516™

IEEE Guide for Maintenance Methods on Energized Power Lines

IEEE Power & Energy Society

Sponsored by the
Transmission and Distribution Committee

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

24 June 2009

IEEE Std 516™-2009
(Revision of
IEEE Std 516-2003)

IEEE Std 516™-2009
(Revision of
IEEE Std 516-2003)

IEEE Guide for Maintenance Methods on Energized Power Lines

Sponsor

Transmission and Distribution Committee
of the
IEEE Power & Energy Society

Approved 13 May 2009

IEEE-SA Standards Board

Abstract: General recommendations for performing maintenance work on energized power lines are provided. Technical explanations as required to cover certain laboratory testing of tools and equipment, field maintenance and care of tools and equipment, and work methods for the maintenance of energized lines and for persons working in the vicinity of energized lines are included.
Keywords: energized, equipment, maintenance, power lines, tools

---

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

PDF: ISBN 978-0-7381-5911-9 STD95910
Print: ISBN 978-0-7381-5912-6 STDPD95910

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

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

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

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

In publishing and making this document available, the IEEE is not suggesting or rendering professional or other services for, or on behalf of, any person or entity. Nor is the IEEE undertaking to perform any duty owed by any other person or entity to another. Any person utilizing this, and any other IEEE Standards document, should rely upon his or her 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.

Interpretations: Occasionally questions may arise regarding the meaning of portions of standards as they relate to specific applications. When the need for interpretations is brought to the attention of IEEE, the Institute will initiate action to prepare appropriate responses. Since IEEE Standards represent a consensus of concerned interests, it is important to ensure that any interpretation has also received the concurrence of a balance of interests. For this reason, IEEE and the members of its societies and Standards Coordinating Committees are not able to provide an instant response to interpretation requests except in those cases where the matter has previously received formal consideration. A statement, written or oral, that is not processed in accordance with the IEEE-SA Standards Board Operations Manual shall not be considered the official position of IEEE or any of its committees and shall not be considered to be, nor be relied upon as, a formal interpretation of the 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, explanation, or interpretation of the IEEE.

Comments for revision of IEEE Standards are welcome from any interested party, regardless of membership affiliation with IEEE. Suggestions for changes in documents should be in the form of a proposed change of text, together with appropriate supporting comments. Recommendations to change the status of a stabilized standard should include a rationale as to why a revision or withdrawal is required. Comments and recommendations on standards, and requests for interpretations should be addressed to:

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

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

Introduction

This introduction is not part of IEEE Std 516-2009, IEEE Guide for Maintenance Methods on Energized Power Lines.

Live-line maintenance of transmission lines began in the early 1920s and developed into a major working practice as the transmission systems were expanded and the voltages increased.

In the 1950s, when the transmission line voltage exceeded 300 kV line to line, the use of fiberglass to replace wooden tools made a significant change in the industry. Economic conditions prohibited the construction and operation of redundant lines, and the need for live-line maintenance of transmission line increased rapidly.

During the 1950s and 1960s, several papers were written regarding the safety aspects of live-line maintenance. In the early 1970s, the IEEE Transmission and Distribution Committee recognized the need to consolidate information on live-line maintenance, and thus a task group was formed to write a guide. The task group later became the Engineering in Safety, Maintenance, and Operation of Lines (ESMOL) Subcommittee.

This guide was started in the late 1970s and was published in 1986 on a trial-use basis. In 1987, the guide was released as a full-use ANSI/IEEE guide. Since the original publication of the guide, the ESMOL Subcommittee has been working on revisions to the guide to bring it up to the current state of the art and into conformance with other international standards issued in recent years. The ESMOL Subcommittee has added sections from other ESMOL sponsored guides in this edition to expand the scope of the guide to cover more of the industry's needs.

In the guide editions up to 1995, most of table data were obtained from plots. In the 2003 guide, the tables were calculated using the formulas in the guide in a step calculation method.

In this edition of the guide, the tables were calculated using the formulas in the guide. Additional text has been added on the determination of maximum anticipated per-unit transient overvoltage (TOV) T and use of the minimum air insulation distance (MAID) and minimum approach distance (MAD).

During the original development of the guide, it was not intended that it would be used as a document to establish government regulations. However, since its publication in 1986, several government regulatory agencies have used the guide in their rule making. This edition of the guide includes revisions that make it more compatible for use in governmental regulations.

Notice to users

Laws and regulations

Users of these documents should consult all applicable laws and regulations. Compliance with the provisions of this standard 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

This document is copyrighted by the IEEE. It is made available 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 this document available for use and adoption by public authorities and private users, the IEEE does not waive any rights in copyright to this document.

Updating of IEEE documents

Users of IEEE standards 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. 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 Standards Association Web site at http://ieeexplore.ieee.org/xpl/standards.jsp, or contact the IEEE at the address listed previously.

For more information about the IEEE Standards Association or the IEEE standards development process, visit the IEEE-SA website at http://standards.ieee.org.

Errata

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

Interpretations

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

Patents

Attention is called to the possibility that implementation of this guide may require use of subject matter covered by patent rights. By publication of this guide, no position is taken with respect to the existence or validity of any patent rights in connection therewith. The IEEE 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 guide 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 guide was submitted to the IEEE-SA Standards Board for approval, the Live Line Guide Working Group of the Engineering in Safety, Maintenance, and Operation of Lines (ESMOL) Subcommittee had the following membership:

Charles W. Grose, *Chair*
Thomas Buonincontri, *Vice Chair*

Gernot Brandt
Ken Brown
Kris Buchholz
James F. Christensen
Don Dodds
J. Fred Doering
Brian Erga
George Gela
Donald Gillies*
Randy Horton
Ed Hunt
Robert Isiminger
Ernie Jones
Clay King
Nestor Kolcio
Keith Lindsey
Sandy Martinez
Thomas McCarthy
George Niles
Tim Olson
A. D. Pierce
Tom Rasler
Larry Schweitzer
George Stinnett
Steve Theis
James Tomaseski
Tom Verdecchio
Keith Wallace
David Wallis

* The Live Line Guide Working Group acknowledges the contributions of Donald Gillies, who passed away shortly before the publication of this guide.

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

William J. Ackerman
Chris Ambrose
Gregory Ardrey
Stan Arnot
Ali Al Awazi
Robert Barnett
Robert Bendall
Harvey Bowles
Gernot Brandt
Thomas Buonincontri
William Byrd
James F. Christensen
Robert Christman
Kevin Coggins
Tommy Cooper
Luis Coronado
F. A. Denbrock
J. Fred Doering
Gary L. Donner
Gary Engmann
Brian Erga
David Garrett
Waymon Goch
Edwin Goodwin
Charles W. Grose
Randall Groves
Ajit Gwal
Lee Herron
Werner Hoelzl
Randy Horton
Ed Hunt
Magdi Ishac
R. Jackson
Gael Kennedy
Albert J. Keri
Tanuj Khandelwal
Yuri Khersonsky
J. Koepfinger
Nestor Kolcio
David W. Krause
Jim Kulchisky
Saumen Kundu
Donald Laird
Chung-Yiu Lam
Stephen Lambert
Keith Lindsey
Federico Lopez
Faramarz Maghsoodlou
Keith Malmedal
Thomas McCarthy
Daniel Mulkey
Jerry Murphy
Michael S. Newman
T. Olsen
Tim Olson
Carl Orde
Robert Oswald
A. D. Pierce
Tom Rasler
Keith Reese
Michael Roberts
Charles Rogers
Thomas Rozek
Bob Saint
Bartien Sayogo
Dennis Schlender
Larry Schweitzer
Charles A. Shaw
Jeffrey Sisson
James E. Smith
Jerry Smith
R. Sundararajan
Michael Swearingen
James Tomaseski
John Vergis
Martin Von Herrmann
Carl Wall
Keith Wallace
Daniel Ward
James Wilson

Contents

IEEE Guide for Maintenance Methods on Energized Power Lines

IMPORTANT NOTICE: This standard is not intended to ensure safety, security, health, or environmental protection in all circumstances. Implementers of the standard are responsible for determining appropriate safety, security, environmental, and health practices or regulatory requirements.

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 guide provides the general recommendations for performing maintenance work on energized power lines. It is not intended to include all of the proven practical methods and procedures; however, these selected comprehensive recommendations are based on sound engineering principles, engineering safety considerations, and field experience by many utilities. Included are technical explanations as required to cover certain laboratory testing of tools and equipment, in-service inspection, maintenance and care of tools and equipment, and work methods for the maintenance of energized lines for persons working in vicinity of energized lines.

1.2 Purpose

The purpose of this guide is to

a) Present, in one guide, sufficient details of some of the methods and equipment presently in use to enable the performance of energized line maintenance with maximum safety.

b) Direct attention to appropriate standards and other documents for the acquisition of knowledge on the inspection, care, and use of required tools and equipment.

c) Provide guidance for establishing an appropriate work area, taking into consideration safety and the physical effects of the work area on personnel.

It is not intended that this guide should replace present proven utility practices or imply that these recommendations are superior to existing practices and, therefore, should be universally adopted as utility standards. This compilation of many accepted practices is presented specifically in the form of a guide to be used by those electric utilities and agencies that are seeking guidance in establishing methods and procedures for maintenance of energized power lines.

1.3 Application

This guide, although general in scope and purpose, is specific enough to be applicable to all aspects of energized-line maintenance.

Since energized-line maintenance practices for different projects are influenced by the magnitude and nature of each project and by local conditions and circumstances, some alternative methods that have been successfully employed are presented.

The practices described provide for the performance of energized-line maintenance with maximum safety. They are based on practices of operating utilities with many years of successful experience.

The approach used in this guide is to

a) Indicate the engineering and other technical considerations essential to the performance of energized-line maintenance with maximum safety.
b) Provide guidance for the necessary test equipment and procedures associated with manufacturer and user acceptance, testing, and care of equipment.
c) Detail various work methods for working on or near energized lines and associated devices.

Advancement in technology or changes in system design will probably justify modifying the minimum requirements recommended in this guide.

CAUTION

Requirements of federal, state, or local regulations should be observed. When any conflict exists between this guide and the rules of the owner of the line, the owner's rules shall take precedence.

2. Normative references

The following referenced documents are indispensable for the application of this document (i.e., they must be understood and used; therefore, 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/SIA A92.2, American National Standard for Vehicle-Mounted Elevating and Rotating Aerial Devices.[1]

ASTM D 120, Standard Specification for Rubber Insulating Gloves.[2]

---

[1] ANSI 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/).

[2] ASTM publications are available from the American Society for Testing and Materials, 100 Barr Harbor Drive, West Conshohocken, PA 19428-2959, USA (http://www.astm.org/).

ASTM D 1048, Standard Specification for Rubber Insulating Blankets.

ASTM D 1049, Standard Specification for Rubber Insulating Covers.

ASTM D 1050, Standard Specification for Rubber Insulating Line Hose.

ASTM D 1051, Standard Specification for Rubber Insulating Sleeves.

ASTM F 478, Standard Specification for In-service Care of Insulating Line Hose and Covers.

ASTM F 479, Standard Specification for In-service Care of Insulating Blankets.

ASTM F 496, Standard Specification for In-service Care of Insulating Gloves and Sleeves.

ASTM F 696, Standard Specification for Leather Protectors for Rubber Insulating Gloves and Mittens.

ASTM F 711, Standard Specification for Fiberglass-Reinforced Plastic (FRP) Rod and Tube Used in Live Line Tools.

ASTM F 712, Electrically Insulating Plastic Guard Equipment for Protection of Workers.

ASTM F 855, Standard Specification for Temporary Protective Grounds to be Used on De-Energized Electric Power Lines and Equipment.

ASTM F 968, Standard Specification for Electrically Insulating Plastic Guard Equipment for Protection of Workers.

ASTM F 1236, Standard Guide for Visual Inspection of Electrical Protective Rubber Products.

ASTM F 1701, Standard Specification for Unused Polypropylene Rope with Special Electrical Properties.

ASTM F 2522-05, Standard Test Method for Determining the Protective Performance of a Shield Attached on Live Line Tools or on Racking Rods for Electric Arc Hazards.

CSA C225, Vehicle-Mounted Aerial Devices.[3]

IEC 60060-1, High-Voltage Test Techniques—Part 1: General Definitions and Test Requirements.[4]

IEC 60060-2, High-Voltage Test Techniques—Part 2: Measuring Systems.

IEC 60060-3, High-Voltage Test Techniques—Part 3: Measuring Devices.

IEC 60060-4, High-Voltage Test Techniques—Part 4: Application Guide for Measuring Devices.

IEC 60625-1, Programmable Measuring Instruments—Interface System (byte serial, bit parallel)—Part 1: Functional, Electrical and Mechanical Specification, System Applications and Requirements for the Designer and User.

IEC 60625-2, Programmable Measuring Instruments—Interface System (byte serial, bit parallel)—Part 2: Codes, Formats, Protocols and Common Commands.

---

[3] CSA publications are available from the Canadian Standards Association (Standards Sales), 178 Rexdale Blvd., Etobicoke, Ontario, Canada M9W 1R3 (http://www.csa.ca/).

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

IEC 60855, Insulating Foam-Filled Tubes and Solid Rods for Live Working.

IEC 60895, Live Working—Conductive Clothing for use at Nominal Voltage up to 800 kV AC and 600 kV DC.

IEC 60903, Specifications for Glovers and Mitts of Insulating Material for Live Working.

IEC 60984, Sleeves of Insulating Material for Live Working.

IEC 61057, Aerial Devices with Insulating Boom used for Live Working.

IEC 61111, Matting of Insulating Material for Electrical Purposes.

IEC 61112, Blankets of Insulating Material for Electrical Purposes.

IEC 61229, Rigid Protective Covers for Live Working on AC Installations.

IEC 61230, Live Working—Portable Equipment for Earthing or Earthing and Short-Circuiting.

IEC 61235, Live Working—Insulating Hollow Tubes for Electrical Purposes.

IEC 61236, Saddles, Pole Clamps (Stick Clamps) and Accessories for Live Working.

IEEE Std 62™, IEEE Guide for Diagnostic Field Testing of Electric Power Apparatus—Part 1: Oil Filled Power Transformers, Regulators, and Reactors.[5, 6]

IEEE Std 524™, IEEE Guide to the Installation of Overhead Transmission Line Conductors.

IEEE Std 935™, IEEE Guide on Terminology for Tools and Equipment to be Used in Live Line Working.

IEEE Std 957™, IEEE Guide for Cleaning Insulators.

IEEE Std 1048™, IEEE Guide for Protective Grounding of Power Lines.

IEEE Std 1067™, IEEE Guide for In-Service Use, Care, Maintenance, and Testing of Conductive Clothing for Use on Voltages up to 765 kV ac and ± 750 kV dc.

IEEE Std 1070™, IEEE Guide for the Design and Testing of Transmission Modular Restoration Structure Components.

IEEE Std 1307™, IEEE Standard for Fall Protection for Utility Work.

IEEE Std 1313.2™, IEEE Guide for the Application of Insulation Coordination.

IEEE Std C62.92.1™-2000 (Reaff 2005), IEEE Guide for the Application of Neutral Grounding in Electrical Utility Systems—Part I: Introduction.

ISO 2307, Fiber Ropes—Determination of Certain Physical and Mechanical Properties.[7]

---

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

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

[7] ISO publications are available from the ISO Central Secretariat, 1 ch. de la Voie-Creuse, Case Postale 56, CH-1211, Genève 20, Switzerland/ Suisse (http://www.iso.ch/). ISO 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/).

3. Definitions, acronyms, and abbreviations

3.1 Definitions

This subclause provides definitions for terms used in this guide. Additional terminology can be found in IEEE Std 935.[8] For terminologies not listed below or in IEEE Std 935, consult *The Authoritative Dictionary of IEEE Standards Terms* [B22].[9]

3.1.1 aerial work: Work performed on equipment used for the transmission and distribution of electricity and performed in an elevated position on various structures, conductors, associated equipment from the structure, an insulating device, or a helicopter for barehand work.

