



IEEE Guide for the Application of Insulation Coordination

IEEE Power and Energy Society

Developed by the
Surge Protective Devices Committee

IEEE Std C62.82.2™-2022



IEEE Guide for the Application of Insulation Coordination

Developed by the

Surge Protective Devices Committee
of the
IEEE Power and Energy Society

Approved 7 December 2022

IEEE SA Standards Board

THIS IS A REDLINE DOCUMENT PRODUCED BY TECHSTREET, AN ASME COMPANY.

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 fast paced 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.

This Redline is produced solely by Techstreet. IEEE has not prepared this Redline and is not responsible for its accuracy.

Redline Processing Notes:

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

Abstract: The calculation method for selection of phase-to-ground and phase-to-phase insulation withstand voltages for equipment is presented. Methods for insulation coordination of different air-insulated systems like transmission lines and substations are outlined. The methods of analysis are illustrated by practical examples.

Keywords: atmospheric correction factor, backflash, basic lightning impulse level (BIL), basic switching impulse insulation level (BSL), clearances, crest value, ground fault factor, insulation coordination, IEEE C62.82.2™, insulation design, overvoltage, phase-to-ground insulation configuration, phase-to-phase insulation configuration, protective margin, protective ratio, shielding failures, standard withstand voltages, voltage stress

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

Copyright © 2023 by The Institute of Electrical and Electronics Engineers, Inc.
All rights reserved. Published 17 March 2023. Printed in the United States of America.

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

National Electrical Safety Code and NESC are both registered trademarks and service marks of the Institute of Electrical and Electronics Engineers, Inc.

PDF: ISBN 978-1-5044-9507-3 STD26007
Print: ISBN 978-1-5044-9508-0 STDPD26007

IEEE prohibits discrimination, harassment, and bullying.

For more information, visit <https://www.ieee.org/about/corporate/governance/p9-26.html>.

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

Important Notices and Disclaimers Concerning IEEE Standards Documents

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

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

IEEE Standards documents are developed within the IEEE Societies and the Standards Coordinating Committees of the IEEE Standards Association (IEEE SA) Standards Board. IEEE develops its standards through an accredited consensus development process, which brings together volunteers representing varied viewpoints and interests to achieve the final product. IEEE Standards are documents developed by volunteers with scientific, academic, and industry-based expertise in technical working groups. Volunteers are not necessarily members of IEEE or IEEE SA, and participate without compensation from IEEE. While IEEE administers the process and establishes rules to promote fairness in the consensus development process, IEEE does not independently evaluate, test, or verify the accuracy of any of the information or the soundness of any judgments contained in its standards.

IEEE does not warrant or represent the accuracy or completeness 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. In addition, IEEE does not warrant or represent that the use of the material contained in its standards is free from patent infringement. IEEE Standards documents are supplied “AS IS” and “WITH ALL FAULTS.”

Use of an IEEE standard is wholly voluntary. The existence of an IEEE Standard does not imply that there are no other ways to produce, test, measure, purchase, market, or provide other goods and services related to the scope of the IEEE standard. Furthermore, the viewpoint expressed at the time a standard is approved and issued is subject to change brought about through developments in the state of the art and comments received from users of the standard.

In publishing and making its standards available, IEEE is not suggesting or rendering professional or other services for, or on behalf of, any person or entity, nor is IEEE undertaking to perform any duty owed by any other person or entity to another. Any person utilizing any IEEE Standards document, should rely upon his or her own independent judgment in the exercise of reasonable care in any given circumstances or, as appropriate, seek the advice of a competent professional in determining the appropriateness of a given IEEE standard.

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

Translations

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

Official statements

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

Comments on standards

Comments for revision of IEEE Standards documents are welcome from any interested party, regardless of membership affiliation with IEEE or IEEE SA. However, **IEEE does not provide interpretations, consulting information, or advice pertaining to IEEE Standards documents.**

Suggestions for changes in documents should be in the form of a proposed change of text, together with appropriate supporting comments. Since IEEE standards represent a consensus of concerned interests, it is important that any responses to comments and questions also receive the concurrence of a balance of interests. For this reason, IEEE and the members of its Societies and 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 evaluating comments or in revisions to an IEEE standard is welcome to join the relevant IEEE working group. You can indicate interest in a working group using the Interests tab in the Manage Profile & Interests area of the [IEEE SA myProject system](#). An IEEE Account is needed to access the application.

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

Laws and regulations

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

Data privacy

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

Copyrights

IEEE draft and approved standards are copyrighted by IEEE under US and international copyright laws. They are made available by IEEE and are adopted for a wide variety of both public and private uses. These include both use, by reference, in laws and regulations, and use in private self-regulation, standardization, and the promotion of engineering practices and methods. By making these documents available for use and adoption by public authorities and private users, IEEE does not waive any rights in copyright to the documents.

Photocopies

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

Updating of IEEE Standards documents

Users of IEEE Standards documents should be aware that these documents may be superseded at any time by the issuance of new editions or may be amended from time to time through the issuance of amendments, corrigenda, or errata. An official IEEE document at any point in time consists of the current edition of the document together with any amendments, corrigenda, or errata then in effect.

Every IEEE standard is subjected to review at least every 10 years. When a document is more than 10 years old and has not undergone a revision process, it is reasonable to conclude that its contents, although still of some value, do not wholly reflect the present state of the art. Users are cautioned to check to determine that they have the latest edition of any IEEE standard.

In order to determine whether a given document is the current edition and whether it has been amended through the issuance of amendments, corrigenda, or errata, visit [IEEE Xplore](#) or [contact IEEE](#). For more information about the IEEE SA or IEEE's standards development process, visit the IEEE SA Website.

Errata

Errata, if any, for all IEEE standards can be accessed on the [IEEE SA Website](#). Search for standard number and year of approval to access the web page of the published standard. Errata links are located under the Additional Resources Details section. Errata are also available in [IEEE Xplore](#). Users are encouraged to periodically check for errata.

Patents

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

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

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

IMPORTANT NOTICE

IEEE Standards do not guarantee or ensure safety, security, health, or environmental protection, or ensure against interference with or from other devices or networks. IEEE Standards development activities consider research and information presented to the standards development group in developing any safety recommendations. Other information about safety practices, changes in technology or technology implementation, or impact by peripheral systems also may be pertinent to safety considerations during implementation of the standard. Implementers and users of IEEE Standards documents are responsible for determining and complying with all appropriate safety, security, environmental, health, and interference protection practices and all applicable laws and regulations.

