfunction. Note that higher voltage is required after ~~around~~ approximately 3.5 cycles to keep the contactor operational at the 0° and 180° points-on-wave of initiation ~~for an example~~ (e.g., 60 Hz contactor). Conversely, the contactor will hold in down to lower voltages after 3.5 cycles if the voltage sag event begins at 90° point-on-wave as well as 270°. Figure 4 shows the rms voltage magnitude of the sag versus the point-on-wave of initiation of the event. Voltage sags below the curve will cause the contactor to malfunction magnetically in the form of contactor chatter and electrically by opening the contacts and disconnecting the associated electrical circuit [B22]. For this contactor, the average percent difference at five cycles between 0° tolerance and 90° tolerance was 5.9% for the contactors (Djokic, et al. [B7]).

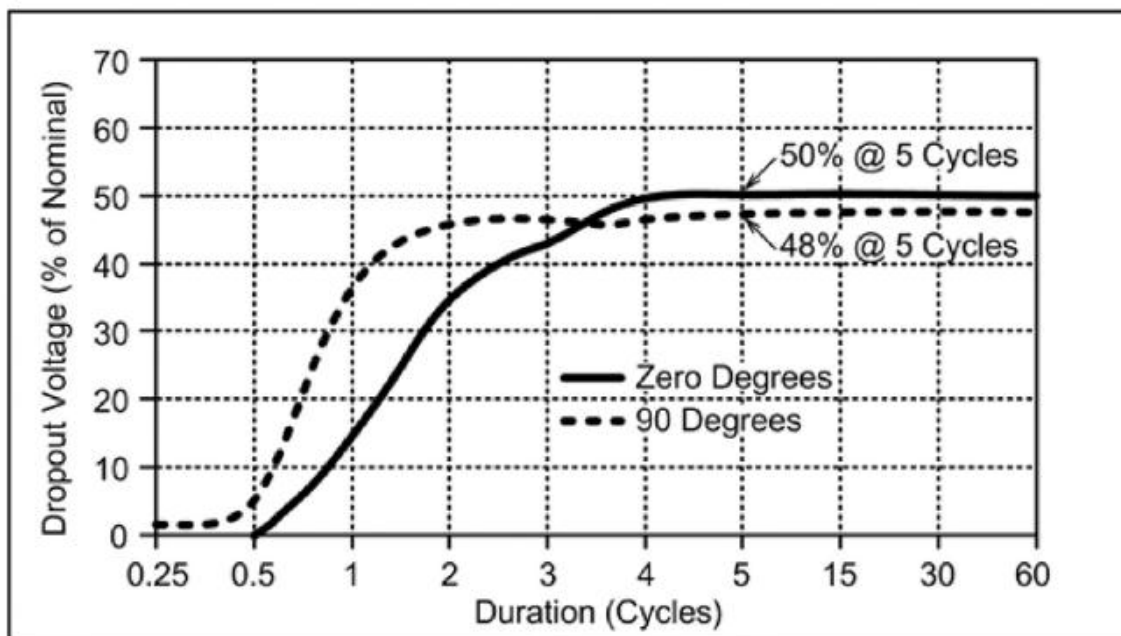


Figure 4— Example of point-on-wave of voltage-sag initiation influencing the trip level of an ac contactor ~~(EPRI TR-113044~~ [B11]

As a result of a voltage sag, the sine-wave voltage during the sag can also experience a phase-angle change, or phase shift. The phase shift typically results from a complex interaction between the fault current and impedance in the electrical system. In the real-world electrical environment, phase shifts in voltage can occur and can result in a brief deviation from the line frequency, possibly resulting in equipment malfunction or interruption. An ac voltage waveform that crosses the zero point after the voltage normally would indicate a positive phase shift. An ac voltage waveform that crosses the zero point before the voltage normally would indicate a negative phase shift. Figure 5 shows an example of a voltage sag with a negative and positive phase shift. The waveforms show a typical three-phase supply system. The V_{bn} and V_{cn} waveforms indicate a deviation from the nominal voltage as a result of a voltage sag to 58% of nominal. In the case of the V_{cn} waveform, note that the voltage sag crosses the zero crossing before it normally would have, resulting in a negative phase shift. The V_{bn} waveform crosses the zero crossing later than it normally would have, resulting in a positive phase shift. Voltage-sag susceptibility testing conducted by EPRI one source [B21] shows that relays can be more sensitive to voltage sags that include phase shifts [B3].