3.1.2 barehand work: A technique of performing live maintenance on energized wires and equipment whereby one or more line workers work directly on an energized part after having been raised and bonded to the same potential as the energized wire or equipment. These line workers are normally supported by an insulating ladder, insulating rope, insulating aerial device, helicopter, or the energized wires or equipment on which they are working. Most barehand work includes the use of insulating tools.

3.1.3 bonded: The mechanical interconnection of conductive parts to maintain a common electrical potential. *Syn:* **connected**.

3.1.4 bucket: A device designed to be attached to the boom tip of a line truck, crane, or aerial device and used to support workers in an elevated working position. It is normally constructed of fiberglass to reduce its physical weight, maintain strength, and obtain good dielectric characteristics. For some applications, the device is a platform with a railing generally constructed of conductive material. *Syn:* **basket**; **platform**.

3.1.5 capacitive current: The component of the measured current that leads the applied voltage by 90° due to the capacitance of the tool or equipment.

3.1.6 clear live tool insulation distance: The distance measured longitudinally along the insulating part of the tool between the points where the tool contacts the live parts and parts at ground potential.

3.1.7 clearance: *See:* **work permit**.

3.1.8 conduction current: The component of the measured current in phase with the applied voltage that is delivered to the volume of the tool or equipment due to the electrical resistance of the material comprising the tool or equipment.

3.1.9 conducting body: A conductive object or mass such as a structure.

3.1.10 conductive clothing: Clothing made of natural or synthetic material that is either conductive or interwoven with conductive thread to provide mitigation of the effects of the electric fields of high-voltage energized electrical conductors and equipment and of radio frequency (RF) fields of public communication system (PCS) antennas.

3.1.11 conductor: A wire or combination of wires not insulated from one another, suitable for carrying an electrical current. Conductors can be bare or insulated. *Syn:* **cable**; **wire**.

---

[8] Information on references can be found in Clause 2.

[9] The numbers in brackets correspond to the numbers of the bibliography in Annex A.

3.1.12 cover-up equipment: Equipment designed to protect persons from brush or inadvertent contact to energized parts in a specific worksite. Many different types are available to cover conductors, insulators, dead-end assemblies, structures, and apparatus. Cover-up material might be either flexible or rigid. *Syn:* **blanket**; **cover-up**; **eel**; **hard cover**; **hose**; **snake**.

3.1.13 critical flashover (CFO) voltage: Fifty percent probability of sparkover voltage.

3.1.14 current-carrying part: A conducting part intended to be connected in an electric circuit to a source of voltage. Noncurrent-carrying parts are parts not intended to be connected in such a manner.

3.1.15 de-energized: Disconnected from all intentional sources of electrical supply by open switches, jumpers, taps, or other means. De-energized conductors or equipment could be electrically charged or energized through various means, e.g., induction from energized circuits, portable generators, lightning.

3.1.16 disruptive discharge: The phenomenon associated with the failure of insulation, under electric stress, that includes a collapse of voltage and the passage of current. The term applies to electrical breakdown in solid, liquid, and gaseous dielectrics and combinations of these.

3.1.17 energized: Electrically connected to a source of potential difference or electrically charged to have a potential different from that of the ground. *Syn:* **alive**; **current-carrying**; **hot**; **live**.

3.1.18 equipotential: A nearly identical state of electrical potential for two or more items.

3.1.19 flashover: A disruptive discharge through air around and over a surface of solid or liquid insulation, between parts at different potential or polarity, produced by application of voltage wherein the breakdown path becomes sufficiently ionized to maintain an electric arc.

3.1.20 floating object: An object that may or may not be conductive in the air gap at unknown potential.

3.1.21 floating potential: An electric charge impressed upon conductive objects suspended in the air gap that are not electrically connected to the energized conductor or ground.

3.1.22 gloving: A method of performing live work on energized electrical conductors and equipment where one or more workers, wearing specially made and tested insulating gloves, with or without sleeves, work directly on the energized electrical conductor or equipment.

3.1.23 grounded: Connected to earth or to some extended conducting body that serves instead of the earth. *Syn:* **earthed**.

3.1.24 ground potential: Potential equal to or near that of ground, normally zero volts.

3.1.25 helicopter work: A technique of using a helicopter for performing live work on energized wires and equipment, where one or more line workers work directly on an energized part after being raised and bonded to the energized wire or equipment. *See also:* **aerial work**; **barehand work**.

3.1.26 hot: *See:* **energized**.

3.1.27 insulated tool or **device:** A tool or device that has conductive parts and is either coated or covered with a dielectric material to provide electrical insulation.

3.1.28 insulated personal equipment: Personal equipment made of natural or synthetic material that is designed primarily to provide electric insulation from an energized part or conductor.

3.1.29 insulating tool or **device:** **(A)** A tool or device designed primarily to provide insulation from an energized part or conductor. It can be composed entirely of insulating materials. Examples include conductor cover, stick, and insulating tape. **(B)** A tool or device that has conductive parts separated by dielectric parts. *Syn:* **hot stick**.

3.1.30 insulator cover: Electrical protection equipment designed specifically to cover insulators. Examples include dead-end cover, pole-top cover, and ridge-pin cover. *Syn:* **hood**; **pocketbook**. *See also:* **cover-up equipment**.

3.1.31 isolated: **(A)** Physically separated, electrically and mechanically, from all sources of electric energy. Such separation may not eliminate the effects of electric or magnetic induction. **(B)** Not readily accessible to persons unless special means for access are used.

3.1.32 leakage current: A component of the measured current that flows along the surface of the tool or equipment, due to the properties of the tool or equipment surface, including any surface deposits.

3.1.33 line worker: A person qualified to perform various line work operations, including elevated aerial and groundwork. *Syn:* **lineman**.

3.1.34 line work: Various operations performed by a person on electrical facilities, including groundwork, elevated work, aerial work, and associated maintenance.

3.1.35 live: *See:* **energized**.

3.1.36 live parts: Items at the normal line operating voltage or some potential above ground potential.

3.1.37 live work: Work on or near energized or potentially energized lines (i.e., grounding, insulating tool work, gloving, barehand work). *Syn:* **live-line work**; **hot stick work**.

3.1.38 maximum power frequency operating voltage (V_M): The maximum system operating root-mean-square (rms) line-to-line (or line-to-ground for single phase or pole-to-ground for dc) voltage, which is also equal to the 1 per-unit (p.u.) base.

NOTE—For purposes of this guide, the maximum operating voltage is 5% higher than the rated (nominal) system voltage: 1.05 × rated (nominal) system voltage.[10]

3.1.39 minimum air insulation distance (MAID): The shortest distance in air between an energized electrical apparatus and/or a line worker's body at different potential. This distance, with a floating electrode in the gap, is equal to or greater than the sum of the individual minimum approach distances (MADs). This is the electrical component and does not include any factor for inadvertent movement. *Syn:* **electrical distance**.

NOTE—For the definition of electrical distance, see IEC 61472 [B21].

3.1.40 minimum tool insulation distance (MTID): The minimum length of insulation distance required, measured using the shortest distance between the conducting part at the live end and the closest point at ground potential. This term applies to tools that are not subject to inadvertent movement.

3.1.41 minimum approach distance (MAD): The minimum air insulation distance (MAID) plus a factor for inadvertent movement.

---

[10] Notes in text, tables, and figures are given for information only and do not contain requirements needed to implement the guide.

3.1.42 minimum approach distance for tools (MAD for Tools): The minimum length of insulation distance required, measured using the shortest distance between the conducting part at the live end and the closest point at ground potential. This term applies to tools that are subject to inadvertent movement.

3.1.43 minimum helicopter approach distance (MHAD): The shortest distance in air between an energized conductor and the closest point of helicopter.

3.1.44 overvoltage: Voltage that exceeds the maximum operating line-to-ground voltage. This voltage may be the result of a transient or switching surge. *Syn:* **transient overvoltage (TOV)**.

3.1.45 protective grounding equipment: *See:* **temporary protective grounding equipment**.

3.1.46 portable protective air gap (PPAG): A gap placed between live parts and ground to limit the overvoltage that may otherwise occur. *Syn:* **personal protective air gap**.

3.1.47 power loss: A means used to determine dielectric strength of an object by measuring the power loss through the object. *Syn:* **Doble Test**; **watts loss**.

3.1.48 puncture: A disruptive discharge through the body of a solid dielectric.

3.1.49 qualified: Having been trained in and having demonstrated adequate knowledge of the installation, construction, or operation of lines and equipment and the hazards involved, including identification of, and exposure to, electric supply and communication lines and equipment in, or near, the workplace. An employee, who is undergoing on-the-job training and who, in the course of such training, has demonstrated an ability to perform duties safely at his or her level of training, and who is under the direct supervision of a qualified person, is considered to be a qualified person for the performance of those duties.

3.1.50 rigging: An assembly of material used to manipulate or support various tools and equipment in energized, de-energized and not grounded, and grounded line work.

3.1.51 sparkover: A disruptive discharge between preset electrodes in either a gaseous or a liquid dielectric.

3.1.52 sparkover voltage: A voltage level at which a sparkover probably will occur under the stated conditions.

3.1.53 statistical sparkover voltage: A transient overvoltage (TOV) level that produces a 97.72% probability of sparkover (i.e., two standard deviations above the 50% sparkover voltage value).

3.1.54 statistical withstand voltage: A transient overvoltage (TOV) level that produces a 0.14% probability of sparkover (i.e., three standard deviations below the 50% sparkover voltage value).

3.1.55 stick: A type of insulating tool used in various operations of live work. *Syn:* **hot stick**; **live line tool**; **pole**; **work pole**; **work stick**.

3.1.56 stray current: Currents or components that do not constitute information desired for measurement. Examples are currents due to the stray capacitance of an object to the ground plane, walls, etc.

3.1.57 structure: Material assembled to support conductors or associated apparatus, or both, used for transmission and distribution of electricity (e.g., service pole, tower).

3.1.58 suspension of reclosing: To make inoperative automatic reclosing equipment. *Syn:* **auto-reclosing off**; **block reclosing**; **hold off**; **hold order**; **hold out**; **live line permit**; **non-reclose**.

3.1.59 switching surge: An overvoltage resulting from the operation of a circuit-interrupting device. *Syn:* **switching impulse**.

3.1.60 temporary protective grounding equipment: A system of ground clamps, ferrules, cluster bar, and covered cables designed and suitable for carrying maximum anticipated fault current and grounding conductive objects.

NOTE—See ASTM F 855, IEC 61230, IEEE Std 1048.

3.1.61 tool or **equipment leakage current:** The total leakage current delivered to the tool or equipment. The tool or equipment provides only one path for the current, and this current is equal to the leakage current. *See also:* **leakage current**.

3.1.62 withstand voltage: A voltage level at which a sparkover probably will not occur under the stated conditions.

3.1.63 work permit: The authorization to perform work, such as work on a circuit. It is often part of a lockout-tagout procedure. *Syn:* **clearance**, **guarantee**.

3.2 Acronyms and abbreviations

a	switching surge air saturation factor
A	altitude correction factor
C_1	60 Hz rod gap withstand (100 kVrms/ft)
C_2	the tool factor
CFO	critical flashover
D_{CM}	distance in centimeters
D_{FT}	distance in feet
D_{M}	distance in meters
E_{MAX}	maximum transient overvoltage (TOV_{MAX})
FRP	fiberglass-reinforced plastic
I_W	only the current in the phase from watt loss testing, in amperes
K	gap factor
M	inadvertent movement factor
MAD	minimum approach distance
MAID	minimum air insulation distance
MHAD	minimum helicopter approach distance
MTID	minimum tool insulation distance
PPAG	portable protective air gap
p.u.	per unit
Peak	transient peak (crest)
RF	radio frequency
rms	root mean square
T	maximum anticipated per-unit transient overvoltage (TOV)
TOV	rms transient overvoltage
TOV_{Peak}	peak transient overvoltage
TTOCD	temporary transient overvoltage control devices

V_{50}	transient or temporary overvoltage level that produces a 50% probability of sparkover, in kilovolts
$V_{L\text{-}G}$	ac voltage line-to-ground (rms), in kilovolts
V or $V_{L\text{-}L}$	ac voltage line-to-line (rms), in kilovolts
V_M	maximum power frequency operating voltage (rms), in kilovolts, line-to-line
$V_{M\,P\text{-}G}$	maximum power frequency operating voltage (rms), in kilovolts, pole-to-ground
V_{NEG}	peak voltage of the negative side of a sine wave
$V_{P\text{-}G}$	dc voltage pole-to-ground, in kilovolts
$V_{P\text{-}P}$	dc voltage pole-to-pole, in kilovolts
V_{POS}	peak voltage of the positive side of a sine wave
V_{Peak}	switching surge or transient overvoltage peak or crest voltage, in kilovolts
V_R	manufacturer's rating, in kilovolts
$V_{R\,Peak}$	manufacturer's rating, in kilovolts, peak
V_W	withstand voltage, peak
α	(Greek small letter alpha) line-to-line insulation strength, which is the proportion of negative switching impulse voltage in the total line-to-line impulse voltage
σ	(Greek small letter sigma) probability
μ	(Greek small letter mu) 50% critical sparkover value
$\mu+2\sigma$	sparkover voltage
$\mu-3\sigma$	withstand voltage

4. Technical considerations

4.1 Introduction

The performance of live work requires the use of equipment and tools that in many cases are specific to the work operation. Development of equipment and tools is based on requirements generated from field needs and experiences related to technical considerations and work method safety. For live work, minimum air insulation distance (MAID), minimum tool insulation distance (MTID), minimum approach distance (MAD), minimum approach distance for tools (MAD for Tools), and minimum helicopter approach distance (MHAD) have been developed in this clause for operating voltages up to 800 kV. These distances are used when working near the following:

- Overhead conductors supported by suspension and tension insulators
- Overhead conductors supported by post insulators
- Overhead tubular bus supported by post insulators
- Equipment entrance bushing and cable potheads
- Live equipment such as "live tank" circuit breakers, high-speed circuit switching devices, isolating switches, wave traps, series capacitors and reactors
- Insulated phase conductors not covered with a continuous conducting shield or sheath at ground potential and supported from a conductor at ground potential[11]

---

[11] Since the condition of the conductor insulation is not known, conductors should be considered as live at their operating voltage.

The major hazard in live work on high-voltage lines and equipment is a sparkover of air gap insulation to ground at the worksite. This results in the rapid release of a large amount of energy, which may cause injury to the workers and/or damage equipment.

In an operating electrical power supply system, the phase conductors are insulated from each other and ground using the support insulators and air. When live work is performed on high-voltage systems, the primary insulation is air. However, in systems below 72.5 kV, rubber gloves and sleeves, insulating cover-up, and insulating barriers can provide additional protection for the worker. Insulating cover-up is designed only for inadvertent contact, i.e., brush contact.

4.2 Insulating properties

Personal safety and operational security during energized-line work depend on the insulating properties of the air gap and the insulating materials that are placed in the air gap for the live work.

4.2.1 Sparkover of air gap

A sparkover of the air gap insulation at the worksite can be caused by any of the following:

a) A reduction of the air gap distance caused by the introduction of conductive objects
b) Transient overvoltages (TOVs)
c) Tool insulation breakdown

4.2.2 Preventing sparkover of air gap insulation at worksite

For live work, MAID, MTID, MAD, MAD for Tools, and MHAD have been developed, based on the maximum operating voltage of the system and the maximum anticipated per-unit TOV (*T*) of the line, to provide guidance to the workers on the required air gap insulation.

4.3 Air as insulation

The insulating characteristics of air are defined in terms of its dielectric strength and its capability to withstand electric stresses. The dielectric strength of air is expressed in the unit of kilovolts/meter or an equivalent unit. The dielectric strength of the air gap should be greater than the electric stress to which it is exposed. The dielectric strength of air is influenced by the following:

a) Temperature
b) Barometric pressure
c) Altitude (height of the worksite above sea level)
d) Relative humidity
e) Airborne impurities in the air gap
f) Dimensions, shape of electrodes, and configuration of the spacing
g) Time-dependent characteristics of the applied voltage

4.3.1 Insulating materials and tools used in live work

Insulating materials are generally defined in terms of their dielectric strength. The dielectric strength of the insulating material or tool should be greater than the electrical stress to which it is exposed. When two or more insulating materials are used in series within the air gap, the dielectric strength of each should be greater than the electrical stress to which each is exposed. See 4.10.4.1.