Participants

At the time this IEEE guide was completed, the 3.4.18 Working Group had the following membership:

Iuda Morar, *Chair*
Christine Goldsworthy, *Vice Chair*

Ahmad Abdullah
Michael Champagne
Michael Comber

Huang Fang
Steven Hensley
Jon Leman
Craig Polchinski

Thomas Rozek
Carl Schuetz
Jonathan Woodworth

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

Roy Alexander
Saleman Alibhay
Roberto Asano
Anthony Baker
Thomas Barnes
Frank Basciano
Philip Beaumont
Jacob Ben Ary
W. J. (Bill) Bergman
Jean-Marc BIASSE
Wallace Binder
William Bloethe
W. Boettger
Kenneth Bow
Jeffrey Brogdon
Andrew Brown
Gustavo Brunello
William Byrd
Thomas Callsen
Paul Cardinal
Stephen Cary
Michael Champagne
Arvind Chaudhary
William Chisholm
Keith Chow
Robert Christman
Michael Comber
Stephen Conrad
Jerry Corkran
Randall Crellin
Matthew Davis
Davide De Luca
Wayne Dilling
Dieter Dohnal
Gary Donner
Edgar Dullni
Douglas J. Edwards
Cliff Erven
Jorge Fernandez Daher
Namal Fernando
Rabiz Foda
Rostyslaw Fostiak
Dale Fredrickson
Fredric Friend

George Gela
Michael George
Frank Gerleve
Kenneth Gettman
David Gilmer
Alexander Glaninger-Katschnig
Waymon Goch
Jalal Gohari
Edwin Goodwin
James Graham
Stephen Grier
Randall C. Groves
Ajit Gwal
Jeffrey Helzer
Steven Hensley
Werner Hoelzl
Robert Hoerauf
Ronald Hotchkiss
James Houston
Todd Irwin
Richard Jackson
John
Laszlo Kadar
Jeffrey Kester
Yuri Khersonsky
Morteza Khodaie
Gary Kobet
Boris Kogan
Bruce Kraemer
Jim Kulchisky
Saumen Kundu
Chung-Yiu Lam
Benjamin Lanz
James Lau
Michael Lauxman
Maurice Linker
Hua Liu
Albert Livshitz
Reginaldo Maniego
Richard Marek
Michael Maytum
William McBride
John McClelland
Tom Melle

John Miller
Sujeet Mishra
Jerry Murphy
R. Murphy
Ryan Musgrove
K. R. M. Nair
Rhonda Netzel
Michael Newman
Raymond Nicholas
Paul Nikolich
Joe Nims
Gearold O. H. Eidhin
Tim Olson
Carl Orde
Lorraine Padden
Mirko Palazzo
Bansi Patel
Shawn Patterson
Howard Penrose
Christopher Petrola
Donald Platts
Alvaro Portillo
Douglas Proctor
Iulian Profir
Benjamin Quak
Reynaldo Ramos
John Randolph
Samala Santosh Reddy
Carl Reigart
Robert Resuali
Johannes Rickmann
Michael Roberts
Timothy Robirds
Charles Rogers
Thomas Rozek
Daniel Sabin
Steven Sano
Bartien Sayogo
Dennis Schlender
Carl Schuetz
Nikunj Shah
Devki Sharma
Harish Sharma
Hyeong Sim

Jeremy Smith
Jerry Smith
Gary Smullin
Allan St. Peter
Wayne Stec
Ralph Stell
John Stevens
K. Stump
Michael Swearingen
David Tepen

Demetrios Tziouvaras
Joe Uchiyama
Nijam Uddin
James Van De Ligt
Gerald Vaughn
Roger Verdolin
John Vergis
Sukhdev Walia
Eric Wall
Daniel Ward
Hung-Yu Wei

Yingli Wen
Donald Wengerter
Charles White
Kenneth White
James Wilson
Jennifer Yu
Jian Yu
Kipp Yule
Dawn Zhao
Xi Zhu

When the IEEE SA Standards Board approved this guide on 7 December 2022, it had the following membership:

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

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

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

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

*Member Emeritus

Introduction

This introduction is not part of IEEE Std C62.82.2-2022, IEEE Guide for the Application of Insulation Coordination.

This guide is the second part of a major revision of ANSI C92.1-1982.¹ The guide is divided into two parts: IEEE Std C62.82.1™ [formerly IEEE Std 1313.1™-1996 (Part 1)] presents the definitions and the procedure for insulation coordination. IEEE Std C62.82.2™ [formerly IEEE Std 1313.2™-1999 (Part 2)] is an application guide, which presents practical examples.

New additions to this guide include the concepts of phase–phase insulation coordination and longitudinal insulation coordination, which considers switching surges and the power frequency voltage across an open switch. The introduction of the very fast-front, short-duration overvoltage is an acknowledgment of the problems observed when a disconnect switch operates in a gas-insulated substation (GIS).

The basic concept of insulation coordination remains the same as in ANSI C92.1-1982. The first step is the determination of voltage stresses using digital computer simulation, transient analyzer, or mathematical methods such as those presented in this guide. These analyses result in nonstandard overvoltage waveforms, which are converted into equivalent standard wave shapes. The second step is the selection of insulation strength to achieve the desired level of probability of failure. The guide describes the determination of both the conventional and the statistical basic lightning impulse level (BIL) and basic switching impulse insulation level (BSL).

¹ Information on references can be found in Clause 2.

Contents

1. Overview	11
1.1 Scope	11
1.2 Purpose	11
1.3 Word usage	11
2. Normative references	12
3. Voltage stresses	13
3.1 Origin and classification of voltage stresses	13
3.2 Characteristics of overvoltage protective devices	20
4. Insulation strength	24
4.1 General	24
4.2 Insulation behavior at power frequency voltages	24
4.3 Influences of atmospheric conditions on external insulation	25
4.4 Probability of disruptive discharge	25
4.5 Influence of polarity and overvoltage shape	26
4.6 Phase-phase and longitudinal insulation	26
5. Performance/reliability criterion	27
5.1 Transmission lines	27
5.2 Substations	27
6. Insulation coordination procedures	28
6.1 Procedures for continuous power frequency voltage and temporary overvoltages	28
6.2 Procedures for switching overvoltages (SOVs)	35
6.3 Procedures for lightning overvoltages	48
7. Final selection	78
7.1 Transmission lines	78
7.2 Substations	78
Annex A (informative) Bibliography	80

IEEE Guide for the Application of Insulation Coordination

1. Overview

1.1 Scope

The insulation coordination standard and guide apply to three-phase ac systems above [15.4](#) kV and are divided into two parts.

~~IEEE Std 1313.1-1996 (Part 1) specifies the procedure for selection of the withstand voltages [basic lightning impulse insulation level (BIL) and basic switching impulse insulation level (BSL)] for equipment phase-ground and phase-phase insulation systems. It also identifies a list of standard insulation levels. Although the principles of this standard also apply to transmission line insulation systems, the insulation levels may be different from those identified as standard insulation levels.~~

This guide, [the second](#) part, ~~(2)~~ is an application guide with practical examples, intended to provide guidance in the determination of the withstand voltages and to suggest calculation methods and procedures. The insulation coordination examples for selected equipment are designed to explain the principles of Part 1, [IEEE Std C62.82.1](#). The guide is intended for air-insulated ac systems; Caution should be exercised in the case of gas-insulated systems (GIS).

1.2 Purpose

It should be recognized that absolute protection of station equipment is theoretically impossible. Even if arresters are located at the terminals of all apparatuses, equipment failures can occur. The probabilistic method, that is, designing for a mean time between failures (MTBF) criterion, is proposed here not only to permit a realistic basis of design, but [also](#) perhaps more importantly, to form a consistent measure of design based on reliability.

1.3 Word usage

The word *shall* indicates mandatory requirements strictly to be followed in order to conform to the standard and from which no deviation is permitted (*shall* equals *is required to*).^{2, 3}

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

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

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

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.