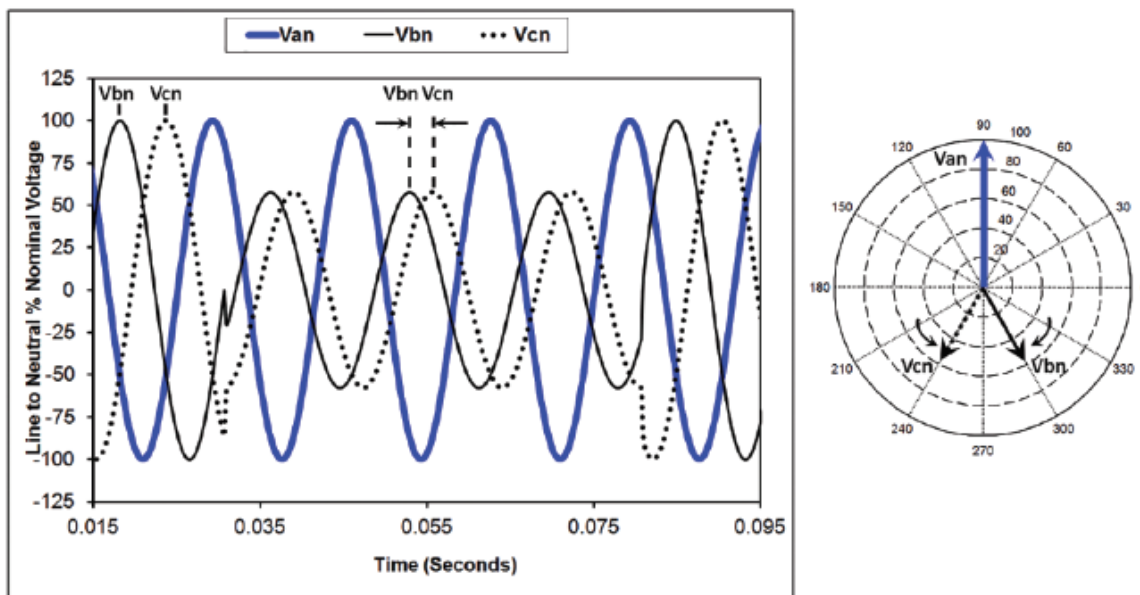


Figure 5—Two-phase voltage sag with positive and negative phase shift

Up to this point, all the reviewed characteristics apply to all voltage sags. When dealing with three-phase systems, it is important to understand that, based on their origins, some voltage sags are balanced and others are unbalanced, based on their origin (e.g., type of fault). Balanced voltage sags affect all three phases equally, and the normal phase angle relationship between the voltages remains at 120° . In unbalanced voltage sags, the voltage magnitudes differ, as does the relationship between the phase angles. Unbalanced voltage sags occur much more frequently in the real-world electrical environment than balanced sags. For example, when the load(s) is (are) all three-phase, a balanced phase-to-phase sag is more likely than when the loads are all phase-to-neutral or a mixture of phase-to-phase and phase-to-neutral. A fault on one phase-to-neutral would not affect all three phases. This phenomenon is described in greater detail later in Figure 14. An example of a three-phase balanced voltage sag is shown in Figure 6, whereas an unbalanced voltage sag impacting two phases is shown in Figure 7. Note how the phasor magnitudes and phase angle relationship between the phasors are the same for the balanced voltage sag and different for the unbalanced voltage sag.