The primary factors that affect the electrical performance of insulating materials are the following:

a) Temperature
b) Barometric pressure
c) Altitude (height of the worksite above sea level)
d) Relative humidity
e) Airborne impurities
f) Dimensions, shape of electrodes, and the configuration of the spacing
g) Time-dependent characteristics of the applied voltage
h) Surface contamination
i) Impurities
j) Aging

4.3.2 Insulating tools used in live work in air gap insulation

When insulating devices (e.g., live work tools, insulating aerial lift devices, insulating ladders, rope) are used in the air gap, they are generally defined in terms of their dielectric strength. The dielectric strength or rating of this equipment should be greater than the operating voltage to which it is being applied. When two or more insulating devices are used in series within the air gap, the rating of each should be greater than the voltage to which it is being applied.

The desirable property of the insulating devices is their ability to reduce the flow of current through them to a very low value. Dielectric strength is defined as the potential gradient at which electric failure or breakdown occurs.

Factors that affect the electrical performance of insulating materials include the following:

a) Temperature
b) Barometric pressure
c) Altitude (height of the worksite above sea level)
d) Relative humidity
e) Airborne impurities
f) Dimensions, shape of electrodes, and configuration of the spacing
g) Time-dependent characteristics of the applied voltage
h) Surface contamination
i) Impurities
j) Aging

4.4 Factors that affect the air insulation

4.4.1 Atmospheric conditions

The laboratory test data used to develop the formulas and tables in the guide were obtained under atmospheric conditions that are defined as temperatures above freezing, wind speed under 24 km/h (15 mph), unsaturated air, normal barometric pressure [76 cm (29.92 in) of mercury] at sea level, and uncontaminated air, with clean and dry insulators.

4.4.2 Contamination

The equipment used for gloving, cover-up materials, and insulating sections of aerial devices and tools shall be kept free from contamination. Live work can be performed on dry contaminated insulators. Work on wet contaminated insulator should be avoided.

4.4.3 Adverse weather conditions

Live work should not be performed when the following adverse conditions exist:

a) Lightning activity in the worksite area
b) Relative humidity at or near 100%
c) Relative humidity at or above 85% for high-voltage dc work above 72.5 kV
d) Rain or snow

4.5 Air gap distances

This subclause describes the two methods for determining the MAID, MTID, MAD, MAD for Tools, and MHAD for use in work involving energized lines and equipment.

a) Calculation of distances using the formulas in 4.6 and 4.7 is recommended.
b) Distance tables calculated from the formulas in 4.6 and 4.7 have been provided in Annex D. The distance tables for line-to-line voltages above 72.5 kV are applicable for live work only when the worksite altitude is below 900 m (3000 ft) above sea level. To use the table distances when the worksite altitude is above 900 m (3000 ft) above sea level, an altitude correction should be applied. See 4.7.6.

The MAID, MTID, and MAD should not be confused with other electrical distances, such as insulator creepage distance and National Electrical Safety Code® (NESC®) (Accredited Standards Committee C2-2007) [B1] conductor spacing, etc.

This guide does not address live work on lines and equipment with an ac and dc line-to-line or line-to-ground or pole-to-ground voltage below 50 V.

This guide recommends that contact be avoided for live work on lines with an ac and dc line-to-line or line-to-ground or pole-to-ground voltage between 51 and 300 V.

CAUTION

Additional precautions may be required when working on lines and conductors used on distribution network, transportation system catenary, and long low-capacity rural distribution circuits due to fault clearing. In some of these cases, the primary current source may not be automatically opened or interrupted if the fault is beyond the reach of the protection.

Additional precautions may also be required on dc and low-frequency circuits since a considerably larger switch gap is required to break the arc when opening a circuit.

This guide recommends the following rounding-up of the distance and switching surge air saturation factor calculation:

Item	Number of decimal places
Distance in meters, D_M	2
Distance in feet, D_{FT}	2
Distance in centimeters, D_{CM}	2
Switching surge air saturation factor, “a”	7

To round up, add 1 to the last decimal place to be retained if the next decimal place is not zero.

Example: 2.2224 rounded up to 3 decimal places is 2.223

4.5.1 Minimum air insulation distance (MAID)

The MAID for line-to-ground work is the minimum air gap distance required to prevent a sparkover at the worksite between the energized parts and a conducting object at ground potential during live work. This distance is normally measured in meters or feet along a straight line between the conductor and nearest item at ground potential. The nearest item at ground potential may be the worker or part of the supporting structure.

The MAID for line-to-line work is the minimum air gap distance required to prevent a sparkover at the worksite between the energized parts of two different phase conductors during live work. This distance is normally measured in meters or feet along a straight line between the conductors.

4.5.1.1 Determining MAID for line-to-ground and line-to-line work for ac and dc line-to-line voltages from 300 V and below 72.5 kV

The MAID is the required undisturbed air insulation distance required to prevent a sparkover at the worksite during a system event that results in the maximum anticipated TOV.

The formulas for MAIDs for line-to-line voltages below 72.5 kV are based on the 60 Hz rod gap test data from IEEE Std 4™-1995 [B28]. See 4.6.1, 4.7.1.1, 4.7.1.2, 4.7.4.1, and 4.7.5 for further details.

For dc lines, see also 4.7.4.4.

4.5.1.2 Determining MAID for line-to-ground work for ac line-to-line voltages above 72.5 kV

The MAID is the required undisturbed air insulation distance required to prevent a sparkover at the worksite during a system event that results in the maximum anticipated TOV.

The formulas for MAID line-to-ground distances for line-to-line voltages above 72.5 kV are based on the rod gap test data from “Recommendations for safety” [B25]. See 4.6.2.1 and 4.7.1.3 for further details.

4.5.1.3 Determining MAID for line-to-line work for ac line-to-line voltages above 72.5 kV

The MAID is the required undisturbed air insulation distance required to prevent a sparkover at the worksite during a system event that results in the maximum anticipated TOV.

The formulas for MAID line-to-line distance for line-to-line voltages above 72.5 kV are based on test data (for the live-to-line gap) published the 1993 paper by Vaisman et al. [B41]. The paper presents and compares such published test data from five laboratories found in the literature. These test data are fitted with a modified Gallet equation used to determine line-to-line MAID (see Gallet et al. [B16] and [B17]). See 4.6.2.2 and 4.7.1.4 for further details.

4.5.1.4 Reducing MAID

When using cover-up material, rubber gloves and sleeves, or insulating barriers that are properly rated and tested for the operating voltage on which the work is being done, the distance from the worker to the task location may be reduced. However, the air distance to exposed energized parts should be maintained in the area where these are applied or used.

An exception to this is when the worker is using the rubber gloving method. In this case, the distance to the exposed energized conductor may be reduced by eliminating or reducing the inadvertent movement factor distance when the worker’s movement is restricted. When using the rubber gloving method, secondary supporting insulation, such as insulating footwear, an insulating platform, or an insulating aerial device, is utilized. Insulating cover-up is designed only for inadvertent contact. It may be necessary to use_insulating aerial devices or insulating platforms to limit the leakage current below the worker’s threshold of feeling (see Kolcio [B31]). Insulating aerial devices act as the principal insulation should the rubber gloves fail or should the worker accidentally contact the conductor.

Insulated conductors supported by a conductive material at ground potential and insulated conductors supported by insulating material from conductive material at ground potential should be considered as live at their line-to-ground voltage since the condition of conductor insulation is not known.

Insulated conductors with a continuous concentric metal shield that is maintained at ground potential should be considered as being at ground potential.

4.5.2 Minimum tool insulation distance (MTID)

The MTID is the required undisturbed air insulation distance that is needed to prevent a tool flashover at the worksite during a system event that results in the maximum anticipated TOV.

4.5.2.1 MTID for ac and dc line-to-line voltages at and below 72.5 kV

The MTID for ac and dc line-to-line voltages at and below 72.5 kV has not been determined. Industry practices normally use an MTID that is the same as or greater than the MAID. See 4.5.1.1.

4.5.2.2 MTID for ac and dc line-to-ground work with line-to-line voltages above 72.5 kV

When any foreign object, such as tools or other devices used to perform work on the line, is placed in the air gap, the MTID is used.

This guidance includes floating objects, insulating maintenance tools, and aerial devices that are tested and rated for the line-to-ground or line-to-line voltage applied across them. This distance is normally measured in meters or feet along a straight line between the conductor and nearest item at ground potential. Small conducting items [e.g., tool splices (used to join tool sections together), clamps, cradle brackets] placed on or within the insulating medium do not affect this distance.

4.5.2.3 MTID for ac and dc line-to-line work with line-to-line voltages above 72.5 kV

The definition of MTID applies only to line-to-ground application. It is rare that a worker would be at the potential of one phase while working on another phase. If a nonconductive object, such as an insulated tool, is placed in the air gap joining two phases, an engineering study should be performed. Addition testing is required to develop a line-to-line MTID. If a line-to-line MTID is required, the same factor as used in the line-to-ground distance may be used. Industry practices normally use an MTID that is the same as or greater than the MAID.

4.5.2.4 Determining MTID for ac and dc line-to-ground work with line-to-line voltages above 72.5 kV

The MTIDs are calculated using a similar formula as the MAIDs with the addition of the C_2 factor. See 4.6.2.1 and 4.7.2 for further details.

4.5.2.5 Determining MTID for ac and dc line-to-line work with line-to-line voltages above 72.5 kV

Line-to-line live working methods are normally based on when the worker is only at the potential of the phase on which live work is being conducted. In other words, the worker is not at the potential of one phase while working on the other phase. For this reason, the application of insulated tools between phases is very limited. If a nonconductive object, such as insulated tool, is placed in the air gap between two phases, the application of C_2 factor (which is used in line-to-ground MTID) is questionable because there are no test data to support this. Until such test data are available, the line-to-line MTID is not provided in this guide. However, page 520 of the EPRI *Red Book* [B9] states “tests performed with a nonceramic insulator string between two conductors at midspan of the test line have shown that the flashover pattern, also, is not appreciably altered by the presence of the string and its associated hardware.” Additional tests are planned in the near future.

4.5.3 Minimum approach distance (MAD)

To provide additional protection for workers during energized-line maintenance or while working in the vicinity of other energized lines, MAD has been developed. This distance allows for any inadvertent movement that may occur during live work.

4.5.3.1 Determining MAD for ac and dc line-to-line voltages at and above 300 V

The MAD is determined from the MAID, plus a factor for inadvertent movement (M). The M factor is not adjusted for altitude. See 4.6.1 and 4.6.2 for further details. See also 4.5.1.1.

4.5.3.2 Reducing MAD

The use of barriers that physically limit the worker's inadvertent movement can reduce the MADs between the worker and the energized or grounded parts. They can be used on any voltage lines or equipment provided proper MAID is observed. Barriers are not relied on for electrical insulation, but act only as physical barriers.

4.5.4 Minimum approach distance for tools (MAD for Tools)

To provide additional protection for workers during energized-line maintenance or while working in the vicinity of other energized lines when any foreign object, such as tools or other devices used to perform work on the line, is placed in the air gap, the MAD for Tools is used. See 4.6.1 and 4.6.2 for further details.

4.5.4.1 MAD for Tools for ac and dc line-to-line voltages at and below 72.5 kV

The MTID for ac and dc line-to-line voltages at and below 72.5 kV has not been determined. Industry practices normally use an MTID that is the same as or greater than the MAID. See 4.5.1.1.

4.5.4.2 Determining line-to-ground MAD for Tools for ac and dc line-to-line voltages above 72.5 kV

The MAD for Tools is determined from the MTID, plus a factor for inadvertent movement (M). The M factor is not adjusted for altitude.

4.5.4.3 Determining line-to-line MAD for Tools for ac and dc line-to-line voltages above 72.5 kV

Addition testing is required to develop a MAD for Tools for line-to-line voltages above 72.5 kV. If a line-to-line MAD for Tools is required, the same factor as used in the line-to-ground distance may be used. Industry practices normally use a MAD for Tools that is the same as or greater than the MAD.

4.5.5 Minimum helicopter approach distance (MHAD)

To provide additional protection for workers during energized-line maintenance from helicopters, the MHAD has been developed. This distance covers possible corona on the helicopter, rotor wash, and movement due to wind.

4.5.5.1 Determining MHAD for ac line-to-line voltages above 72.5 kV

The MHAD is derived from the MAD, plus an industry suggested value of 10% MAD. Data for this subclause was obtained from "Helicopter-Based Live Work" [B10]. See 4.6.1 and 4.6.2 for further details.

4.6 Distance equations

When a distance equation is used, the distances that result are in the same units as the reference data source. In the United States, most of the line workers use the “English” or feet measurement in their work, and in other counties, the metric measurements are used.

For this reason, formulas and tables have been developed in both measurement systems. Table 1 lists the distance conversion factors used in this guide.

Table 1—Distance conversion factors

To convert to	From		
	Centimeters	**Feet**	**Meters**
	Multiply by		
Feet	0.0328	1.0	3.281
Meters	0.01	0.3048	1.0

The distances obtained from the equations in 4.6 should be rounded up.

4.6.1 Work on ac and dc line conductors and equipment for line-to-ground and line-to-line voltages from 50 V to 72.5 kV

These distances apply to conductors and equipment supported by insulators where air is the primary insulating medium. They do not apply to insulated cables where it has been determined that insulation is good.

The following terms are used in the formulas in this subclause:

D_{M}	is distance, in meters
D_{FT}	is distance, in feet
TOV_{Peak}	is the maximum anticipated peak transient overvoltage (see 4.6.1.4) for a given voltage, in kilovolts (see 4.7.1)
T	is the maximum anticipated per-unit TOV on the line (see 4.7.4)
$V_{L\text{-}G}$	is the line-to-ground rms voltage, in kilovolts (see 4.7.5)
$V_{L\text{-}L}$	is the line-to-line rms voltage, in kilovolts (see 4.7.5)
M	is the inadvertent movement factor (see 4.7.7)

The equations in 4.6.1.2 through 4.6.1.6 were developed from the 60 Hz sparkover distance for rod-to-rod configuration for a given voltage in kilovolts. See 4.7.1.

4.6.1.1 Work on ac and dc line conductors and equipment for line-to-ground and line-to-line voltages from 50 V to below 300 V

When the line-to-ground and line-to-line voltage is between 50 and 300 V, this guide recommends that contact be avoided.

4.6.1.2 Work on ac and dc line conductors and equipment for line-to-ground and line-to-line voltages from 300 V to below 750 V

When the line-to-ground and line-to-line voltage is between 300 and 750 V, sufficient test data are not available to calculate the MAID, which is less than 2 cm or 0.07 ft. This guide recommends the following:

a) **MAID, line-to-ground and line-to-line**
   1) $D_{\mathrm{M}} = 0.02$
   2) $D_{\mathrm{FT}} = 0.07$
b) **MAD, line-to-ground and line-to-line**
   1) $D_{\mathrm{M}} = 0.32$
   2) $D_{\mathrm{FT}} = 1.07$

4.6.1.3 Work on ac and dc line conductors and equipment for line-to-ground and line-to-line voltages above 750 V and below 5.0 kV

When the line-to-ground and line-to-line voltage is between 750 V and 5.0 kV, sufficient test data are not available to calculate the MAID, which is less than 2 cm or 0.07 ft. This guide recommends the following:

a) **MAID, line-to-ground and line-to-line**
   1) $D_{\mathrm{M}} = 0.02$
   2) $D_{\mathrm{FT}} = 0.07$
b) **MAD, line-to-ground and line-to-line**
   1) $D_{\mathrm{M}} = 0.63$
   2) $D_{\mathrm{FT}} = 2.07$

4.6.1.4 Work on ac and dc line conductors and equipment for line-to-line voltages from 5.0 kV to 72.5 kV

To find which equation to use when the line-to-line voltage is between 5.0 and 72.5 kV, first determine the peak transient overvoltage, TOV_{Peak}.

a) **For line-to-ground work**

$$TOV_{L-GPeak} = \sqrt{2}\left(T\right)\left(V_{L-G}\right) \tag{1}$$

b) **For line-to-line work**

$$TOV_{L-LPeak} = \sqrt{2}\left(T\right)\left(V_{L-L}\right) \tag{2}$$

If the TOV_{Peak} is less than 27.00 kV, use 4.6.1.5.