~~This guide shall be used in conjunction with the following publications. When the following standards are superseded by an approved revision, the revision shall apply~~

² The use of the word *must* is deprecated and cannot be used when stating mandatory requirements, *must* is used only to describe unavoidable situations.

³ The use of *will* is deprecated and cannot be used when stating mandatory requirements, *will* is only used in statements of fact.

ANSI C84.1-~~1995~~, Electric Power System and Equipment—Voltage Ratings (60 Hz). ⁴~~1~~

ANSI C92.2-~~1987~~, American National Standard for Power Systems—Alternating-Current Electrical Systems and Equipment Operating at Voltages Above 230 kV Nominal Preferred Voltage Ratings.

[IEC 60071-1, Insulation Coordination—Part 1: Definitions, principles, and rules.](#)⁵

[IEC 60071-2, Insulation Coordination—Part 2: Application guidelines.](#)

[IEC 60815-1, Selection and dimensioning of high-voltage insulators intended for use in polluted conditions—Part 1: Definitions, information and general principles.](#)

[IEC 60815-2, Selection and dimensioning of high-voltage insulators intended for use in polluted conditions—Part 2: Ceramic and glass insulators for a.c. systems.](#)

[IEC 60815-3, Selection and dimensioning of high-voltage insulators intended for use in polluted conditions—Part 3: Polymer insulators for a.c. systems.](#)

IEEE Std 4TM-~~1995~~, IEEE Standard Techniques for High-voltage Testing. ^{6,7}~~2~~

⁴ ¹ ANSI publications are available from the ~~Sales Department~~, American National Standards Institute, ~~11 West 42nd Street, 13th Floor, New York, NY 10036, USA~~ (<https://www.ansi.org/>).

⁵ IEC publications are available from the International Electrotechnical Commission (<https://www.iec.ch>) and the American National Standards Institute (<https://www.ansi.org/>).

⁶ The IEEE standards or products referred to in Clause 2 are trademarks owned by The Institute of Electrical and Electronics Engineers, Incorporated.

⁷ ² IEEE publications are available from The Institute of Electrical and Electronics Engineers, ~~445 Hoes Lane, P.O. Box 1331, Piscataway, NJ 08855-1331, USA~~ (<https://www.standards.ieee.org/>).

~~IEEE Std 24-1984, IEEE Standard Performance Characteristics and Dimensions for Outdoor Apparatus Bushings.~~

~~IEEE Std 100-1996, IEEE Standard Dictionary of Electrical and Electronics Terms, Sixth Edition.~~

IEEE Std 516TM, 1995, IEEE Guide for Maintenance Methods on Energized Power Lines.

~~IEEE Std 987-1985, IEEE Guide for Application of Composite Insulators (withdrawn).³~~

IEEE Std 998TM, 1996, IEEE Guide for Direct Lightning Stroke Shielding of Substations.

~~IEEE Std 1313.1-1996, IEEE Standard for Insulation Coordination—Definitions, Principles, and Rules.~~

IEEE Std C2-1997, National Electric Safety Code[®] (NESC[®]).⁸

~~IEEE Std C37.04-1999, IEEE Standard Rating Structure for AC High-Voltage Circuit Breakers Rated on a Symmetrical Current Basis.~~

~~IEEE Std C37.48-1988 (Reaff 1992), IEEE Guide for Application, Operation, and Maintenance of High-Voltage Fuses, Distribution Enclosed Single-Pole Air Switches, Fuse Disconnecting Switches, and Accessories.~~

~~IEEE Std C57.12.00-1993, IEEE Standard General Requirements for Liquid-Immersed Distribution, Power and Regulating Transformers.~~

⁸ [National Electrical Safety Code and NESC are both registered trademarks and service marks of the Institute of Electrical and Electronics Engineers, Inc.](#)

³ ~~IEEE Std 987-1985 has been withdrawn; however, copies can be obtained from Global Engineering, 15 Inverness Way East, Englewood, CO 80112-5704, USA, tel. (303) 792-2181 (<http://global.ihs.com/>).~~

~~IEEE Std C57.12.01-1989, IEEE Standard General Requirements for Dry-Type Distribution and Power Transformers Including Those with Solid Cast and/or Resin-Encapsulated Windings (withdrawn).~~⁴

~~IEEE Std C57.13-1993, IEEE Standard Requirements for Instrument Transformers.~~

~~IEEE Std C57.21-1990 (Reaff-1995), IEEE Standard Requirements, Terminology, and Test Code for Shunt Reactors Rated Over 500 kVA.~~

~~IEEE Std C62.1-1989 (Reaff-1994), IEEE Standard for Gapped Silicon Carbide Surge Arresters for AC Power Circuits.~~

IEEE Std C62.11TM 1999, IEEE Standard for Metal-Oxide Surge Arresters for Alternating Current Power Circuits.

~~IEEE Std C62.2-1987 (Reaff-1994), IEEE Guide for the Application of Gapped Silicon Carbide Surge Arresters for Alternating Current Systems.~~

IEEE Std C62.22TM 1997 (Reaff-1993), IEEE Guide for the Application of Metal-Oxide Surge Arresters for Alternating-Current Systems.

[IEEE C62.82.1TM, IEEE Guide for Insulation Coordination—Definitions, Principles, and Rules.](#)

IEEE Std C62.92. [5TM 1-1987 \(Reaff-1993\)](#), IEEE Guide for the Application of Neutral Grounding in Electrical Utility Systems, Part [V—Transmission and Subtransmission Systems](#) ~~I—Introduction~~.

[OSHA 1910.269, Electric power generation, transmission, and distribution.](#)⁹

⁹ This standard is available from the Occupational Safety and Health Administration at <https://www.osha.gov/lawsregs/regulations/standardnumber/1910/1910.269>

⁴ ~~IEEE Std C57.12.01-1989 has been withdrawn; however, copies can be obtained from Global Engineering, 15 Inverness Way East, Englewood, CO 80112-5704, USA, tel. (303) 792-2181 (<http://global.ihs.com/>).~~

3. Voltage stresses

3.1 Origin and classification of voltage stresses

IEEE Std [C62.82.1-2010](#) ~~1996~~ identifies classes and shapes of different types of overvoltages. In addition, [it Part 1](#) identifies the continuous (power frequency) voltages that ~~are the result of~~ [from](#) normal operation of the power system. There are many possible causes for each ~~type of the different types~~ of overvoltage. Some of the common overvoltages are [as follows](#):

- a) Temporary overvoltages ~~that are~~ caused by faults, load rejection, line energizing, resonance conditions, ferroresonance, or ~~by~~ some combination of these factors.
- b) Switching (slow-front) overvoltages ~~that are~~ caused by switching operations, fault initiation, or remote lightning strokes.
- c) Lightning (fast-front) overvoltages ~~that are~~ caused primarily by lightning strikes but can also be caused by some switching operations or fault initiation.
- d) Very fast-front overvoltages that ~~are the result of~~ [from](#) switching operations or faults and [that](#) are usually associated with high-voltage disconnect switch operation, GIS, and cable-connected motors.