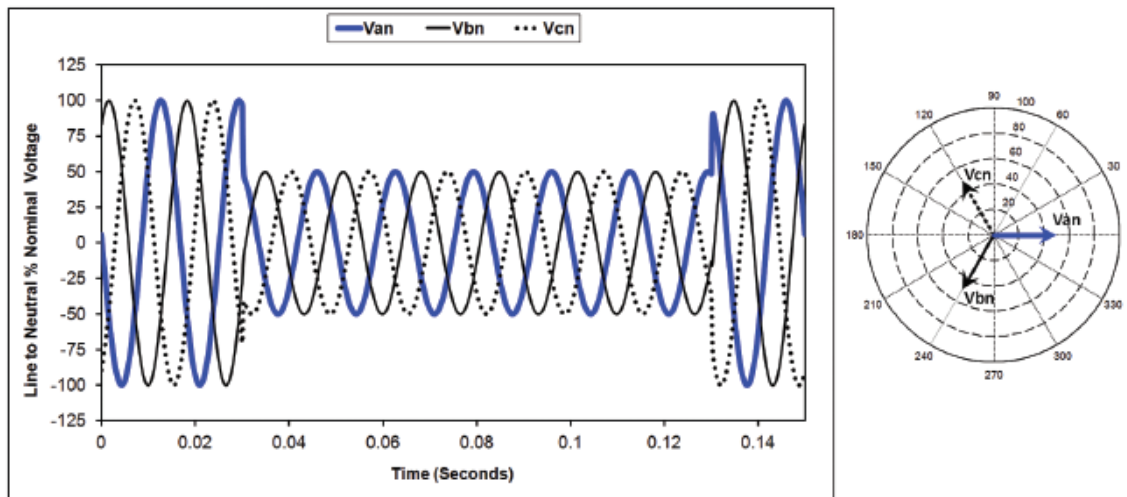


Figure 6—Balanced voltage sag simulation

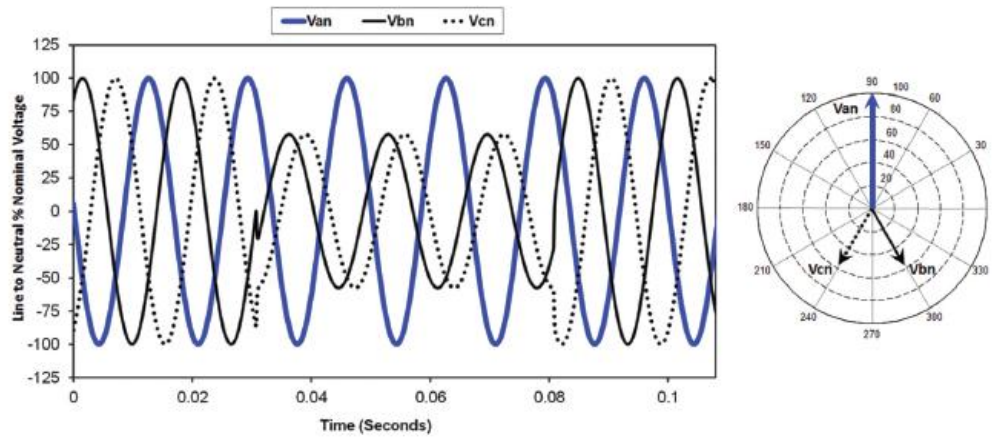


Figure 7—Unbalanced voltage-sag simulation

4.4 Faults and voltage sags

While minor voltage sags can occur as a result of starting large motors and energizing transformers, most severe voltage sags are the result of electrical faults on power systems. When faults occur, protective relaying plays a critical role in detecting the fault current and then isolating the fault (i.e., disconnecting the faulted part of the system) in a timely manner and restoring the nominal supply conditions elsewhere. During the time it takes to clear the fault, a voltage sag occurs, the magnitude of which is based on the type and location of the fault and strength of the system (system impedance). Clearing times vary considerably based on the location of the fault within the power system. However, a general rule of thumb is that protective relaying systems should be designed to operate more quickly for greater magnitudes of fault current. Based on this methodology, it should come as no surprise that faults on transmission systems are more quickly isolated than faults on distribution systems. Faults in transmission systems are typically cleared within two to three cycles, while on sub-transmission systems, faults are cleared within three to six cycles. However, some protective relaying schemes can take as long as 20 cycles to clear the fault (60 Hz). Fault clearing times on distribution systems and at the utilization level vary widely. Figure 8 shows two different voltage sags: one on the transmission system (solid waveform), which clears in three cycles; and the other on the sub-transmission system (dotted-line waveform—also smallest magnitude), which clears in six cycles (60 Hz).