If the TOV_{Peak} is equal to or greater than 27.0084.88 kV, use 4.6.1.6.

For dc line conductors, see 4.7.4.4, 4.7.5.5, and 4.7.5.6.

4.6.1.5 TOV_{Peak} less than 27.00 kV

When the TOV_{Peak} is less than 27.00 kV, sufficient test data are not available to calculate the MAID, which is less than 2 cm or 0.06 ft. This guide recommends the following:

a) **MAID, line-to-ground and line-to-line**
   1) $D_M = 0.02$
   2) $D_{FT} = 0.07$

b) **MAD, line-to-ground and line-to-line**
   1) $D_M = 0.63$
   2) $D_{FT} = 2.07$

4.6.1.6 TOV_{Peak} equal to or greater than 27.00 kV

When the TOV_{Peak} is equal to or greater than 27.00 kV, this guide recommends the following:

a) **MAID, line-to-ground**

$$D_M = \frac{\left(\frac{\left(TOV_{L-GPeak} - 36.7\right)}{5.6} + 2.75\right)}{100} \tag{3}$$

$$D_{FT} = 3.28\left(\frac{\left(\frac{\left(TOV_{L-GPeak} - 36.7\right)}{5.6} + 2.75\right)}{100}\right) \tag{4}$$

b) **MAD, line-to-ground**

$$D_M = \left(\frac{\left(\frac{\left(TOV_{L-GPeak} - 36.7\right)}{5.6} + 2.75\right)}{100}\right) + M \tag{5}$$

$$D_{FT} = \left(3.28\left(\frac{\left(\frac{\left(TOV_{L-GPeak} - 36.7\right)}{5.6} + 2.75\right)}{100}\right)\right) + M \tag{6}$$

c) **MAID, line-to-line**

$$D_M = \frac{\left(\frac{\left(TOV_{L-LPeak} - 63.6\right)}{5.15} + 5.65\right)}{100} \tag{7}$$

$$D_{FT} = 3.28\left(\frac{\left(\frac{\left(TOV_{L-LPeak} - 63.6\right)}{5.15} + 5.65\right)}{100}\right) \tag{8}$$

d) **MAD, line-to-line**

$$D_{M} = \left(\frac{\left(\frac{\left(TOV_{L-LPeak} - 63.6\right)}{5.15} + 5.65\right)}{100}\right) + M \tag{9}$$

$$D_{FT} = \left(3.28\left(\frac{\left(\frac{\left(TOV_{L-LPeak} - 63.6\right)}{5.15} + 5.65\right)}{100}\right)\right) + M \tag{10}$$

4.6.2 Work on ac and dc line conductors and equipment for line-to-line voltages above 72.5 kV

4.6.2.1 Line-to-ground work

The line-to-ground distance formulas for line-to-line voltages above 72.5 kV used in this guide are developed from basic formulas for live tool withstand from Figure 2 (used in previous editions of the guide). See 4.7.1.3 for further details.

$$D = \left(0.011 + a\right)\left(S\right)kV_{L-G} \tag{11}$$

where

D is distance, in feet
a is saturation factor
S is per-unit switching surge

From Equation (11), the following equations have been developed:

$$D_{MAID} = \left(C_1 + a\right)\left(V_{L-G}\right)\left(T\right)\left(A\right) \tag{12}$$

$$D_{MTID} = \left(\left(\left(C_1\right)\left(C_2\right)\right) + a\right)\left(V_{L-G}\right)\left(T\right)\left(A\right) \tag{13}$$

$$D_{MAD} = \left(\left(C_1 + a\right)\left(V_{L-G}\right)\left(T\right)\left(A\right)\right) + M \tag{14}$$

$$D_{MADforTools} = \left(\left(\left(\left(C_1\right)\left(C_2\right)\right) + a\right)\left(V_{L-G}\right)\left(T\right)\left(A\right)\right) + M \tag{15}$$

$$D_{MHAD} = \left(\left(\left(C_1 + a\right)\left(V_{L-G}\right)\left(T\right)\left(A\right)\right) + M\right)\left(H\right) \tag{16}$$

where

D	is the distance (MAID, MTID, MAD, MAD for Tools, MHAD), in feet, since C_1 is in feet/kilovolts
C_1	is 0.01 ft/kVrms (60 Hz rod gap withstand) (100 kVrms/ft)
a	is the adjustment ratio to compensate for air saturation expressed as a ratio of distance to kilovolts
C_2	is the MAIDs, which are increased based on an additional 6% for the effect of the insulating tools in the air gap plus additional 4% for intangibles. The 6% factor may range from an additional 2% to 20% depending upon the structure and electrode configuration and the surface condition of the tool. Used for MTID calculations with the line-to-line voltage above 72.5 kV (see 4.7.2)
V	is the nominal voltage across the air gap, which may be $V_{L\text{-}G}$ or $V_{L\text{-}L}$
$V_{L\text{-}G}$	is the line-to-ground rms voltage, in kilovolts (see 4.7.5)
$V_{L\text{-}L}$	is the line-to-line rms voltage, in kilovolts (see 4.7.5)
T	is the maximum anticipated per-unit TOV, which can occur across the air gap (see 4.7.4)
A	is the altitude correction factor (see 4.7.6)
H	is the helicopter factor for calculations in this guide (H is 110% of MAD) (see 4.7.8)
M	is the inadvertent movement factor (see 4.7.7)

CAUTION

If the *TOV* [($V_{L\text{-}G}$) × (T)] is greater than 449 kV rms, determine the air saturation ratio, *a*, first to use in these equations (see 4.7.3.2).

a) **MAID for line-to-ground work**

$$D_M = 0.3048\left[\left(C_1 + a\right)\left(V_{L-G}\right)\left(T\right)\left(A\right)\right] \tag{17}$$

$$D_{FT} = \left(C_1 + a\right)\left(V_{L-G}\right)\left(T\right)\left(A\right) \tag{18}$$

b) **MTID for line-to-ground work**

$$D_M = 0.3048\left[\left(\left(\left(C_1\right)\left(C_2\right)\right) + a\ \right)\left(V_{L-G}\right)\left(T\right)\left(A\right)\right] \tag{19}$$

$$D_{FT} = \left(\left(\left(C_1\right)\left(C_2\right)\right) + a\right)\left(V_{L-G}\right)\left(T\right)\left(A\right) \tag{20}$$

c) **MAD for line-to-ground work**

$$D_M = 0.3048\left[\left((C_1 + a)(V_{L-G})(T)(A)\right) + M\right] \tag{21}$$

$$D_{FT} = \left((C_1 + a)(V_{L-G})(T)(A)\right) + M \tag{22}$$

d) **MAD for Tools for line-to-ground work**

$$D_M = 0.3048\left[\left(\left((C_1)(C_2) + a\right)(V_{L-G})(T)(A)\right) + M\right] \tag{23}$$

$$D_{FT} = \left(\left(\left((C_1)(C_2)\right) + a\right)(V_{L-G})(T)(A)\right) + M \tag{24}$$

e) **MHAD for line-to-ground work**

$$D_M = 0.3048\left[\left[\left((C_1 + a)(V_{L-G})(T)(A)\right) + M\right][H]\right] \tag{25}$$

$$D_{FT} = \left[\left((C_1 + a)(V_{L-G})(T)(A)\right) + M\right][H] \tag{26}$$

4.6.2.2 Line-to-line work

The MAID for line-to-line voltages above 72.5 kV is based on test data (for the conductor-to-conductor gap) published the 1993 paper by Vaisman et al. [B41]. The paper presents and compares such published test data from five laboratories found in the literature. These test data are fitted with a modified Gallet equation used to determine line-to-line MAID (see Gallet et al. [B16] and [B17]). The methodology used to develop these formulas can be found in 4.7.1.4.

a) **MAID, line-to-line,** for line-to-line voltages equal to and less than 242 kV

$$D_M = \left(\frac{8}{\left(\frac{4621}{\left((1.35)(T) + 0.45\right)(V_{L-L})}\right) - 1}\right)(A) \tag{27}$$

$$D_{Ft} = 3.281\left(\frac{8}{\left(\frac{4621}{\left((1.35)(T) + 0.45\right)(V_{L-L})}\right) - 1}\right)(A) \tag{28}$$

b) **MAID, line-to-line,** for line-to-line voltages greater than 242 kV

$$D_M = \left(\frac{8}{\left(\frac{4875}{\left((1.35)(T) + 0.45 \right)\left(V_{L-L} \right)} \right) - 1} \right)(A) \tag{29}$$

$$D_{Ft} = 3.281 \left(\frac{8}{\left(\frac{4875}{\left((1.35)(T) + 0.45 \right)\left(V_{L-L} \right)} \right) - 1} \right)(A) \tag{30}$$

c) **MAD, line-to-line,** for line-to-line voltages equal to and less than 242 kV

$$D_M = \left[\left(\frac{8}{\left(\frac{4621}{\left((1.35)(T) + 0.45 \right)\left(V_{L-L} \right)} \right) - 1} \right)(A) \right] + M \tag{31}$$

$$D_{Ft} = \left[3.281 \left(\frac{8}{\left(\frac{4621}{\left((1.35)(T) + 0.45 \right)\left(V_{L-L} \right)} \right) - 1} \right)(A) \right] + M \tag{32}$$

d) **MAD, line-to-line,** for line-to-line voltages greater than 242 kV

$$D_M = \left[\left(\frac{8}{\left(\frac{4875}{\left((1.35)(T) + 0.45 \right)\left(V_{L-L} \right)} \right) - 1} \right)(A) \right] + M \tag{33}$$

$$D_{Ft} = \left[3.281 \left(\frac{8}{\left(\frac{4875}{\left((1.35)(T) + 0.45 \right)\left(V_{L-L} \right)} \right) - 1} \right)(A) \right] + M \tag{34}$$

e) **MHAD, line-to-line,** for line-to-line voltages equal to and less than 242 kV

$$D_M = \left(\left[\left(\frac{8}{\left(\frac{4621}{\left((1.35)(T)+0.45\right)(V_{L-L})}\right)-1}\right)(A)\right]+M\right)H \tag{35}$$

$$D_{Ft} = \left(\left[3.281\left(\frac{8}{\left(\frac{4621}{\left((1.35)(T)+0.45\right)(V_{L-L})}\right)-1}\right)(A)\right]+M\right)H \tag{36}$$

f) **MHAD, line-to-line,** for line-to-line voltages greater than 242 kV

$$D_M = \left(\left[\left(\frac{8}{\left(\frac{4875}{\left((1.35)(T)+0.45\right)(V_{L-L})}\right)-1}\right)(A)\right]+M\right)H \tag{37}$$

$$D_{Ft} = \left(\left[3.281\left(\frac{8}{\left(\frac{4875}{\left((1.35)(T)+0.45\right)(V_{L-L})}\right)-1}\right)(A)\right]+M\right)H \tag{38}$$

where

D	is the distance (MAID, MAD, MHAD)
V_{L-L}	is the line-to-line rms voltage, in kilovolts (see 4.7.5)
T	is the maximum anticipated per-unit TOV, which can occur across the air gap (see 4.7.4)
A	is the altitude correction factor (see 4.7.6)
H	is the helicopter factor for calculations in this guide (H is 110% of MAD) (see 4.7.8)
M	is the inadvertent movement factor (see 4.7.7)

4.7 Factors used to determine MAID, MTID, MAD, Mad for Tools, and MHAD

4.7.1 MAID factors

4.7.1.1 60 Hz MAID for ac and dc line-to-line voltages from 300 V to below 5.0 kV

For ac and dc line-to-line and line-to-ground work between 300 V and 5.0 kV, sufficient test data are not available to calculate the MAID, which is less than 2 cm or 0.07 ft. For this voltage range, it is assumed that MAID is 0.02 m or 0.07 ft and that an M distance of 0.61 m or 2.0 ft is added to the MAID for the MAD.

4.7.1.2 60 Hz MAID for ac and dc line-to-line voltages from 5.0 to 72.5 kV

For line-to-line voltages from 5.0 to 72.5 kV, the distance (gap spacing, in centimeters) used to calculate the MAIDs is for line-to-line voltages based on the 60 Hz rod-to-rod sparkover voltage found in Table 11 in Annex 2B of IEEE Std 4-1995 [B28].

The determinations of the MAID for line-to-line voltages from 5.0 to 72.5 kV in this guide are based on the following:

a) Subclause 4.5.1.1 of this guide gives the basis for determining MAID as “The MAID is the required undisturbed air insulation distance required to prevent a sparkover at the worksite during a system event that results in the maximum anticipated TOV.”

b) The 60 Hz rod gap sparkover data from IEEE Std 4-1995 is used in place of the maximum TOV, which is used for determining MAID for lines above 72.5 kV.

c) There is a significant difference in electrical stress characteristics between the 60 Hz (power frequency) and the TOV surges. Maximum stresses on power lines occur during transient surges and not from power frequency.

d) During 60 Hz voltage testing, the withstand and sparkover voltage values are very close, and there is no 3-sigma relationship between them; therefore, the critical flashover (CFO) voltage is not used. When 60 Hz data are used, the withstand and sparkover voltages are very critical for live working. The risk of flashover is very high because the withstand and sparkover voltages are so close in comparison with TOVs, where the risk (3-sigma) is about 1/1000.

e) In one respect, the rod gap data from IEEE Std 4-1995 is useful for determining MAID because it provides a good range of sparkover values. However, a number of modifications have to be made to convert the 60 Hz sparkover data to withstand TOV (switching surge) values. An impulse test factor (F_{im}) of 1.3 has been used in IEC 61472 [B21] to convert 60 Hz sparkover voltage to the CFO of a TOV. Then a margin of 3-sigma (sigma = 5%) as $(1\text{-}3\sigma) = 0.85$ is applied to the CFO values of the TOV to determine the withstand transient (TOV) voltage. This TOV voltage is then used to select the appropriate gap distance (MAID) in IEEE Std 4-1995, or as shown in Table 2.

   CFO TOV = 60 Hz rod-to-rod sparkover voltage (1.3)

   Withstand TOV = [60 Hz sparkover voltage (1.3)] (0.85)

f) The impulse test factor (F_{im}) of 1.3 for impulse and switching surge transients can be verified from test results where the 60 Hz sparkover voltage is compared to the CFO of a TOV for the same gap distances representing rod-to-rod or other gap configurations (see CIGRÉ/SC 33 [B4] and Esmeraldo and Fonseca [B11]). It was found that the average CFO value of the positive and the negative TOVs is about 1.3 times higher than the 60 Hz sparkover voltages. Other tests conducted with live line protective equipment (e.g., line guards, insulating gloves, line hoses) showed the same 1.3 ratio.

g) In Table 2, the impulse (TOV) withstand rod-to-rod kilovolt peak (column 1) is calculated from the 60 Hz rod-to-rod sparkover voltage shown in column 2, using an impulse test factor of 1.3 to convert 60 Hz sparkover to the CFO) of a TOV. A margin of 3-sigma (sigma = 5%) as ($1-3\sigma$) = 0.85 is then applied to the CFO values of the TOV to determine the impulse (TOV) withstand voltage in kilovolt peak or TOV peak, as shown in column 1. The values in column 1 versus column 3 are plotted and shown in the graph of Figure 1.