3.1.1 Continuous power frequency voltages

The designated maximum system voltage is identified in ANSI C84.1-~~1995~~ and ANSI C92.2-~~1987~~ and is used for insulation coordination. For systems whose maximum system voltage exceeds that given in the standards, the actual maximum system operating voltage should be used. [It is important to note that operating equipment above the rated maximum voltage may result in additional risks to the application of insulation coordination because the equipment may not be tested for these elevated continuous voltage conditions.](#)

3.1.2 Temporary overvoltages

The temporary overvoltage is described by an amplitude-duration characteristic, which is determined by system analysis.

3.1.2.1 Fault overvoltages

Faults produce temporary, power frequency, phase-ground overvoltages on the unfaulted phases. Temporary overvoltages between phases or across longitudinal insulation normally do not occur. The magnitude of the overvoltage depends on the system grounding and on the fault location. Depending on the system configuration, during fault clearing, separated portions of the system may become ungrounded. A ground fault in the separated part of the system produces high overvoltages, which can be controlled by fast grounding of the neutral points or by the proper application of surge arresters that short-circuit the neutral when the fault occurs.

In effectively grounded systems, the temporary overvoltage is approximately ~~about~~ 1.3 pu, and the duration of the overvoltage, considering backup clearing, is generally less than 1 s. In resonant grounded neutral systems, the temporary overvoltage is approximately ~~about~~ 1.73 pu or greater, and, with fault clearing, the duration is generally less than 10 s. In systems without fault clearing, this duration is undefined. ~~The overvoltages are expressed in pu with reference to $\sqrt{2}V_m$ or $\sqrt{3}V_m$ is the maximum system voltage.~~

In a wye-connected, resistively grounded system, the temporary overvoltage will approach 1.73 pu phase-to ground on unfaulted phases for a single phase-to-ground fault. This occurs because of a voltage shift of the neutral point of the power transformer due to the fault current flowing in the resistor and will approach 1.0 pu of the phase-to-phase voltage. This coupled with the normal voltage of 1.0 pu across the wye-connected winding of the unfaulted phase (at some angle with reference to the neutral resistor voltage) will produce a 1.73 pu phase-to-ground voltage on the unfaulted phases.

In a delta-connected system, the temporary overvoltage will approach 1.73 pu phase-to-ground on unfaulted phases for a single phase-to-ground fault. This occurs because the delta-connected winding that is normally connected phase-to-phase is connected phase-to-ground during the fault. If the system has a high phase-to-ground capacitance ($X_0 / X_1 \leq -1$), such as networks primarily constructed with underground cables, this value can be even higher. (See IEEE Std C62.92.5.)

The overvoltages are expressed in per-unit values with reference to $\sqrt{2V_m} / \sqrt{3}$, where V_m is the maximum system voltage.

3.1.2.2 Load rejection overvoltages

Temporary overvoltages caused by load rejection are a function of the load rejected, the system topology after disconnection, and the characteristics of the sources, ~~that is i.e.~~, short-circuit power at the station, speed and voltage regulation of the generators, ~~and so on etc.~~ These overvoltages are especially important in the case of load rejection at the remote end of a long line due to the Ferranti effect. Primarily, it affects the apparatus at the station connected on the line side of the remote circuit breaker.

A distinction should be made between various system configurations when large loads are rejected. A system with ~~relatively~~ short lines and high short-circuit ~~power~~ fault current at terminal stations will have low overvoltages. A system with long lines and low short-circuit ~~power~~ fault current at generating sites will have high overvoltages.

In a symmetrical three-phase power system, the same relative overvoltages occur phase ~~to-~~ ground and phase ~~to-~~ phase. The longitudinal temporary overvoltages depend on whether phase opposition is possible. Phase opposition can occur when the voltages on each side of the open switching device are not synchronized.

A description of the degree and duration of phase-ground and longitudinal overvoltages for two types of substations follows:

- *System substation:* In a moderately extended system, for a full load rejection, the temporary overvoltage is usually less than 1.2 pu. The duration depends on the voltage control operation and may be up to several minutes. In extended systems, the overvoltages may reach 1.5 pu or even more when Ferranti effects or resonance occur. The duration may be in the order of seconds. The longitudinal overvoltage across a switching device is usually equal to the phase-ground overvoltage unless motors or generators, connected to the rejected side, produce phase opposition.
- *Generator station:* For a full load rejection, the overvoltage at the substation may reach up to 1.5 pu. The duration may be up to 3 s depending on the generator characteristics and control. The longitudinal temporary overvoltage is the difference between the phase-ground operating voltage at one terminal and the phase-ground temporary overvoltage on the other terminal. In the case of phase opposition, the longitudinal overvoltages could be as high as 2.5 pu.

Shunt reactors, static [voltage-amp reactive \(VAR\)](#) compensators, or special (grouped) arresters can control these overvoltages.

3.1.2.3 Resonance and ferroresonance overvoltages

Temporary overvoltages in this category arise from the interaction of capacitive elements (lines, cables, series capacitors) and inductive elements having nonlinear magnetizing characteristics (transformers, shunt reactors). The resonant overvoltage is initiated by a sudden change in the system configuration, such as a load rejection, single-phase switching of a transformer terminated line, or isolation of a bus potential transformer (PT) through breaker capacitance. Resonant and ferroresonant overvoltages can have magnitudes greater than 3.0 pu and last until the condition is cleared. They should be limited by detuning the system from the resonant frequency, by changing the system configuration, or by damping resistors.

3.1.2.4 Transformer energization caused overvoltages

Across-the-line ~~The~~ energization of a transformer causes in-rush-current and overvoltages at the transformer terminal. These overvoltages may last for seconds and have magnitudes in the range of 1.5 pu to -2.0 pu. Interaction of the in-rush current with the power system during energization of a transformer can result in high transient overvoltages especially during system restoration procedures. Surge arresters are usually installed phase to ground. However, to protect the windings of a transformer, surge arresters might also be installed phase to phase.

3.1.2.5 Limitation of temporary overvoltages by surge arresters

Arresters are not normally sized to control temporary overvoltages except in special cases. However, surge arresters may be applied to limit or even prevent resonant overvoltages. In this case, the thermal stress on the arresters should be investigated to determine if arresters in parallel or special switched arresters are required.

3.1.3 Switching overvoltages

Switching overvoltages may have a time-times to-crest value from 20 μs to - 5000 μs and a time-to-half value of less than 20 000 μs. They are generally a result of the following:

- Line energization~~;~~
- Faults and fault clearing~~;~~
- Load rejections~~;~~~~or~~
- Switching of capacitive or inductive currents~~;~~

In general, the time to crest (wavefront) is of more importance since the critical flashover voltage (CFO) is a function of the wavefront. The minimum CFO occurs at the critical wavefront (CWF), which in microseconds ~~μs~~ is equal to approximately ~~about~~ 50 times the strike distance in meters~~(m)~~. For a wavefront smaller or greater than the CWF, the CFO increases. The CFO increases by ≈ ~~about~~ 10% when the wavefront is in the order of 1000 μs to 2000 μs~~,~~ which usually occurs when employing low-side transformer switching.