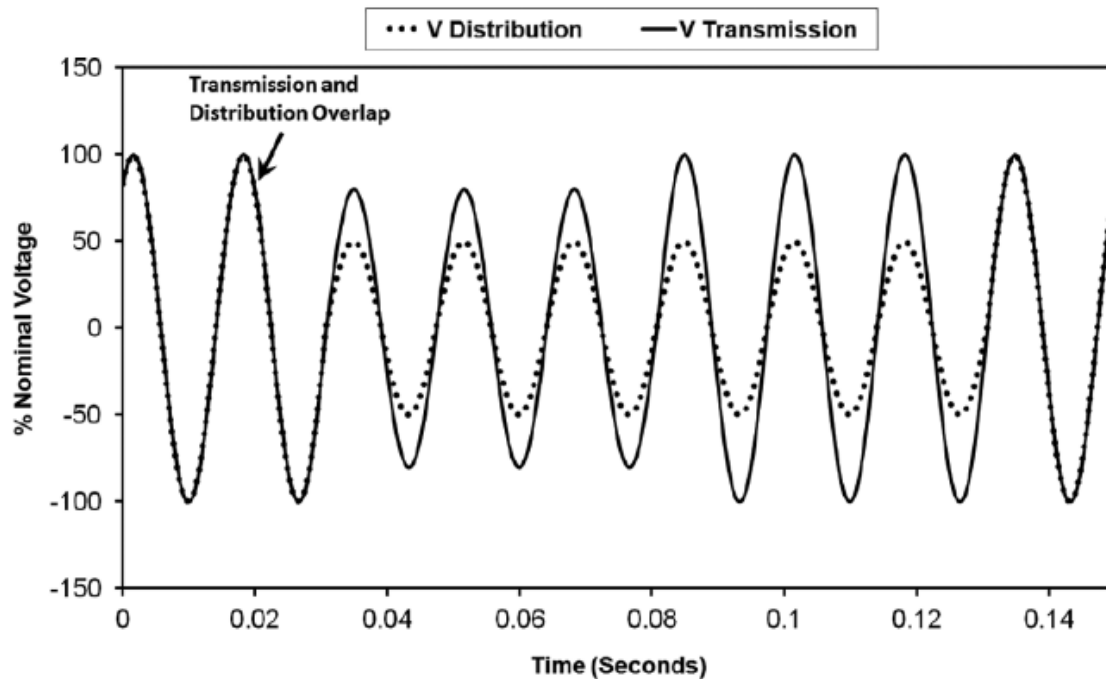


Figure 8— Example of voltage sags and fault clearing times for distribution and transmission lines

Once protective relaying clears the fault, the voltage can recover to pre-faulted conditions, given that there is an adequate supply of reactive power. This usually occurs quickly, as seen in Figure 9, where the voltage returns to nominal in 15 ms (60 Hz). In some cases, customer loads can stay online, causing significant post-sag inrush current and requiring reactive power flow from generation to return the system to pre-faulted conditions. Should enough generation be interrupted or critical transmission lines lost due to a fault, voltage collapse or slow voltage recovery can ensue, preventing or delaying the return to nominal voltage. Utilities try to minimize these conditions, but slow voltage recovery will occur on occasion. An example of slow voltage recovery is shown in Figure 10.

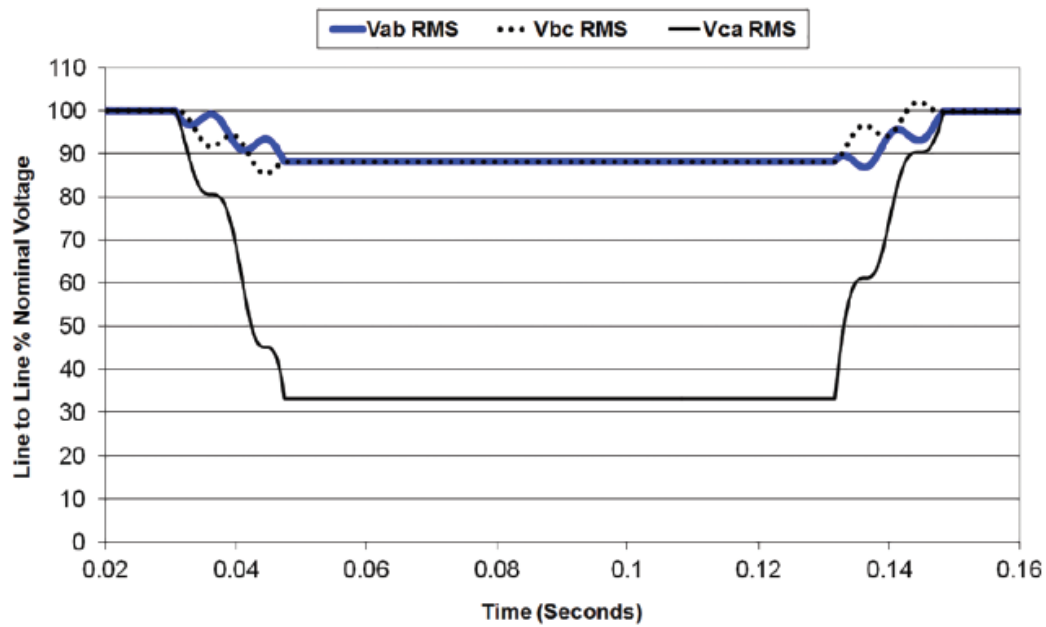


Figure 9— Voltage recovery after fault is cleared (simulation)