Table 2—Distance for rod-to-rod gap

Impulse (TOV) rod-to-rod withstand (kV peak)	60 Hz rod-to-rod sparkover (kV peak)	Gap spacing from IEEE Std 4-1995 [B28] (cm)
27.6	25	2
39.8	36	3
50.8	46	4
58.6	53	5
66.3	60	6
77.4	70	8
87.3	79	10
95	86	12
105	95	14
115	104	16
123.8	112	18
132.6	120	20
158	143	25
184.5	167	30
212.2	192	35
240.9	218	40
268.5	243	45
298.4	270	50
355.8	322	60

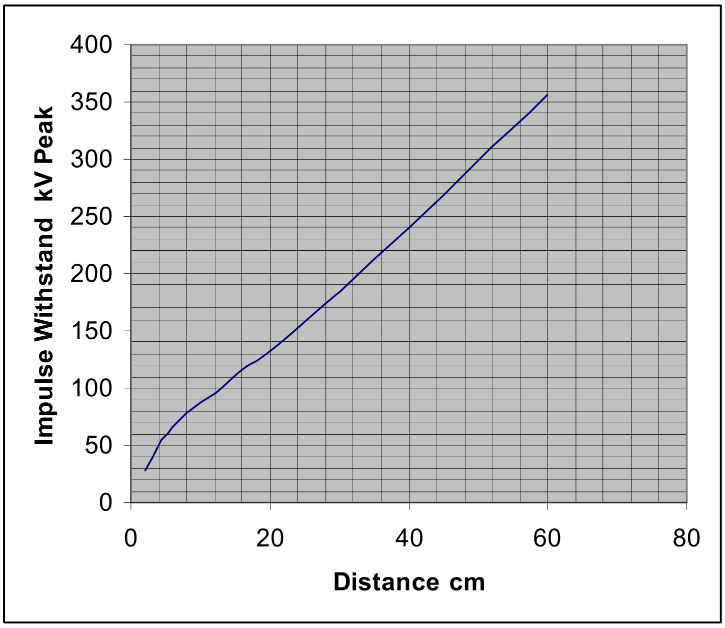


Figure 1—Impulse (TOV) withstand kilovolt peak versus rod-to-rod gap distance, in centimeters (data taken from Table 2)

4.7.1.3 MAID for line-to-ground work on ac and dc line-to-line voltages above 72.5 kV

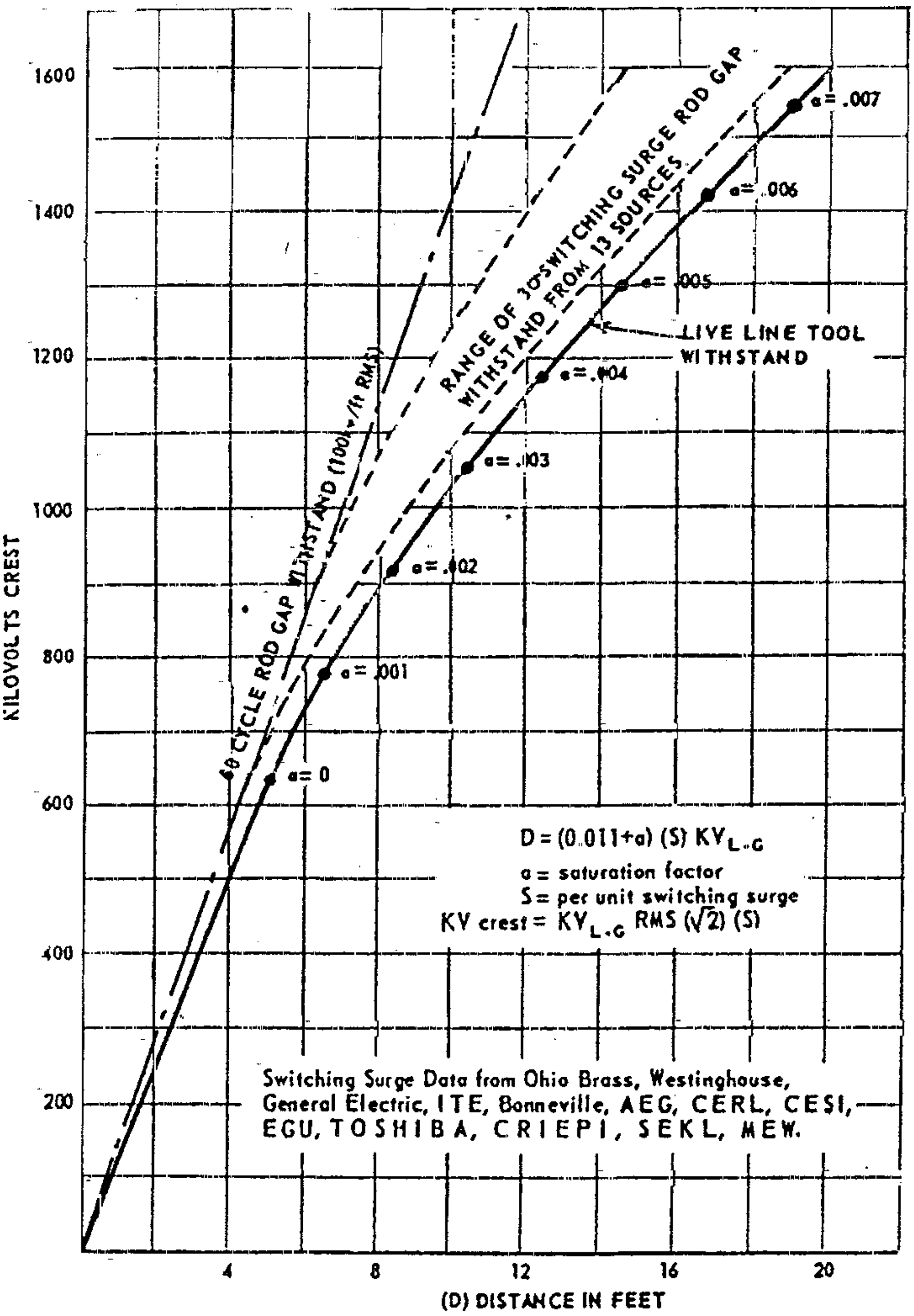
In 1962, Elek and Simpson [B7] published a paper that summarized the results of various testing and data from established practices regarding the required MADs for safety in performing live maintenance. The paper developed a formula for a MAD for line workers that was equal to the spacing of the "phase-to-tower" gap times a safety factor of 1.25, plus an inadvertent movement factor of 36 in.

In 1968, "Recommendations for safety" [B25] was published. This IEEE committee report summarized the results of various testing and data from 13 worldwide high-voltage laboratories that resulted in Figure 2 and established MADs for safety in performing live maintenance. This distance did not include an inadvertent movement factor. This testing also provided data to develop a saturation curve to permit including this effect at voltages over 635 kV_{Peak}. This plot is shown in Figure 2. With these data, the IEEE committee developed equations that relate withstand distance to system peak voltage. The committee also suggested maximum TOV multipliers for various system voltage ranges.

In 1973, "Live-line maintenance methods" [B23] was published. This IEEE committee report updated the data from the previous report and expanded information on live-line work methods. As a result of this work, a new graphic plot, Figure 2, was published. This equation was previously developed to generate a series of MAID tables, one for clear insulating tool length and one for worker approach distance without any factor for inadvertent movement. The clear insulating tool length later became the MAD for Tools in the air gap. This led to the introduction of the portable protective air gap (PPAG) concept.

The earlier editions of this guide used the 1973 committee report as the basis for the formula and tables.

In 2003, the Live Line Guide Working Group further investigated formulas used to calculate the tables. The data from the 13 sources are no longer available. The working group decided to use the 1968 IEEE committee report, "Recommendations for safety" [B25], as its base.



Source: “Recommendations for safety” [B25].

Figure 2—Typical withstand voltages for switching surges

Figure 2 data are plotted in line-to-ground peak kilovolts on the vertical axis and distance in feet on the horizontal axis. On the plot, four plot lines were drawn, using the 60 Hz rod gap withstand-in-air baseline, to show the range of data from the 13 sources. From 0 to 635 kV_{Peak}, the 60 Hz rod gap withstand-in-air baseline was used. Above 635 kV_{Peak}, the plot splits up into three lines: the “60 Hz rod gap withstand-in-air”(left curve), “Low range of the 13 sources,”(second from the left), and “High range of the 13 sources” (third from the left). The fourth line, “Live line tool withstand,” is the right curve or fourth from the left. The center curves (“Low range of the 13 sources” and “High range of the 13 sources”) form an envelope that contains all of the data points from the 13 sources. The right curve, i.e., “Live line tool withstand,” was plotted at the distance values using the 110% factor applied to the MAID curve.

The C_1 are obtained from the “high range of the 13 sources” curve, which is also called the “MAID curve.” The “a” factor values are obtained from the Live line tool withstand” curve, also called the “MTID curve.”

The “Typical withstand voltages for switching surges” drawing from “Live-line maintenance methods” [B23] also contained the formula $D = (0.011+a) \times (S)\ KV_{L-G}$.

where

(0.011 + a) is the slope of the MTID curve

where

a is the air saturation factor

0.011 is $(C_1)(C_2)$, which is composed of

0.01	is C_1 ,which is equal to 0.01 ft/kV_{rms}
1.1	is C_2 ,which increases C_1 by 10% to account for a tool in the air gap
S (now called *T*)	is the per-unit switching surge
KV_{L-G}	is line-to-ground voltage in kilovolts rms

From this formula, the general distance formula $D = (((C_1)(C_2)) + a)(V_{L-G})(T)$ was developed, which is the base for the line-to-ground calculations above 72.5 kV in this edition of this guide.

For line-to-ground work, the C_1 factor is determined from the slope of the 60 Hz rod gap withstand-in-air baseline, which is 100 kV_{rms}/ft or 141.4 kV_{Peak}/ft. The slope of the “Live line tool withstand” line below 635 kV_{Peak} is 134.9 kV_{Peak}/ft since it contains the C_2 factor.

For calculations, this guide uses $C_1 = 0.01$, which results in distance in feet.

When the $(V_{L-G\ rms})(T) > 449$ kV, the “a” factor must be used.

4.7.1.4 MAID for line-to-line work on ac line-to-line voltages above 72.5 kV

The determination of line-to-line MAID should be based on line-to-line gap test data, just as the line-to-ground MAID is based on the line-to-ground gap test data. Several experimental investigations have already been done on line-to-line gaps. These investigations reveal that line-to-line air insulation strength is much more complex than that of line-to-ground air insulation strength. In other words, it is a different physical phenomenon. In particular, as in line-to-ground gaps, the line-to-line insulation characteristics not only depend on the gap spacing (D_{GAP}), but can also be influenced by the conductor height (*H*) above ground (see Risk [B35]). However, this dependence is more complicated because the overvoltage on one conductor is positive with respect to ground while at the same time the overvoltage on the other conductor swings negative with respect to ground.

A fundamental parameter in determining the line-to-line insulation strength is the proportion of negative switching impulse voltage in the total line-to-line impulse voltage.

$$Alpha = \frac{V_{Neg}}{V_{Pos} + V_{Neg}} \tag{39}$$

where

V_{Neg} is the actual value of the negative voltage at the instant of the crest of the positive impulse (V_{Pos}) (see Gallet and Leroy [B15]). The most interesting range of this parameter is 0.33 < alpha < 0.5.

These are a few of the reasons that the electrical stresses in the line-to-line gap and the line-to-ground gap are not the same. Therefore, the test data used for determining the line-to-ground MAID should not be used in obtaining the line-to-line MAID.

Historically, this guide has used rod-to-rod conductor gap data for line-to-ground MAID. One reason for this is that in Figure 2, the 13 sources represent the rod-to-rod data. In addition, in the line-to-ground testing that had been performed, it was found that the rod-to-rod results were in the middle range for a wide range of conductor configurations. The rod-to-rod data presented neither the worst case nor the best. Thus, it was chosen as a reasonable representation of all the possible gap configurations to which a line worker might be exposed. When considering line-to-line MAID, a rod-to-rod gap may not be the most appropriate. Typically the worker will bond onto one phase and will not need to bridge the gap to the other phase. The shape of the adjacent phase electrode will not be changed; it will still be a conductor. The effect of the change in geometry of the phase to which the worker is bonded will be dealt with by introducing an additional factor, the gap factor (K), that accounts for the effect of large conductive objects floating in the air gap.

Gallet, Hutzler, and Riu [B17] conclude in comparing line-to-line geometry to a line-to-ground geometry, that "For both of them, the clearance plays the same role: the breakdown voltage follows a law [Equation 40] which is similar, only the coefficient (gap factor) is varied. This gap factor is largely influenced by the dimensions of the electrodes for line-to-ground insulation, but varies only slightly for industrial symmetrical phase-to-phase geometries."

Therefore, for determining the line-to-line MAID, useful test data for the line-to-line gap for conductor-to-conductor configuration are contained in the 1993 paper by Vaisman et al. [B41]. The paper presents and compares their results with published test data from five other laboratories found in the literature.

The tests data are fitted with a modified Gallet equation (see Gallet et al. [B15] and [B16]), as shown in Equation (40).

$$V_{50} = 3400(k)(k_1)\left(\frac{D}{(D+8.0)}\right) = \frac{3400(k)(k_1)}{1+\left(\frac{8}{D}\right)} \tag{40}$$

where

V_{50} is in $\mathrm{kV_{Crest}}$
D is in meters

Vaisman's modification to the Gallet formula is in the form of two factors for application to line-to-line distance calculations for conductor-to-conductor configurations:

- The K factor, which is the gap factor based on alpha, average conductor height, and conductor-to-conductor separation
- The k_1 factor, which is related to line or span length

For live working purposes, $k_1 = 1.0$, which corresponds to a span length of 75 m. This is done because the length of line section involved at the worksite is short and attention is specifically focused on the probability of sparkover at the worksite itself.

The gap factor (in Equation (41), *k*) is developed in Vaisman et al. [B41].

$$k = 2.17\left(\frac{D_{Design\_L-L}}{H}\right)^{-0.5}\left(\left(0.5 - alpha\right) + \left(3.24\right)\right)\left(alpha\right) \tag{41}$$

where

H	is the average height of the phase above ground (ground clearance plus 1/3 sag)
$D_{Design,L\text{-}L}$	is the design line-to-line clearance

Although an alpha = 0.50 is commonly used in the design of transmission lines, what is important for live work is to know what value of alpha could the worker see when working on the line. A lower alpha can result in a gap strength below that obtained with equal and synchronized peaks (alpha = 0.50).

According to Vaisman et al. [B41],

- "In EHV [extra-high voltage] systems, where there is efficient overvoltage control and hence the overvoltage factor a tends to lie in the range of 0.41 to 0.50, the ratio between the line-to-line (D_1) and the line-to-ground (D) clearance equal to 2.0 is the one which provides a more balanced distribution of flashovers between the two gaps." (See also EPRI *Red Book* [B9], CIGRÉ/SC 33 [B4], and Esmeraldo and Fonseca [B11].)
- "In lower voltage levels (138–230 kV), which present a typical overvoltage relation (a) within the interval 0.33 to 0.50, the number of line-to-line and line-to-ground flashovers is fairly equal for a ratio $D_1/D = 1.5$."

In other words, for lines of 230 kV (i.e., 242 kV) and below, the worker could see an alpha = 0.33. For lines above 242 kV, the worker could see an alpha = 0.41.

Since alpha < 0.50, the ratio of design line-to-line clearance, $D_{Design\ L\text{-}L}$, to average height of the phase above ground, H, must also be determined. Equation (41) is valid for $D_{Design\ L\text{-}L}/H$ only between 0.1 and 0.8. The higher the ratio, the lower the live-to-line gap strength will be. By reviewing the line data in the EPRI *Red Book* [B9], typical ratios are calculated and shown in Annex F-1 of that book. If a ratio of $D_{Design\ L\text{-}L}/H = 0.8$ were used in the calculation of MAID, approximately 95% of the line designs would be included this ratio. If the ratio were lowered to 0.7, approximately 2/3 of the line designs would be included this ratio. If the users' system studies show that their lowest alpha is greater than the 0.33 or 0.41 used here, and their actual $D_{Design\ L\text{-}L}/H$ are less than 0.8, they may use them for calculating the gap factor (K).