The distribution of switching overvoltages is obtained using a transient program where the breakers are randomly closed or reclosed 200 to 400 times with the three poles closing statistically at any point on wave within a sliding quarter cycle window. The sliding quarter cycle window is shifted over a half cycle timeframe using a uniform distribution to capture random switching times within one cycle. These overvoltages are then statistically analyzed to obtain a probability distribution, which approximates the data. Several distribution functions have been used, for example, a e.g., Gaussian, extreme-value Weibull. However, a Gaussian or normal distribution is used most frequently. This distribution is evaluated at ~~defined by~~ its 2% value, called the “statistical switching overvoltage” (E_2), and by its standard deviation σ in per unit pu of E_2 . The variation in per unit standard deviation pu is: σ / E_2 . To clarify the definition, E_2 means that 2% of the switching overvoltages equal or exceed E_2 . The shape of the distribution may be affected by the surge controlling action of an arrester. Typically, the gapless arrester modifies the reflected wave and reduces the voltage stress that caused by the reflective return wave causes.

3.1.3.1 Line energization and reclosing overvoltages

In most cases, a three-phase energization or reclosing of a power line produces switching overvoltages on all three phases. The overvoltage generation depends on the type of circuit breaker; ~~some-of-the~~ circuit breakers may not generate any overvoltages. A typical example is the circuit breaker that closes when the voltage across the contact is zero. The overvoltage calculation should also ~~has to~~ consider trapped charges left on the phases without fault in case of high-speed reclosing.

In the worst case, each switching operation produces three phase-ground and three phase-phase overvoltages. Two methods are in use for characterizing the overvoltage probability distribution function; the case-peak method and the phase-peak method are described as follows:

- *Case-peak method:* From each switching operation, the highest crest overvoltage of the three overvoltages is selected and included in the probability distribution. Each switching operation contributes one value to the overvoltage distribution. This method is based on the observation that the inclusion of the other two values does not significantly affect the probability of flashover. This results in the distribution of switching surge overvoltages per three-phase energization or reclosing operation, and [it](#) is used to calculate the probability of flashover per three-phase switching operation.
- *Phase-peak method:* From each switching operation, the crest switching overvoltage on each of the three-phases is included in the probability distribution. Each operation contributes three crest values to the probability distribution. This results in a per-phase distribution of overvoltages that can be used to calculate a per-phase probability of flashover for the switching operation.

These methods are used to determine both a phase-ground and [a](#) phase-phase overvoltage distribution. Because the probability of positive and negative polarity overvoltages is equal, these methods consider only the absolute value of overvoltages, regardless of the polarity. The effect of negative and positive polarity is considered in the calculation of the switching surge flashover rate.

Line switching overvoltages may be reduced [using the following:](#) ~~through the use of~~

- a) Preinsertion resistors on the circuit breakers;
- b) Controlled closing of the breaker;~~or~~
- c) Surge arresters.

A preinsertion resistor and controlled closing reduces the overvoltage along the entire line. Surge arresters only reduce the overvoltages close to the arresters.

~~However, within a substation, arrester separation effects may be neglected, i.e., the switching impulse voltage is approximately the same throughout the substation. Thus, an arrester provides protection to all connected equipment.~~

~~Surge arresters are usually installed phase-ground.~~ If metal-oxide arresters are used to limit phase-ground switching overvoltages to a level lower than approximately ~~about~~ 70% of E_2 (2% probability), the phase-phase overvoltage level will reach about twice the protective level of the arrester.

3.1.3.2 Typical phase-ground switching overvoltages

Table 1 presents approximate values of reclosing produced overvoltages distribution; E_2 ~~(2% probability)~~ and σ / E_2 at the end of the line when no arresters are present. These values were calculated by the case-peak method. In addition, approximate values of the voltage profile are presented. The voltage profile is the ratio of the switching overvoltage at the switched end to that at the open end of the line (E_2). The provided E_2 values are representative of homogeneous lines; however, lines with discontinuities (e.g., overhead-underground intersections) need careful consideration.

Table 1—Typical overvoltage from reclosing on a trapped charge

Condition	E_2 (pu)	σ / E_2	Voltage profile
Pre-insertion resistor is used	1.8–2.0	0.05–0.08	0.8– 0.9
No pre-insertion resistor is used	2.8–3.0	0.08–0.16	0.6–0.7

(New)

	E_2 pu	σ/E_2	Voltage profile
Preinsertion resistor is used	1.8–2.0	0.05–0.08	0.8– 0.9
No preinsertion resistor is used	2.8–3.0	0.08–0.16	0.6–0.7

~~(Deleted)~~

The maximum switching overvoltage is in the range of 1.0 to 1.5 standard deviations above E_2 .

Comparable values of E_2 for the phase-peak method are from 2% to 5% lower, whereas ~~while~~ the standard deviation may be 40% to 50% higher.

When arresters are present at the end of the line, the overvoltage distribution may be approximated as a combination of two Gaussian distributions, one of which is valid to the point at which the arrester significantly affects the voltage and the other, for higher voltages. The value of E_2 at the open end of the line may be approximated conservatively as the switching impulse discharge voltage of the arrester. The value of σ / E_2 for the arrester portion of the distribution is significantly decreased and is in the range of 0.01 to 0.03. Because the arrester cannot decrease the switching overvoltage along the entire line, the maximum value of E_2 is not at the open end but is within approximately ~~about~~ 1/3 to 1/4 of the line length from the arrester. Therefore, it is difficult to estimate the voltage profile since the voltage initially increases along the line from the arrester location and then decreases for the remainder of the line. The maximum value of E_2 is typically less than 1.3 times ~~30% greater than~~ the arrester protective level.

3.1.3.3 Typical phase-phase switching overvoltages

The phase-phase insulation strength of external insulation (e.g., air gaps, bushings, and station and line insulators, ~~etc.~~) is a function of the voltages and their polarities on each of the two phases. Therefore, the switching overvoltages distribution of both ~~of the~~ components and their correlation coefficient are required. Usually, the phase-phase overvoltage distribution and the positive polarity phase-ground overvoltage distribution (with the correlation coefficient) are obtained as in 3.1.3.2. From these distributions, the negative polarity distribution can be derived, or alternatively, the phase-phase distribution can be used directly as illustrated in Clause 4.

Because the crest phase-phase overvoltages and the positive and negative phase-ground overvoltages may not occur at the same time, the two time instants that follow are usually considered for sampling the overvoltages:

- a) The time instant of the crest of the phase–phase overvoltage: This produces the highest phase–phase overvoltages and represents the highest stress for all insulation configurations for which the dielectric strength between phases is not sensitive to the subdivision into components. A typical example is the internal insulation of a transformer or other types of internal insulation.
- b) The time instant of the crest of the positive phase–ground overvoltage: Although this time instant may produce lower phase–phase overvoltages, the insulation strength may be lower, thus, producing a higher probability of flashover. Typical examples are air clearances or air-porcelain insulation.

The overvoltage values belonging to the selected time instances are used to generate overvoltage probability distributions and their correlation coefficients. This method results in three distribution curves: phase–phase, positive phase–ground, and negative phase–ground for each of the two time instances.

In general, the comparison of these distribution curves indicates that the overvoltage distribution curves for each of the two time instances are approximately equal. Consequently, maximum phase–phase and the maximum phase–ground overvoltage distributions are commonly used.