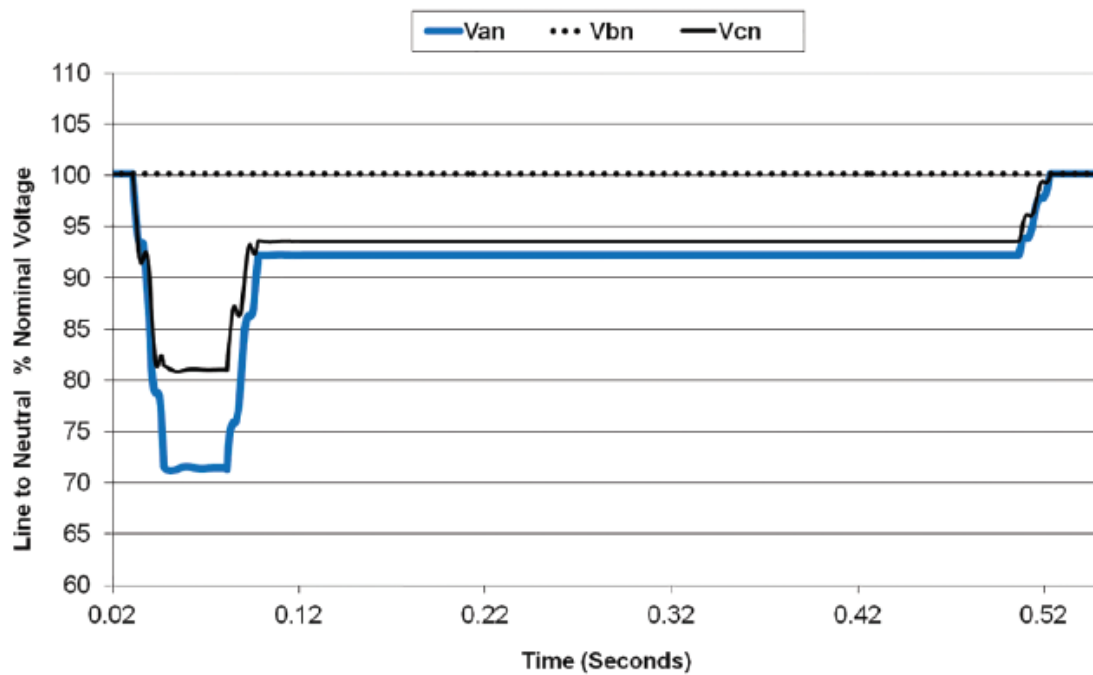


Figure 10.— Slow voltage recovery after fault is cleared (simulation)

It is important to understand how faults throughout the power-delivery system impact customers at the utilization level. Many factors influence what the voltage sag looks like (characteristics of a voltage sag) to these customers—factors such as the number of step-down voltage transformations to the fault. This includes wye-delta, delta-wye, delta-delta, and wye-wye transformer winding configurations. The system impedance to the fault, impedance of the transformations, pre-fault voltage, protective relaying equipment in place, and the type of fault also help shape the magnitude and duration of the voltage sag as seen at the utilization voltage.

Some voltage sags at a facility may result from starting large, line-connected motor loads located within the facility or at one nearby. Faults to ground may also occur within the facility. While faults and voltage sags are known to occur within customers' facilities, the following material deals with effects from voltage sags originating on the utility system.

Faults on transmission systems result in all adjacent and downstream circuits experiencing a voltage sag. Indeed, some transmission-level faults can result in voltage sags hundreds of miles away. Interruptions are rare because transmission systems are almost always networked with multiple sources feeding into the network. Figure 11 shows a single-phase fault on Phase A to ground on a 161-kV transmission line and the resultant voltage sag at a customer's 480-V bus. The utilization voltage (locations where end-use equipment is interconnected), 480 V in this case, is transformed via two delta-wye transformers; the first with a secondary voltage of 13.8 kV and the second with a secondary voltage of 480 V. The transformer connections have a significant impact on how the voltage sag propagates to the utilization level. At the location of the fault, the voltage from Phase A to ground will be 0 V. Note how the phase-to-phase voltages (BC and CA) and phase-to-neutral voltages (AN, BN, and CN) are affected from the single-phase fault due to the two delta-wye transformers.