Table 3 shows the gap factor (K) for a $D_{Design\ L\text{-}L}/H = 0.8$ and an alpha = 0.33 for 242 kV lines and below and an alpha = 0.41 for lines above 242 kV.

Table 3—Recommended gap factor (K)

Line-to-line voltage	alpha	$D_{Design\ L\text{-}L}/H$	K
Less than or equal to 242 kV	0.33	0.8	1.451
Greater than 242 kV	0.41	0.8	1.530

To obtain the 50% sparkover voltage for live working between conductors using the published test data from Vaisman et al. [B41], the following formula is developed:

$$V_{50} = 3400(k)(K_F)\left(\frac{D_{l-l}}{(D_{l-l}+8.0)}\right) = \frac{3400(k)(K_F)}{1+\left(\dfrac{8}{D_{l-l}}\right)} \tag{42}$$

where

V_{50} is in kilovolts
k is the gap factor from Table 3
K_F is 0.9 to account for electrically floating conductive objects in the air gap from CIGRÉ Brochure 151 [B3]
$D_{l\text{-}l}$ is the sparkover distance, in meters

The literature introduces an additional factor, the floating electrode factor (K_F), which is applied to the reference gap factor and accounts for the effect of large conductive objects floating in the gap; specifically $K_F = 0.9$ for a 3.3 m bucket between phases spaced 8.8 m apart (i.e., 4.5 m of air + 3.3 m of bucket), as shown in Figure 10 from CIGRÉ Brochure 151 [B3]. The 10% reduction is for a gap factor of 1.7, and the effect diminishes with lower gap factor. In this case, the gap factor is 1.451 and 1.530. When there is a helicopter between phases, the additional 10% reduction shown in Figure 10 of CIGRÉ Brochure 151, would be accounted for when calculating MHAD.

Test data for conductor-to-conductor configurations typically result in a gap factor of 1.45 to 1.6, as listed in Table 1 of CIGRÉ Brochure 151 [B3]. Where the conductive object is in contact with one of the energized conductors (i.e., the object is not electrically floating), the reference gap factor is reduced by only 5%, as shown in Figure 4 of CIGRÉ Brochure 151. It should be noted that the Figure 4 also shows the 10% reduction when the bucket is floating 1 m away from the positive phase (i.e., $K_F = 0.9$), but only a 5% reduction when attached to the positive phase. No reduction is noted when near or attached to the negative electrode.

Line-to-line MAID is required for live applications involving barehand tasks by workers from aerial devices such as a bucket truck, cart, or helicopter. Design clearances between phases typically provide for adequate line-to-line MAID. However, in situations where an aerial device is used to support/position the worker, the design clearance may be compromised. Since these devices are normally conductive, it is appropriate to consider their effect (K_F) on the gap strength (i.e., on the electric field distribution in the gap) in addition to the reduction of the gap length due to the physical size of the device itself.

Then using $K_F = 0.9$, Equation (42) becomes Equation (43) and Equation (44):

- For line-to-line voltages at and below 242 kV

$$V_{50} = 3400(1.451)(0.9)\left(\frac{D_{l-l}}{(D_{l-l}+8.0)}\right) = \frac{4439}{1+\left(\dfrac{8}{D_{l-l}}\right)} \tag{43}$$

- For line-to-line voltages above 242 kV

$$V_{50} = 3400(1.530)(0.9)\left(\frac{D_{l-l}}{(D_{l-l}+8.0)}\right) = \frac{4683}{1+\left(\dfrac{8}{D_{l-l}}\right)} \tag{44}$$

Equation (43) and Equation (44) relate the 50% sparkover voltage to the line-to-line air gap distance.

For live working purposes, the "3σ" withstand voltage, V_w, is used as follows:

$$V_W = (1-3\sigma)(V_{50}) \tag{45}$$

- For line-to-line voltages at and below 242 kV with σ = 5.0%

$$V_W = \frac{3773}{\left(1+\dfrac{8}{D_{L-L}}\right)} \tag{46}$$

- For line-to-line voltages above 242 kV with σ = 5.0%

$$V_W = \frac{3980}{\left(1+\dfrac{8}{D_{L-L}}\right)} \tag{47}$$

Equation (46) and Equation (47) provide the basis for calculation of line-to-line MAID, where MAID = D_{L-L} in Equation (46) and Equation (47). To use Equation (46) and Equation (47), it is necessary to determine the value of V_w for the system. This is done by first calculating the maximum industry-accepted TOV. The maximum accepted line-to-ground TOV, TOV_{L-G}, is calculated from the rms line-to-ground system voltage, V_{L-G}.

where

T_{L-G}	is a maximum industry-accepted overvoltage factor
$V_{L\text{-}G\ rms}$	is the rms line-to-ground system voltage
$V_{L\text{-}L\ rms}$	is the rms line-to-line system voltage

There are several acceptable methods to convert the line-to-ground overvoltage factor, T_{L-G}, to the line-to-line overvoltage factor, $T_{L-L.}$ Equation (49) from IEC 61472 [B21] was selected for use as follows:

$$T_{L-L} = (1.35(T_{L-G})) + 0.45 \tag{48}$$

Using Equation (48) and Equation (49), the maximum accepted line-to-line TOV is computed as follows:

$$TOV_{L-L}=\left(\frac{\sqrt{2}}{\sqrt{3}}\right)\left(T_{L-L}\right)\left(V_{L-L\_rms}\right)=\left(\frac{\sqrt{2}}{\sqrt{3}}\right)\left(\left(1.35\left(T_{L-G}\right)\right)+0.45\right)\left(V_{L-L\_rms}\right) \tag{49}$$

As an example for line-to-line voltage equal to or less than 242 kV, σ = 5.0%, TOV_{L-L} from Equation (50) is equated to V_w from Equation (46) as follows:

$$\left(\frac{\sqrt{2}}{\sqrt{3}}\right)\left(\left(1.35\left(T_{L-G}\right)\right)+0.45\right)\left(V_{L-L\_rms}\right)=\frac{3773}{1+\frac{8}{D_{L-L}}} \tag{50}$$

Rearranging the equation to calculate D_{L-L} for line-to-line voltage equal to or less than 242 kV, σ =5.0%, results in Equation (51):

$$D_{L-L}=\frac{8}{\left(\frac{\left(\frac{\sqrt{3}}{\sqrt{2}}\right)(3773)}{\left(\left(1.35\left(T_{L-G}\right)\right)+0.45\right)\left(V_{L-L\_rms}\right)}\right)-1}=\frac{8}{\frac{4621}{\left(\left(1.35\left(T_{L-G}\right)\right)+0.45\right)\left(V_{L-L\_rms}\right)}} \tag{51}$$

Using the same criteria, the equations for the other applications can be developed, i.e., calculating D_{L-L} for line-to-line voltage above 242 kV, σ = 5.0%:

$$D_{L-L}=\frac{8}{\left(\frac{\left(\frac{\sqrt{3}}{\sqrt{2}}\right)(3980)}{\left(\left(1.35\left(T_{L-G}\right)\right)+0.45\right)\left(V_{L-L\_rms}\right)}\right)-1}=\frac{8}{\frac{4875}{\left(\left(1.35\left(T_{L-G}\right)\right)+0.45\right)\left(V_{L-L\_rms}\right)}} \tag{52}$$

In the presence of a conductive object(s) that are electrically floating between phases, MAID is the sum of the air gaps on both sides of the conductive object(s). The total required line-to-line distance (i.e., line-to-line MAD without any tool, rope, etc., between phases) is then the MAID plus the ergonomic factor plus the size of the conductive object(s) (i.e., the sum of the dimension of the objects along the imaginary line that one would draw from one phase to the other).

The formulas give in 4.6.2.2 are based on using σ = 5.0%.

The tables located in Annex D were calculated using σ = 5.0%.

4.7.2 Tool factor (C_2) for ac and dc line-to-line voltages

4.7.2.1 Tool factor (C_2) for ac and dc line-to-line voltages at and below 72.5 kV

The C_2 factor is not used in calculations for line-to-line voltages at and below 72.5 kV.

4.7.2.2 Tool factor (C_2) for line-to-ground work on ac and dc line-to-line voltages above 72.5 kV

The MAID and MTID are increased an additional 6% for the effect of insulating tools in the air gap plus additional 4% for intangibles. The 6% factor may range from an additional 2% to 20% depending upon the structure and the electrode configuration and the surface condition of the tool (see "Recommendations for safety" [B25]).

For calculations in this guide, $C_2 = 1.10$ or 110% is used.

4.7.2.3 Tool factor (C_2) for line-to-line work on ac and dc line-to-line voltages above 72.5 kV

Until test data are available, line-to-line MTID is not provided in this guide. See 4.5.2.3.

4.7.3 Air saturation factor ("a") for ac and dc line-to-line voltages

CAUTION

To determine the "a" factor, use V_{Peak}. If V_{Peak} has not been determined from the engineering studies used to determine T, V_{Peak} may be calculated. See 4.7.3.2.

4.7.3.1 . Air saturation factor ("a") for ac and dc line-to-line voltages at and below 72.5 kV

The "a" factor is not used in calculations for line-to-line voltages at and below 72.5 kV.

4.7.3.2 Air saturation factor ("a") for ac and dc line-to-line voltages above 72.5 kV used in line-to-ground distance calculations

After the 2003 publication of this guide, the applicable working group of the ESMOL Subcommittee took a close look at how the distances were calculated since the working group members preferred to have users employ the equations to calculate the distances, rather than using the tables to determine the distances. The 2003 edition was the first document to have equations and calculated tables. The working group also decided that formulas should be provided for all distance calculations for line-to-line voltages above 72.5 kV to avoid double rounding-up. The distances given in tables in earlier editions of the guide contained industry-accepted values, which were obtained from data plots. It has been determined that the factor used to convert the line-to-ground distance to line-to-line distances in the 2003 edition was not properly applied and that line-to-line distances where the "a" factor is greater than zero were not correct.

The working group decided that Figure 1 from the IEEE paper "Recommendations for Safety" [B25] should be used for the line-to-ground distance calculations for line-to-line voltages above 72.5 kV. That figure is Figure 2 in this guide.

Figure 2 was analyzed using an exact copy of the original with the following results:

- The "Live line tool withstand" curve is now called the MTID.
- The right-hand curve (second from the right side) from the envelope of the "Range of 3σ Switching Surge Rod Gap Withstands from 13 Sources" is now called the MAID.
- The difference between the MAID and MTID curve is based on the 10% factor applied to the MAID.

- The values of the “a” factor listed in the figure apply to MTID curve only.

The formula shown on Figure 2, D = (0.011 + a)(S) $kV_{L\text{-}G}$, is same as the MTID formula that is presently used.

$D_{Ft} = (((C_1)(C_2)+a)(T)(V_{L\text{-}G})$

where

C_1 is 0.01 (60 cycle rod gap withstand) from MAID curve
C_2 is 10% of C_1 or 0.001
$(C_1)(C_2)$ is 0.011
a is the air saturation factor
T (S) is the maximum anticipated per-unit TOV
$V_{L\text{-}G}$ ($kV_{L\text{-}G}$) is the rms line-to-ground voltage, in kilovolts

When the “a” factor is not zero, $((C_1)(C_2) + a)$ does not equal $((C_1 + a) + 10\%$ of $(C_1 + a))$. Therefore, there is a different value of the “a” factor for same voltage used to calculate MAID and MTID. To avoid having values of the “a” factors for MAID and MTID, the working group decided to use only the MTID “a” factor since it matches the values of the “a” factor shown on the figure.

The formula for the MTID “a” factor was developed using a curve fitting program from the MTID curve.

To determine the “a” factor, use V_{Peak}. V_{Peak} is the maximum voltage measured from the conductor to ground that is applied across the air gap during a transient event. V_{Peak} is the combination of the 60 Hz voltage of line and the dc impulse resulting from the transient event. If V_{Peak} is not obtained from the system study results, it can be calculated using Equation (53), which is used to obtain peak voltages from rms voltages.

For line-to-ground work, V_{Peak} is calculated as follows:

$$V_{Peak} = \left(V_{L-G}\right)\left(T\right)\left(\sqrt{2}\right) = 1.414\left(\left(V_{L-G}\right)\left(T\right)\right) \tag{53}$$

where

T is the line-to-ground maximum anticipated per-unit TOV

Using a curve fitting program, a formula for the slope of the curve was developed.

Calculated values of the “a” factor are rounded up to 7 decimal places.

a) **For V_{Peak} less than 635 kV**, a = 0
b) **For V_{Peak} from 635.1 to 915.0 kV**

$$a = \left(\left(V_{Peak}\right) - \left(635\right)\right)\left(0.00000714\right) \tag{54}$$

Or

$$a = \frac{\left(\left(V_{Peak}\right) - 635\right)}{140000} \tag{55}$$

c) **For V_{Peak} from 915.1 to 1050.0 kV**

$$a = \left(\left(\left(V_{Peak}\right) - 915\right)\left(0.00000741\right)\right) + 0.002 \tag{56}$$

Or

$$a = \frac{\left(\left(V_{Peak}\right) - 645\right)}{135000} \tag{57}$$

d) **For V_{Peak} from 1050.1 to 1600 kV**

$$a = \left(\left(\left(V_{Peak}\right) - 1050\right)\left(0.00000800\right)\right) + 0.003 \tag{58}$$

Or

$$a = \frac{\left(\left(V_{Peak}\right) - 675\right)}{125000} \tag{59}$$

4.7.4 Maximum anticipated per-unit TOV (*T*) for live work

T for live work is defined as the maximum anticipated per-unit TOV and is determined from an engineering evaluation considering the following factors:

a) Line or system design *T*, which is determined by system studies (see Annex E)
b) The system operating practices
c) The reliability of the system equipment
d) The probability of an event occurring

In this guide, unless otherwise noted, the *T* values are expressed in per-unit values based on line-to-ground voltage.

4.7.4.1 *T* for ac and dc line-to-line voltages between 300 V and 72.5 kV

For ac and dc line-to-line voltages between 300 V and 72.5 kV, this guide used $T = 3.0$ (see Kolcio et al. [B32] and [B33]).

4.7.4.2 *T* for ac and dc line-to-line voltages above 72.5 kV

The line-to-ground maximum anticipated per-unit TOV (*T*) for live work is defined as the ratio of the 2% statistical switching overvoltage expected at the worksite to the nominal peak line-to-ground voltage of the system. In mathematical terms, *T* can be expressed as follows:

$$T = \frac{V_2}{V_{L-GPeak}} \tag{60}$$

where

V_2 is 2% statistical overvoltage, in kilovolts
$V_{L\text{-}G\ Peak}$ is the peak line-to-ground voltage, in kilovolts
T is expressed as a per-unit value based on the line-to-ground voltage

Determining the line-to-line maximum anticipated per-unit TOV is complicated because there is usually a time displacement between line-to-ground transients on the adjacent phases. The time displacement between these transients causes the maximum line-to-line transient voltage to be less than the arithmetic sum of the magnitudes of the line-to-ground transient voltages.

This guide uses the IEC formula from IEC 61472 [B21]. The line-to-line TOV ($T_{L\text{-}L}$) can be determined from the line-to-ground TOV using Equation (61).

$$T_{L-L} = \left((1.35)\left(T_{L-G}\right)\right) + 0.45 \tag{61}$$

4.7.4.3 Industry-accepted values of *T* for live work on ac systems above 72.5 kV

Table 4 shows typical industry-accepted values of *T* for live work being used in North America.

Table 4—Industry-accepted values of *T* for live work

AC line-to-line voltage	*T* for live work
At and below 362 kV	3.0 p.u.
363 to 550 kV	2.4 p.u.
551 to 800 kV	2.0 p.u.

The values shown in the Table 4 are based on the following:

a) At all voltage levels, it is assumed that circuit breakers are being used to switch the subject line while live work is being performed. This further assumes that the restrike probability of a circuit breaker is low and consequently extremely low while a worker is near the MAD and that it can, therefore, be ignored in the calculation of *T*. If devices other than circuit breakers are being utilized to switch the subject line while live work is being performed, then the values listed in the table may not be valid, and an engineering evaluation should be performed to determine *T*.

b) At 242 kV, it is assumed that automatic instantaneous reclosing is disabled. If not, the values shown in the table may not be valid, and an engineering evaluation should be performed to determine *T*.

c) Above 420 kV, it is assumed that either closing resistors or surge arresters (or a combination of both) are being used to limit switching overvoltages to the values provided in the table.