Correlation coefficients between the phase–phase and positive phase–ground overvoltages are generally high, in the range of +0.7 to +0.9, whereas ~~while~~ the coefficients between the positive and negative overvoltages are generally low and may be either positive or negative.

The value of the statistical phase–phase switching overvoltage, E_{2p} , may be estimated from the value of the statistical phase–ground switching overvoltage, E_2 . The ratio of E_{2p} / E_2 only varies between 1.6 and ~~–1.5~~, whereas ~~while~~ the value of E_2 ranges between 2.0 and ~~to~~ 3.0. A ratio of ~ ~~about~~ 1.55 appears reasonable for all values of E_2 . As an example, for an E_2 of 2.8 pu, E_{2p} is 4. 34 ~~35~~ pu. Also, in general, the values for σ / E_{2p} are equal to the values of σ / E_2 . The maximum phase–phase switching overvoltage is approximately 1.0 to 1.5 standard deviations above E_{2p} . In addition, the values of voltage profiles are similar to those for phase– ground overvoltages.

3.1.3.4 Longitudinal switching overvoltages

During energization or reclosing, the longitudinal overvoltage is the difference between the continuous operating voltage at one terminal of the switching device and the switching overvoltage at the other terminal.

In synchronized systems, the highest switching overvoltage and the operating voltage have the same polarity, and the longitudinal insulation is exposed to a lower overvoltage than the phase-ground insulation.

The longitudinal insulation between nonsynchronous systems can be subject to energization overvoltages of one polarity at one terminal and the crest of the operating voltage of the other polarity at the other terminal. Consequently, in this case, the longitudinal insulation is exposed to significantly higher overvoltages than the phase-ground insulation.

3.1.3.5 Fault overvoltages

During line-to-ground fault initiation and clearing, overvoltages with wave shapes similar to those found during switching are produced. Conservative estimates for the maximum overvoltage are shown in Equation (1) and Equation (2):

$$\text{Fault initiation: maximum} = (2k - 1) \text{ pu} \quad (1)$$

$$\text{Fault clearing: maximum} = 2.0 \text{ pu} \quad (2)$$

where

k is the ground fault factor ~~in pu~~ of maximum line-ground system voltage (pu)

Both events cause overvoltages only between phase to-ground. The overvoltages between phases can be generally neglected.

If the switching overvoltages for energizing and reclosing are controlled to below 2.0 pu, fault initiation and fault clearing may produce higher overvoltages. These overvoltages occur at the open breaker end of a connected line.

3.1.3.6 Load rejection overvoltages

Load rejection produces a switching-type overvoltage. This event may increase longitudinal voltage stresses across switching devices, the phase-ground insulator stress and the energy discharged through the arresters. If the arresters are used to limit energization and reclosing overvoltages to below 2 pu, the energy dissipation in the arresters should be studied, especially when generators, transformers, long transmission lines, or series capacitors are present.

3.1.3.7 Inductive and capacitive currents switching overvoltages

The switching of inductive or capacitive currents may produce switching overvoltages. In particular, the following switching operations should be considered:

- a) Interruption of motor starting currents
- b) Interruption of transformer or reactor magnetizing currents
- c) Switching of arc furnaces and their transformers
- d) Switching of unloaded cables and capacitor banks
- e) Interruption of currents by high-voltage fuses

Overvoltages due to restrikes or reignitions of the arc of a switching device during the interruption of capacitive currents (switching off unloaded lines, cables, or capacitor banks) can produce extremely high overvoltage. When energizing capacitor banks, in particular ungrounded banks, the phase-phase overvoltages should be evaluated.

Capacitor bank energizing produces overvoltages at the capacitor location, at line terminations, at transformers, at remote capacitor banks, and at cables. The energizing transient at the switched capacitor location should be less than 2.0 pu phase to-ground and 3.0 pu phase to-phase. The phase-phase transients at line terminations can be 4.0 pu or higher due to traveling wave reflections. These higher phase-phase overvoltages are most commonly associated with energizing ungrounded capacitor banks.

The chopping of inductive current produces high overvoltages due to the transformation of magnetic energy to capacitive energy.

3.1.4 Lightning overvoltages

Lightning overvoltages are caused by [the following](#):

- a) Strokes to the phase conductors (shielding failure)
- b) Strokes to the line shielding system, which flashes over to the phase conductor (backflash)
- c) Strokes to ground [near](#) ~~in close proximity to~~ the line, which induce overvoltages in the phase conductors (induced voltage)

Lightning overvoltages are fast-front overvoltages with times to crest from 0.1 [μs to](#) 20 μs.

For substations, shield failures, backflash, and induced overvoltages generate surge voltages that impinge on the substation equipment. Lightning induced voltages are generally below 400 kV and are important only for lower voltage systems. The incoming surges caused by the backflash are more severe than that caused by shielding failures [due to the higher steepness of the backflash wave](#). As these surges travel from the stroke terminating point to the station, corona decreases front steepness and the crest magnitude. The shield wire has significant impact on the wave propagation. A shield wire grounded at each tower makes the propagation velocity of the ground mode wave component very close to the conductor mode component. The magnitude of the surges caused by a backflash ranges from 70% to 120% of the positive polarity CFO of the line insulation. The front steepness is a function of the conductor size, the distance between the location of the backflash, and the station.

The selected reliability criterion determines the characteristics of the incoming surge. The calculation method is described in Clause 5 and is based on the mean time between failures (MTBF).

For strokes close to the substations, lightning overvoltages between phases have approximately the same magnitude as those for phase [to](#) ground.

Backflashes usually occur on a phase with power frequency voltage that is opposite in polarity to the surge voltage. The maximum longitudinal overvoltage is the difference between the lightning overvoltage on one terminal and the power frequency voltage of opposite polarity on the other terminal of the switching device. For shielding failures, the voltage on the struck phase is random.

3.1.4.1 Lightning ~~type~~ overvoltages caused by switching

The connection or disconnection of nearby equipment produces surges with similar wave shapes to lightning. Generally, these short-duration and fast-rising surges are oscillatory. The insulation strength for this wave shape is closer to that of the standard lightning impulse than that of the standard switching impulse. Arresters do not ~~cannot~~ limit surges with the very steep fronts to the same extent that they do for slower front surges. As the magnitudes usually are smaller than those caused by lightning, their importance is restricted to special cases. The maximum values of these overvoltages are approximately as follows:

- a) Switching without restrike: 2.0 pu
- b) Switching with restrike: 3.0 pu

3.1.4.2 Limitation of lightning overvoltages

Surge arresters primarily limit lightning overvoltages on substation equipment. Another method to limit lightning overvoltages that impinge on equipment is to decrease the steepness and magnitude of the incoming surge. This may be accomplished by reducing the backflash rate of the line for towers adjacent to the substation by decreasing the tower footing resistance.

In some cases, the flashover voltage of lines adjacent to the station is limited by the installation of gaps. However, a reduction in the insulation strength of the line without lowering the tower footing resistance will increase the backflash rate and result in a higher magnitude and steeper incoming surge for the same MTBF. Alternatively, the MTBF will decrease.