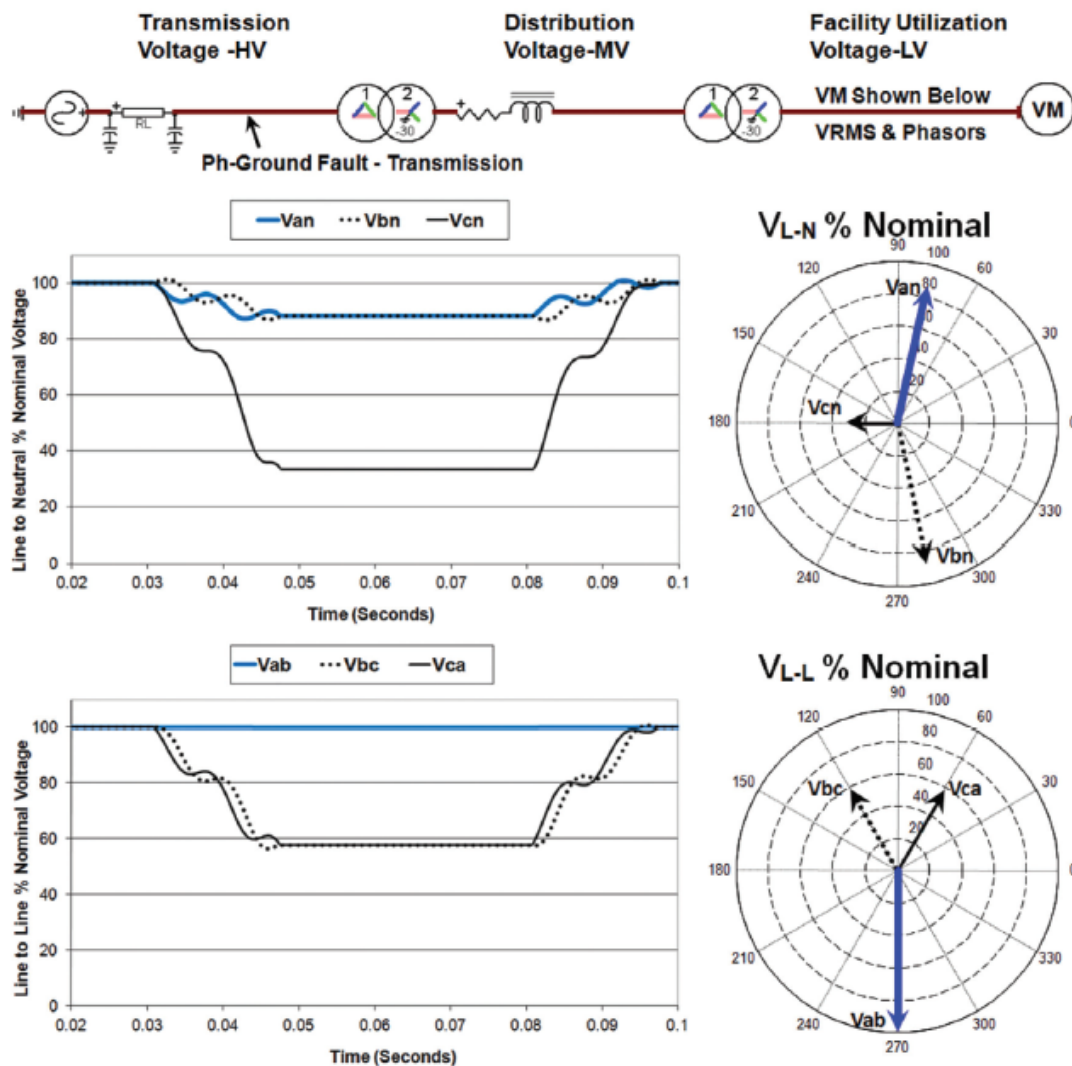


Figure 11— Voltage sag at 480 Vrms utilization voltage from a transmission-system fault (A-G) simulation