CAUTION

An engineering evaluation should be performed to determine *T*.
It is possible to obtain values of *T* greater than the industry-accepted values of *T* listed in this subclause.

4.7.4.4 Industry-accepted values of *T* for dc voltages

a) For dc lines at and below pole-to-ground and pole-to-pole voltages of 72.5 kV, use the ac value

   ***T* = 3.0 p.u.**

b) For dc lines above pole-to-ground and pole-to-pole voltages of 72.5 kV, use

   ***T* = 1.8 p.u.**

4.7.4.5 Controlling and reducing the value of *T*

Temporary transient overvoltage control devices (TTOCDs) can be installed adjacent to the worksite to reduce the worksite TOV. To be most effective, the TTOCDs should be installed between the sources of the TOV and worksite. The following are examples of TTOCDs:

a) PPAGs have a rather large sparkover range due to atmospheric conditions. To protect the worker, the minimum sparkover should be considered. If the PPAG sparks over, the line will fault. Further information regarding PPAG can be found in 4.8.2.1.

b) Portable surge arrestors and other devices are being tested for this use.

For more information about controlling and reducing the value of *T*, see the CIGRÉ reports “Switching Overvoltages” [B5] and “Temporary Overvoltages” [B6].

4.7.5 Voltage (V_{L-G})

This guide uses the line-to-ground voltage (V_{L-G}) as its base for calculating the MAID, MTID, MAD, MAD for Tools, and MHAD. The criteria given in 4.7.5.1 through 4.7.5.6 should be used to determine the maximum steady-state line-to-ground voltage that can occur during live working conditions. See IEEE Std C62.92.1-2000.

4.7.5.1 AC systems, three-phase solidly (effectively) grounded

When line-to-ground faults occur on solidly grounded systems, the line-to-ground voltage on the other unfaulted phases will deviate from their nominal values. However, in most cases, the voltage remains close to its nominal value. Thus, the maximum line-to-ground operating voltage of the system may be used to compute MAID, MTID, MAD, MAD for Tools, and MHAD.

$$V_{L-G} = \frac{V_{L-L}}{\sqrt{3}} = \frac{V_{L-L}}{1.732} \qquad (62)$$

$$V_{L-GPEAK} = \frac{\sqrt{2}\left(V_{L-L}\right)}{\sqrt{3}} = \frac{\left(1.414\right)\left(V_{L-L}\right)}{1.732} = \left(0.8164\right)\left(V_{L-L}\right) \tag{63}$$

where

$V_{L\text{-}L}$	is the line-to-line rms voltage, in kilovolts
$V_{L\text{-}G}$	is the line-to-ground rms voltage, in kilovolts, and is calculated from V
$V_{L\text{-}G\ Peak}$	is the line-to-ground peak voltage, in kilovolts, and is calculated from V

4.7.5.2 AC systems, three-phase impedance grounded

This category of ac systems includes reactance grounded, resistance grounded, and resonant grounded systems. If these grounding types are utilized and a normally energized conductor becomes accidentally grounded, the voltages to ground on the other unfaulted conductors may increase above their normal operating voltages up to the line-to-line voltage. In this case, the system line-to-line voltage should be used as the maximum line-to-ground voltage.

$$V_{L-GPeak} = \left(V_{L-L}\right)\sqrt{2} = \left(1.414\right)\left(V_{L-L}\right) \tag{64}$$

where

$V_{L\text{-}L}$	is the line-to-line rms voltage, in kilovolts
$V_{L\text{-}G}$	is $V_{L\text{-}L}$
$V_{L\text{-}G\ Peak}$	is the peak line-to-ground voltage, in kilovolts, and is calculated from $V_{L\text{-}G}$

4.7.5.3 AC systems, three-phase ungrounded (isolated neutral) or delta

The overvoltages that are experienced during line-to-ground faults on ungrounded systems are similar to the overvoltages experienced in impedance grounded systems. Thus, the system line-to-line voltage should be used as the maximum line-to-ground voltage.

$$V_{L-GPeak} = V_{L-L}\sqrt{2} = \left(1.414\right)V_{L-L} \tag{65}$$

where

$V_{L\text{-}L}$	is the line-to-line rms voltage, in kilovolts
$V_{L\text{-}G}$	is $V_{L\text{-}L}$
$V_{L\text{-}G\ Peak}$	is the peak line-to-ground voltage, in kilovolts, and is calculated from $V_{L\text{-}G}$

4.7.5.4 AC single-phase systems, two or three wires, one leg or center tap grounded

The grounding type of the three-phase source feeding this arrangement must be known in order to properly determine the maximum line-to-ground voltage. In the case of the two-wire or three-wire arrangement, if it is fed from any source other than a solidly grounded wye system, then the line-to-line system voltage should be used as the maximum line-to-ground voltage. Otherwise, the system line-to-ground voltage can be used.

$$V_{L-GPeak} = \left(V_{L-L}\right)\sqrt{2} = \left(1.414\right)\left(V_{L-L}\right) \tag{66}$$

where

$V_{L\text{-}L}$ is the line-to-line rms voltage, in kilovolts
$V_{L\text{-}G}$ is the highest rms line-to-ground rms voltage, in kilovolts, that can be obtained
$V_{L\text{-}G\,Peak}$ is the peak line-to-ground voltage, in kilovolts, and is calculated from $V_{L\text{-}G}$

4.7.5.5 DC systems, one or two wires, one pole grounded

$$V_{L-G} = \frac{V_{P-G}}{\sqrt{2}} = \frac{V_{P-G}}{1.414} \tag{67}$$

where

$V_{P\text{-}G}$ is the pole-to-ground voltage, in kilovolts
$V_{L\text{-}G}$ is the equivalent ac rms voltage, in kilovolts

$$V_{L-GPeak} = V_{P-G} \tag{68}$$

where

$V_{L\text{-}G\,Peak}$ is the equivalent ac voltage, in kilovolts

4.7.5.6 DC bi-polar systems, two or three wires

$$V_{L-G} = \frac{\left(\frac{V_{P-P}}{2}\right)}{1.414} = \frac{V_{P-P}}{2.828} \tag{69}$$

where

$V_{P\text{-}P}$ is the pole-to-pole voltage, in kilovolts
$V_{L\text{-}G}$ is the equivalent ac rms pole-to-ground voltage, in kilovolts

$$V_{L-GPeak} = \frac{V_{P-P}}{2} \tag{70}$$

where

$V_{L\text{-}G\,Peak}$ is the peak pole-to-ground voltage, in kilovolts

4.7.5.7 DC bi-polar systems, voltage above 72.5 kV

It is extremely unlikely that a TOV would occur on both poles at the same time. Since there is no coupling between poles of a dc transmission line, this guide uses the sum of TOV from each pole.

To obtain the pole-to-pole MAID and MTID, determine the pole-to-ground distances using T for one pole and $T = 1$ for the other pole. Add the two pole-to-ground distances together.

$$MAID_{P-P} = \left(MAID_{P1-G}\right) + \left(MAID_{P2-G}\right) \tag{71}$$

$$MTID_{P-P} = \left(MTID_{P1-G}\right) + \left(MTID_{P2-G}\right) \tag{72}$$

To obtain the pole-to-pole MAD, add *M* to $MAID_{P\text{-}P}$.

$$MAD_{P-P} = \left(MAID_{P-P}\right) + \left(M\right) \tag{73}$$

To obtain the pole-to-pole MAD for Tools, add *M* to $MTID_{P\text{-}P}$.

$$MADforTools_{P-P} = \left(MTID_{P-P}\right) + \left(M\right) \tag{74}$$

To obtain the pole-to-pole MHAD, multiply $MAD_{P\text{-}P}$ by 110%.

$$MHAD_{P-P} = \left(MAD_{P-P}\right)\left(1.1\right) \tag{75}$$

4.7.6 Altitude correction factor (A)

It has been determined by laboratory testing that an altitude correction factor (A) is needed for live work on lines operating above 72.5 kV when the worksite is more than 3000 ft or 900 m above sea level.

4.7.6.1 Voltages at and below 72.5 kV

Altitude correction is not required, i.e., A = 1.

4.7.6.2 Voltages above 72.5 kV

For voltages above 72.5 kV, the altitude correction factor (A) is given in Table 5.

Table 5—Altitude correction factor (A)

Meters	Feet	A
0 to 900	0 to 3000	1.00
901 to 1200	3001 to 4000	1.02
1201 to 1500	4001 to 5000	1.05
1501 to 1800	5001 to 6000	1.08
1801 to 2100	6001 to 7000	1.11
2101 to 2400	7001 to 8000	1.14
2401 to 2700	8001 to 9000	1.17
2701 to 3000	9001 to 10 000	1.20
3001 to 3600	10 001 to 12 000	1.25
3601 to 4200	12 001 to 14 000	1.30
4201 to 4800	14 001 to 16 000	1.35
4801 to 5400	16 001 to 18 000	1.39
5401 to 6000	18 001 to 20 000	1.44

The correction factor applies only to the MAID and MTID. It does not apply to the inadvertent movement factor (M) contained in MAD, MAD for Tools, and MHAD.

The general equations are as follows:

$$AltidudeCorrectedMAID = (MAID)(A) \tag{76}$$

$$AltidudeCorrectedMTID = (MTID)(A) \tag{77}$$

$$AltitudeCorrectedMAD = ((MAID_{ALTCorrected})(A)) + M \tag{78}$$

$$AltitudeCorrectedMADforTools = ((MTID_{ALTCorrected})(A)) + M \tag{79}$$

$$AltitudeCorrectedMHID = (((MAID_{ALTCorrected})(A)) + M)(1.10) \tag{80}$$

When using the MAD, MAD for Tools, and MHID tables in Annex D for altitudes above 900 m or 3000 ft, the correction factor should be applied directly to the MAID and MTID values, and then the MAID and MTID values should be converted to MAD and MAD for Tools by adding the inadvertent movement factor (M).

a) **Example:** For work at an altitude of 1600 m
   MAID corrected to 1600 m = (MAID from Annex D) (1.08)

b) **Example:** For work at an altitude of 1600 m
   MAD corrected to 1600 m = ((MAID from Annex D) (1.08)) + (M)

4.7.7 Inadvertent movement factor (M)

The M factor is used to convert MAID and MTID to MAD, MAD for Tools, and MHAD. See Table 6.

Table 6—Inadvertent movement factor (M)

Line-to-line voltage	**M**		
	Meters	**Centimeters**	**Feet**
0.0 to 50 V	Not specified	Not specified	Not specified
51 to 300 V	Avoid contact	Avoid contact	Avoid contact
301 to 750 V	0.30	30.0	1.0
751 V to 72.5 kV	0.61	61.0	2.0
72.6 to 800 kV	0.30	30.0	1.0

4.7.8 Helicopter factor (H)

The helicopter and lineman configuration represents a floating object in the air gap. This floating object will divide the air gap into two parts, and the sum of the two parts must be greater than or equal to MHAD.

The insulating air space is also affected by the air movement over the rotor, referred to as *rotor wash*.

The MHAD between the helicopter/lineman configuration and any conductor at a different potential or grounded object should be maintained. This factor covers possible corona on the helicopter, rotor wash, and movement due to wind. This guide uses an industry-accepted value of 10% adder to MAD know as H.

To maintain MHAD, the overvoltage may need to be reduced by blocking the reclosing function, prohibiting switching on the circuit being maintained, and/or using other overvoltage controls on the circuit. Reducing the overvoltage may also be accomplished by installing a PPAG device not further than 2 circuit miles from the worksite.

4.7.9 Additional factors that affect the MAID, MTID, MAD, MAD for Tool, and MHAD

4.7.9.1 Worksite configuration

To do live work, the following information must be known to determine which distance is to be applied:

- To determine which formulas and tables are to be used, the worker should evaluate the work procedure and worksite to determine the exposure to the line conductors.
- At and below 72.5 kV, due to the distance between phase conductors, using both the line-to-ground and line-to-line formulas and tables may be required.
- Above 72.5 kV, most of the live work is performed between an energized phase, including phases that may be located above or below, and ground using line-to-ground formulas or tables.
- If work is being performed in the air gap between two energized phases, the line-to-line formulas or tables are used.
- Some barehand and helicopter work involves the use of both formulas or tables for line-to-ground and line-to-line voltages.

The following items will affect the worksite configuration and should be considered in the evaluation:

- The MAIDs basically define the worksite limits.
- The MADs basically define the worker’s limits.
- The MTID basically defines the insulating length of the tools.
- The MADs for Tools basically define the tool insulating length of as well as the worker’s limits.

4.7.9.2 Floating objects in the air gap

When a large floating object, not at ground or the conductor potential, is in the air gap, additional compensation may be needed to provide for the size and location of the floating object in the air gap.

4.8 Control of TOVs

TOVs can be controlled at various locations involving a number of methods, as discussed in 4.8.1 and 4.8.2.

4.8.1 At stations on the line terminals

At stations on the line terminals, the following methods can be used to control TOV:

a) Station and intermediate class surge arrestors will clip and maintain the voltage to limit the surge magnitude.
b) Fixed air gaps will spark over when the TOV exceeds its rated voltage withstand and result in a fault on the circuit. These should not be confused with air gaps installed on disconnect switches to prevent sparkover of the open switch.
c) Blocking automatic reclosing prevents automatic closing of the high-speed circuit switching devices after the switching devices are opened. This will allow the trapped charge to dissipate prior to reenergization and reduce the closing TOV.
d) Shunt-connected devices, such as transformers, and reactors will tend to reduce the trapped charge on the line and, therefore, limit the overvoltages due to reenergization.

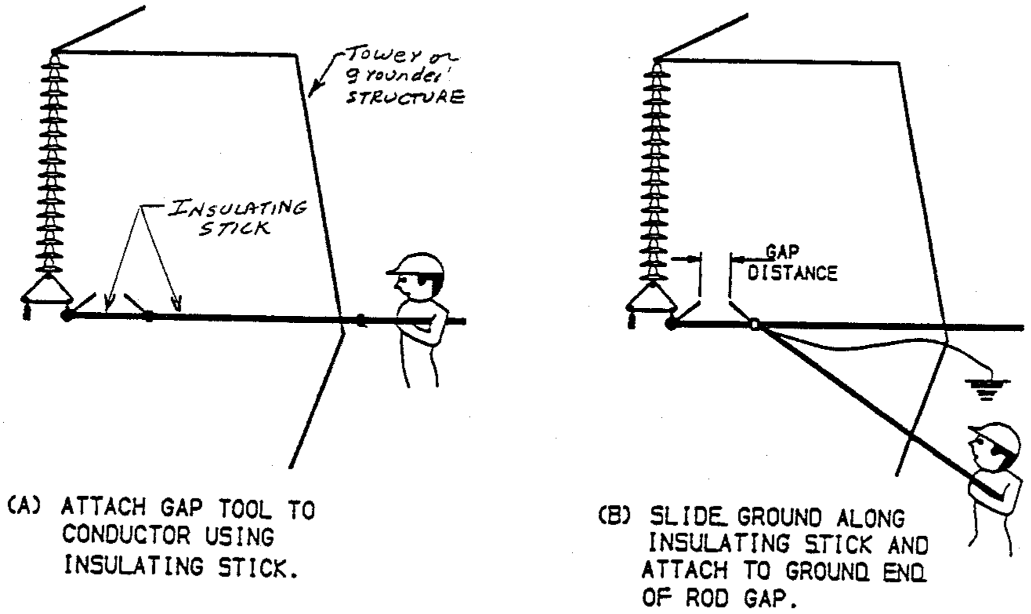
4.8.2 Adjacent to the worksite

TTOCDs can be installed adjacent to the worksite to reduce the worksite TOV. To be most effective, the TTOCDs should be installed between the sources of the TOV and worksite. The following are examples of TTOCDs:

a) PPAGs have a rather large sparkover range due to atmospheric conditions. To protect the worker, the minimum sparkover should be considered. If the PPAG sparks over, the line will fault. Further information regarding PPAG can be found in 4.8.2.1.
b) Portable surge arrestors and other devices are being tested for this use.