3.2 Characteristics of overvoltage protective devices

3.2.1 General

The following three basic types of surge arresters are used:

- a) Gapless metal-oxide surge arrester
- b) Gapped metal-oxide surge arrester
- c) Gapped silicon-carbide surge arrester

The voltage across the terminals of the arrester consists of a discharge voltage and a sparkover voltage if the arrester contains a gap. The discharge voltage is the voltage across the arrester when discharging a current. This voltage is defined as the crest voltage across the terminals of the arrester. The discharge voltage is a function of the magnitude and time to crest of the discharge current. For arresters employing a gap in series with the valve block, the sparkover voltage is a function of the steepness of the front. For gapped arresters, both of these voltages must be considered.

3.2.2 Gapless metal-oxide surge arresters

The ranges ~~for~~ of the maximum discharge voltages are given in IEEE Std C62.22. ~~The -1997.~~ actual values for a specific arrester may be obtained from manufacturers' literature.

3.2.2.1 Lightning overvoltages

Manufacturers provide the discharge voltage for the following conditions:

- a) For a 1.5 kA to 40 kA, 8/20 μ s discharge current: This results in a discharge voltage with a time to crest of approximately ~~about~~ 7 μ s. Table 2 provides the classifying current magnitudes for various arrester classes and system voltages.
- b) For a discharge current having a front such as to produce a time to crest of the discharge voltage of 0.5 μ s: This is referred to as the 0.5 μ s discharge voltage or the front-of-wave (FOW) protective level. The classifying current magnitude is the same as the lighting impulse classifying current presented in Table 2.

**Table 2 — Lightning impulse classifying currents (IEEE Std [C62.11-2020](#)
1999)**

Arrester class	Maximum system voltage (kV)	Discharge current (kA)
Distribution	All system voltages	5
Normal & light duty		10
Heavy duty		
Intermediate	Less than 170	5
Station	Less than 550	10
	550	15
	800–1200	20

(New)

Arrester class	Max. system voltage kV	Discharge current kA
Station	800	20
	550	15
	Less than 550	10
Intermediate	Less than 161	5
Distribution	All system voltages	
Heavy duty		10
Normal & light duty		5

(Deleted)

3.2.2.2 Switching overvoltages

The maximum discharge voltages are provided by the manufacturers for a discharge current having a time to crest of between 45 μ s and 60 μ s and a crest value equal to the switching impulse classifying current given in Table 3. The discharge voltage is insensitive to the variation of [the](#)

[switching surge](#) discharge current because of the extreme nonlinearity of the metal-oxide material. This discharge voltage is also known as the switching impulse protective level. The dependence of metal-oxide arresters' discharge voltage on the front time of the switching overvoltage is negligible.

**Table 3— Switching impulse classifying currents (IEEE Std [C62.11-2020](#)
~~1999~~)**

Arrester class	Max system voltage (kV)	Discharge current (A)
Station	3–150	500
	151–325	1000
	326–1200	2000
Intermediate	3–161	500

(New)

Arrester class	Max system voltage kV	Discharge current kA
Station	3–150	500
	151–325	1000
	326–900	2000
Intermediate	3–161	500

(Deleted)

3.2.3 Gapped metal-oxide arrester

[Gapped metal-oxide arresters provide a similar function as gapless arresters, except that the gapped arresters have a gap either in series with or partially in parallel to the metal-oxide blocks. The maximum voltage across the arrester is the lightning impulse](#) ~~The lightning~~ protective level [that](#) is

either the maximum of ~~either the lightning impulse~~ sparkover ~~voltages~~ ~~voltage~~ or the discharge voltage at the lightning impulse classifying current given in Table 2.

Consequently, sparkover tests are prescribed for comparison at three discharge voltage levels. The tests required are as follows:

- a) For a voltage steepness of 100 kV/ μ s per 12 kV of arrester rating up to a maximum of 2000 kV/ μ s, this value is defined as the front of wave sparkover or FOW protective level.
- b) The 1.2/50 impulse protective level test series determines whether the arrester sparkover voltage for a standard 1.2/50 lightning impulse can exceed the discharge voltage obtained from an 8/20 discharge current.
- c) The slow-front (switching surge) impulse protective level test series determines whether the arrester sparkover for a slow-front impulse voltage can exceed the switching surge discharge voltage at the classifying current at the following times from zero to crest on the prospective voltage wave:
 - 30 μ s to 60 μ s
 - 150 μ s to 300 μ s
 - 1000 μ s to 2000 μ s

These tests determine whether the protective level provided for a specified wave shape is a function of the arrester's maximum sparkover value or its corresponding arrester discharge voltage for the specified waveshape.

The technical requirements for these tests are prescribed in IEEE Std C62.11.

3.2.4 Gapped silicon-carbide arresters

3.2.4.1 Lightning overvoltages

The manufacturers provide the discharge voltage for a 1.5 kA to ~~40~~ kA, 8/20 μ s discharge current.

This results in a discharge voltage with a time to crest of about $1.2 \mu\text{s}$.

In addition, the manufacturer provides the gap sparkover voltages for the following conditions:

- a) For a standard lightning impulse wave shape, ~~i.e.,~~ $1.2/50 \mu\text{s}$: This value is defined as the full wave sparkover voltage.
- b) For a voltage steepness of $100 \text{ kV}/\mu\text{s}$ per 12 kV of arrester rating up to a maximum of $2000 \text{ kV}/\mu\text{s}$: This value is defined as the FOW ~~front-of-wave~~ sparkover or FOW ~~front-of-wave~~ protective level.

The maximum voltage across the arrester is the lightning impulse protective level ~~that~~ ~~which~~ is either the maximum of the sparkover voltages or the discharge voltage at the lightning impulse classifying current given in Table 2.

3.2.4.2 Switching overvoltages

The arrester protective level is provided by the manufacturers and is the sum of the discharge voltage and the voltage drop across the active gap. The protection level is determined by a current impulse having a time to crest of between $45 \mu\text{s}$ and $60 \mu\text{s}$ and a crest value equal to the switching impulse classifying current in Table 3.

3.2.5 Spark gaps

The spark gap is a surge protective device consisting of an open air or enclosed gap ~~that is~~ connected phase ~~to~~ ground. The breakdown voltage versus time (or time lag) characteristics describes the protective capability. The gap spacing is generally selected such that the switching surges, under normal operating conditions, do not operate the gap. The selected gap spacing should consider the gap/insulation volt-time characteristics and atmospheric conditions. The gap characteristics must be obtained from the manufacturer or be established by test. The gap spacing is often a compromise between the protection obtained and the number of short-circuits produced by the gap operation.

Spark gaps are sometimes used to provide protection to equipment in areas of low lightning ground flash density or for protection of the open circuit breaker from lightning surges caused by subsequent strokes of lightning flash.

CAUTION

For oil circuit breakers (or any interrupting technology), flashover across the open contacts immediately following a low current interruption may cause a catastrophic failure of the circuit breaker as its interrupting capability depends on the appropriate generation of gasses in the interrupting chamber. See also 6.3.2.2.

This condition is not limited to low current interruption; it can occur with any current level from the smallest charging transformer magnetizing currents to fully rated fault currents. The phrase “immediately following an interruption” means the rated delay time for the interrupting medium of the breaker to restore its interrupting capability before the breaker is allowed to close. Breaker standards define the rated duty cycle with emphasis placed on this reclose delay time, which is necessary for the ionized path in air to recover so that the same fault path is not reestablished on breaker close. The fault path is assumed to be initiated through a self-restoring insulation path such as air. The breaker switching performance also relies on this delay time for the interrupting medium of the breaker to restore its interrupting capability. Considering more closely the time elements involved in the interruption and recover process, the transient recovery voltage (TRV) peak will be imposed across the breaker contacts on the order of a few hundred microseconds following interruption at a current zero. The reclose delay time is several orders of magnitude greater. Any external overvoltage imposed on the breaker during this time period, such as those caused by flashovers across spark gaps, would present a significant risk of failure to the breaker because it would be added to the TRV and, thus, exceed the capability of the breaker.

4. Insulation strength

4.1 General

~~Several~~ ~~A number of~~ factors influence the dielectric strength of insulation. The main factors include the following:

- a) The magnitude, shape, and polarity of the applied voltage
- b) The type of the insulation (gaseous, liquid, solid, or a combination of these; impurities and local inhomogeneities)
- c) The physical state of the insulation medium (temperature, pressure, and other ambient conditions; mechanical stresses)
- d) Prior duty on the insulation
- e) Chemical effects
- f) Conductor surface effects, and so on ~~etc.~~

4.1.1 Self-restoring insulation

The breakdown in air is strongly dependent on the gap configuration, wave shape and polarity of the surge, and ~~on~~ the ambient conditions. For outdoor insulators, the effect of humidity, fog, frost, rain, ice, and pollution on the surface of the insulation also become important. ~~For metal-enclosed gas insulated systems, the effect of the internal pressure and temperature as well as the local inhomogeneities and impurities play an important role.~~

4.1.2 Non-self-restoring insulation

In liquid insulation, particle impurities and, bubbles caused by chemical and physical effects, or by local discharges, can drastically reduce the insulation strength. Another ~~An~~ important aspect is ~~also~~ that the amount of chemical degradation of the insulation may tend to increase in time. The same is

valid for solid insulation. However, in this case, the mechanical stress may also affect the insulation strength. [For metal-enclosed, gas-insulated systems, the effects of the internal pressure and temperature, as well as the local inhomogeneities and impurities, play an important role.](#)

4.2 Insulation behavior at power frequency voltages

In general, discharges while operating under power frequency voltage and normal operating conditions, and under temporary overvoltages, will be caused by a significant reduction in equipment insulation withstand due to severe environmental conditions or by aging of the insulation.

Rain reduces the external dielectric strength of insulators but makes no practical reductions in the strength of air gaps. The greatest reductions in dielectric strength can be expected for power frequency voltages or for switching impulses. In addition to the rate of rainfall, the insulator configuration and the conductivity of water influence the reduction of the dielectric strength.

Rain together with pollution can drastically reduce the insulation strength. Fog, dew formation, or light [freezing](#) rain together with pollution or contamination usually causes the worst conditions.

The statistical description of the ambient conditions usually requires a large amount of data. The statistical description of aging is even more difficult. Therefore, [single-variable](#) statistical procedures are not [fully developed](#) ~~recommended~~ for estimation of the insulation behavior at power frequency voltages.

4.3 Influences of atmospheric conditions on external insulation

Flashover voltages for air gaps depend [on](#) both ~~on~~ air humidity and relative air density. Insulation strength increases with absolute humidity up to the point where condensation forms on the insulator surfaces. Insulation strength decreases with decreasing air density.

For atmospheric conditions other than the standard conditions, IEEE Std 4 [2013 and IEC 60071-2](#) [provide](#) ~~1995 provides~~ methods to estimate the insulation strength.

At a given location, the variation with time of the relative air density, the absolute humidity, the

humidity correction factor, and the product of the humidity correction factor and the relative air density may each be approximated by a Gaussian distribution. The standard deviations of these distributions are small and may be neglected. Thus, the insulation strength at nonstandard atmospheric conditions may be based on the average or mean values of the variables.

The design of line or substation insulation is universally based on rain conditions. Therefore, the atmospheric corrections are based on wet conditions. For station insulation, the BSL is defined for wet conditions. However, the BIL is tested under dry conditions under the premise that wet conditions do not severely degrade the insulation strength. Although this [premise](#) is not universally true, the wet BIL is assumed equal to the dry BIL.

For line insulation, the dry CFO is normally obtained from parametric tests. The wet CFO is estimated by multiplying the dry CFO with an experimentally determined correction factor.

4.4 Probability of disruptive discharge

[No widely accepted](#) ~~There are no~~ methods [are currently](#) ~~presently~~ available for determining the probability of a disruptive discharge of non-self-restoring insulation. Therefore, the probability of a withstand is assumed to be 100% at or below the BIL and BSL. However, for stresses above the BIL and BSL level, the probability of withstand is assumed to be zero.

For self-restoring insulation, the probability of flashover may be described by an insulation strength characteristic curve. This curve has two basic parameters: the CFO, corresponding to the 50% probability of flashover for a single impulse application, and the standard deviation (for coefficient of variation, σ_f/CFO , [where \$\sigma_f\$ is the standard deviation of flashover intensity](#)). The insulation strength characteristic is modeled by a cumulative Gaussian distribution function and is considered valid to at least four standard deviations below the CFO. The actual truncation point, below which no flashover can occur, is not known. The insulation strength characteristic may be estimated by statistical test methods given in IEEE Std 4-1995. The statistical BIL or BSL, defined by the 10% probability of flashover, is mathematically defined as shown in Equation (3):

$$\text{BIL or BSL} = \text{CFO} \left[1 - 1.28 \frac{\sigma_f}{\text{CFO}} \right] \quad (3)$$

where

BIL is the basic impulse insulation level (kV)

BSL is the basic switching insulation level (kV)

CFO is the critical flashover voltage of insulation (kV)

σ_f is the standard deviation of flashover intensity (kV)

CFO is the 50% probability of flashover for a single lightning impulse or for a single switching impulse, respectively.

In addition, for evaluation of the switching surge flashover rate, a statistical withstand voltage, V_{3-} is used, which is three standard deviations below the CFO. The truncation point is usually neglected. For self-restoring insulation, the value of the coefficient of variation is smaller for lightning impulses than for switching impulses. For lightning impulses, this coefficient is $\approx$ ~~about~~ 3%. For switching impulses for line or tower insulation, the coefficient increases to an average of $\approx$ ~~about~~ 5%. For station insulation, the coefficient of variation is generally assumed to be between 6% and 7%.

4.5 Influence of polarity and overvoltage shape

When the more highly stressed electrode in air is positively charged, the breakdown voltage is lower than if the electrode is negatively charged. For most ~~the majority of~~ gaps, the high-voltage conductor is more stressed and is the more irregularly shaped electrode. If the grounded electrode of a gap is more highly stressed, the dielectric strength to negative impulses is lower. For air-porcelain insulation, such as ~~e.g.~~ tower or line insulation, positive polarity impulses produce the lower insulation strength. For self-restoring station insulation, apparatus standards specify that the polarity that ~~which~~ results in the lower insulation strength be used to establish the BIL or BSL.