4.8.2.1 Portable protective air gaps (PPAGs)

A PPAG can be employed to provide worker protection by establishing a controlled sparkover path that is coordinated with the sparkover voltage of the MAD. Recognizing that the protective gap at the worksite may operate, these gaps are generally installed at an adjacent structure. Figure 3 shows a typical PPAG being installed.



(A) ATTACH GAP TOOL TO CONDUCTOR USING INSULATING STICK.

(B) SLIDE GROUND ALONG INSULATING STICK AND ATTACH TO GROUND END OF ROD GAP.

Figure 3—Installing a PPAG

If the PPAGs are placed on the structure at the work location, care should be taken to evaluate the proximity of the worker and the arc, if the gap operates. Workers on the ground near the structure supporting the PPAG should be protected from any step and touch voltages should the PPAG operate by sparking over. See 8.6.

When gaps are installed at the terminals (line ends), their ability to control the TOV level at the remote worksite should also be considered in determining the required protection.

The key to the use of PPAGs is in establishing the statistical withstand and statistical sparkover voltage of the PPAG. The withstand and sparkover characteristics of a PPAG are determined by sparkover probability data for the particular protective gap geometry, gap distance, and conductor bundle geometry.

The sparkover voltage (V_{50}), the statistical withstand voltage, and statistical sparkover voltage of the PPAG are determined by test. The papers by Gela et al. [B18] and Task Force 15.07.04.01 [B36] provide discussions on the testing and application of PPAGs as well as extensive bibliographies of papers that contributed to the development of PPAGs back to 1968.

Figure 4 illustrates the determination of the distribution of sparkovers for one gap setting. The μ value would be the 50% probability sparkover value. The μ-3σ value is the statistical withstand voltage and the $\mu + 2\sigma$ value is the statistical sparkover voltage. The same information is illustrated in Figure 6 on probability graph paper. Point A is the statistical withstand voltage, the 50% point is the V_{50}, and point B is the statistical sparkover voltage.

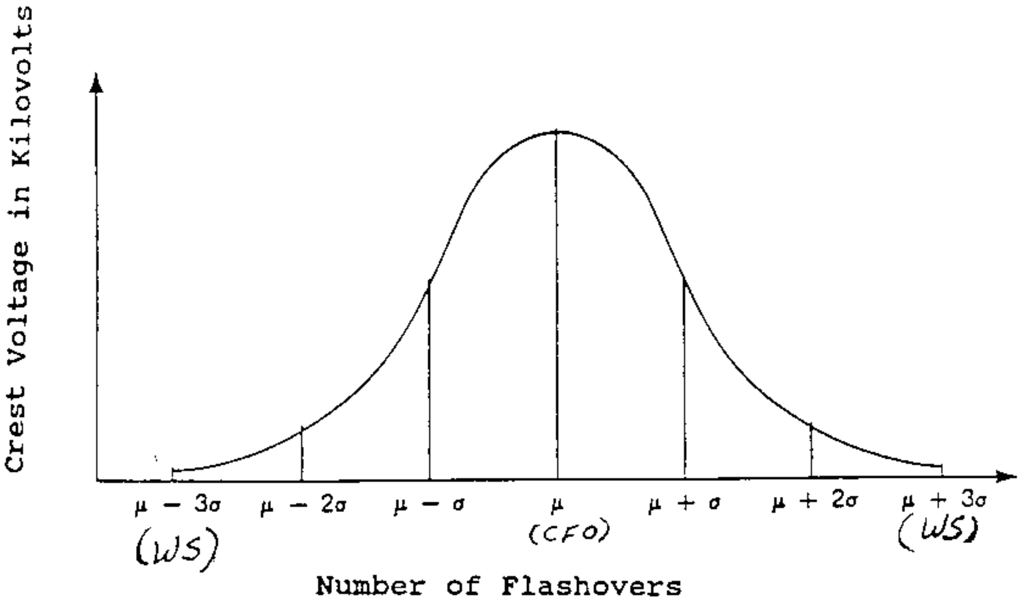


Figure 4—Number of flashovers versus voltage across the gap, assuming normal flashover distribution

When a second gap is added, the two gaps can be coordinated as shown in Figure 5.

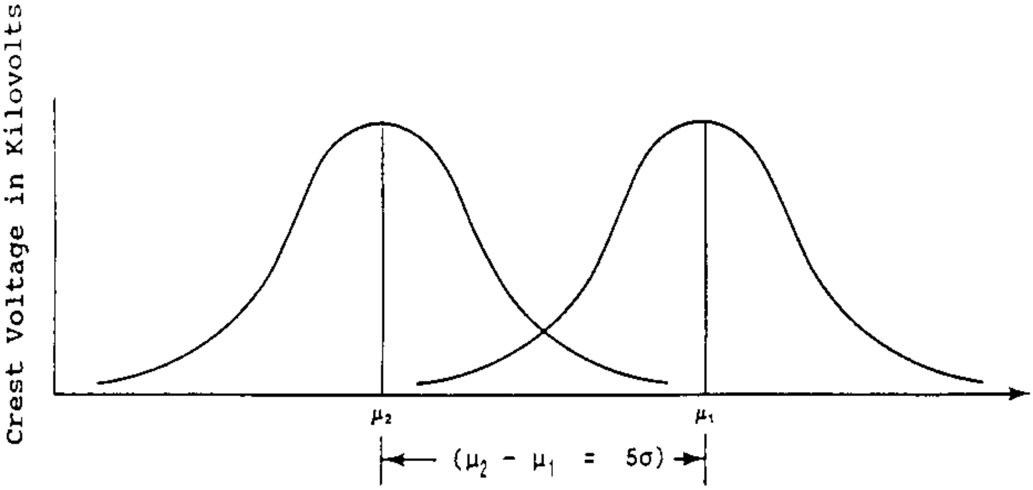


Figure 5—Coordinated probability density functions of two gaps

The Figure 6 plot is a typical textbook statistical plot and is used as an example.

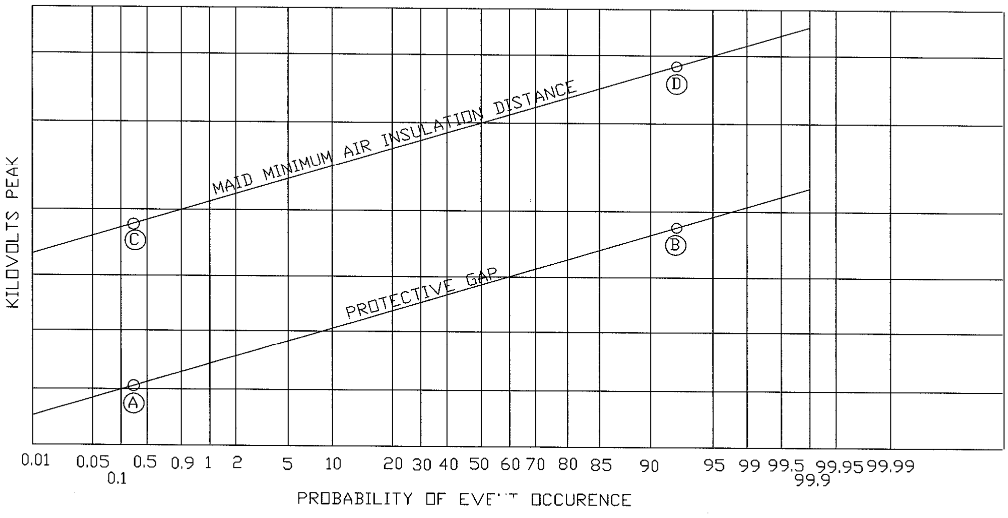


Figure 6—Peak voltage in kilovolts versus probability of withstand

The setting of the withstand voltage of the PPAG is dependent upon the probability of the protective gap sparkover that the user is willing to accept. Some users may be willing to use settings very near the maximum operating voltage and accept the probability that minor TOVs may cause sparkover of the PPAG and, therefore, a line outage. Users should investigate the probability that the PPAG may spark over for their particular line or system. Each of the TOV possibilities and their anticipated magnitudes above the maximum operating voltage should be reviewed.

With this information for several protective gap distances, both the protective gap and the reduction of the MAD can be determined as outlined in Annex C.

4.9 Application of MAID, MTID, MAD, MAD for Tools, and MHAD

This subclause applies to overhead line and equipment and does not apply to underground cables and equipment in grounded enclosure.

In order to effectively use the MAID, MTID, MAD, MAD for Tools, and MHID, the condition for their use should first be defined.

4.9.1 Live parts

The following are considered to be live parts at their normal operating voltage unless they are properly grounded:

- Conductors – bare
- Conductors – insulated unless they have solidly grounded and tested shields (The condition of the conductor insulation exposed to weather is unknown and may be damaged or defective.)
- Rigid bus
- Bushings, surge arrestors, potential transformers, current transformers, and pothead energized ends and terminal connections

- Circuit-switching devices
- Disconnect switch blade and terminals
- Wave traps and series reactors
- Workers and equipment bonded to the conductor (barehand work)
- Helicopters that support workers performing live work
- Rubber glove protectors

The following are considered to be live parts at their normal operating voltage or less since the voltage gradient is disturbed across them:

- Support insulator
- Insulating sections of bushings, surge arrestors, potential transformers, current transformers, and potheads
- Dry wood poles and cross arms without bonded or grounded insulator hardware, which may be part of the insulation system and may have potential across them
- Insulating boom of aerial devices in contact with the conductor
- Live working tools bridging the air gap
- Insulating ladders and platforms bridging the air gap
- Insulating rope between the conductor and a part at ground potential
- Link or lift sticks
- Strain pole
- Cross arm extensions

4.9.2 Floating objects

The following are considered to be floating objects at unknown potential since they are floating within the fields from the various live parts in the area:

- Helicopters flying and not bonded to the live parts
- Workers supported by insulating ladders, platforms, or aerial work devices (bucket trucks) not bonded to the live parts
- The insulating section of insulating tools, ladders, platforms, and aerial work devices

4.9.3 At ground potential

The following are considered to be at ground potential:

- Workers unless they are performing barehand work and are supported by the live parts or an insulating aerial device, ladder, or work platform
- Metal and concrete supporting structures
- Wood poles
- Cross arms with bonded hardware

- Insulators, bushings, surge arrestors, potential transformers, current transformers, potheads, and other equipment bases
- Disconnect switch bases
- Overhead ground wire
- Guy wires without insulated breaks in them
- Support wires (messengers)
- Insulated aerial cable with a grounded shield

4.10 Insulation systems

Several insulating systems are used in overhead power lines. In normal operation, the air gap and support insulators are the means that allow the system to operate. The insulation systems function as very high impedance paths with very low current flow and thereby cause the voltage gradient across them. In general, the voltage gradient is highest at the line end. When performing live work, the insulation systems in 4.10.1 through 4.10.12 need to be considered.

4.10.1 Air gap insulation

Under normal atmospheric conditions, the insulating values of the air gap are stated as the MAID, MTID, MAD, and MAD for Tools.

The line-to-ground MAID, MTID, MAD, and MAD for Tools are calculated as the straight line distance through air between the live parts and items at ground potential.

The line-to-line MAID, MTID, MAD, MAD for Tools, and MHAD are calculated as the straight line distance through air between the live parts of two different phases.

The MAID and MAD in the air gap are used when the air gap is clear of any foreign objects.

4.10.2 Principal insulation system

The following means are used to permit workers at ground potential to work on the live parts using only the principal insulation:

a) Rubber gloves, providing that the following are met:
    - The length of cuff is greater than line-to-ground MAID for tools in the air gap. In practice, the cuff length is determined from ASTM F 496.
    - The exposure voltage is less than maximum voltage for that class of rubber gloves.

    Rubber gloves act as an insulator between the live part and worker's hand at the point of contact. The cuff length is needed to provide for the air insulation between the unprotected worker's body and the live part.

    The use of glove protectors is recommended although they have no insulating value.

    Cotton or similar glove liners may be used inside of the gloves and have no insulating value.

b) Rubber gloves and sleeves, providing that the following are met:

   - The distance from the unprotected parts of the worker to the exposed live parts that are being maintained is greater than the MAID value, and the distance to all other exposed facilities has a clearance greater than MAD.
   - The exposure voltage is equal to or less than maximum voltage for that class of rubber gloves and sleeves.

   Rubber gloves act as an insulator between the live part and worker's hand at the point of contact. The cuff and sleeve length are needed to provide for the air insulation between the unprotected worker's body and the live part.

   The use of glove protectors is recommended although they have no insulating value.

   Cotton or similar glove liners may be used inside of the gloves and have no insulating value.

c) Live working tools used as handheld tools, providing that the following are met:

   - The clear live tool insulation distance is equal to or greater than the line-to-ground MAD for Tools in the air gap.
   - The live working tool is a very high impedance element, which allows for the voltage gradient to be spread across the stick from the line part to ground. To do this, a very low leakage current must pass through the worker holding the stick to ground. This current should be very low and may not be detected by the worker. For the above reason, it is not recommended that rubber gloves be worn when holding a live working tool on lines operating above the rating of the gloves.

   Example: Work sticks

d) Live working tools used as support tools, providing that the clear live tool insulation distance is equal to or greater than the line-to-ground MAID for tools in the air gap or the length of the insulator assembles.

   Example: Link sticks, strain poles

e) Insulating ladders and platforms used to bridge the gap between the live parts and items at ground potential, providing that the clear live tool insulation distance is equal to or greater than the line-to-ground MAD for Tools in the air gap plus an addition distance to offset the distance taken up by the worker on the ladder or platform. See 7.8.1.1.

f) Aerial booms, providing that the clear live tool insulation distance is equal to or greater than the line-to-ground MAID for tools in the air gap.

   Example: Bucket trucks

4.10.3 Supplemental insulation

When the required line-to-ground MAD for Tools in the air gap distance cannot be obtained using the primary insulation alone, supplemental insulation is used.

a) Natural rubber and rubber-like materials, allowing that if three-phase exposure voltage exists, the maximum use voltage rating of the equipment should be greater than or equal to the nominal line-to-line voltage of the system line-to-line voltage.

   Example: Blankets, line hose and hoods, hand cover-up, gloves

b) Rigid materials, providing that the three-phase exposure voltage is equal to or less than maximum voltage for that class of material.

   Example: Line guards, couplers, cross arm guards, pole covers, cutout covers, and insulating barriers

4.10.4 Secondary insulation

4.10.4.1 Worker at ground potential

The insulating medium nearest the live parts is considered to be the principal insulation, and the insulating medium nearest the ground is considered to be the secondary insulation.

When two different insulating mediums are used in series, both mediums should be able to withstand the line-to-ground voltage since the division of the voltage gradient across the series combination is not determined. Use of rubber gloves as secondary insulation is not recommended where system voltage dictates an electrical stress beyond the capacity of the rubber gloves.

4.10.4.2 Worker between the two insulating mediums

The insulating medium nearest the live parts is considered to be the principal insulation, and the insulating medium nearest the ground is considered to be the secondary insulation. In this case, the worker is at a floating potential.

The principal insulation should be able to withstand the line-to-ground voltage and meet the MAD for Tools in the air gap requirements for line-to-ground and line-to-line voltages (if exposed to multiple phases).

Since the division of the voltage gradient across the series combination of the two insulation system is not determined, the worker is considered to be at a floating potential somewhere between the live parts and ground. The dielectric strength of the secondary insulating medium determines the voltage level of worker. It is recommended that the insulating value be equal to or exceed the principal insulation requirements.

The secondary insulating medium may be any of the following:

a) Insulating aerial device
b) Bucket liners
c) Insulating platforms
d) Insulating ladders

Example: A worker is working on a 15 kV three-phase line using rubber gloves, sleeves, and cover-up material from an insulating aerial device. The insulating aerial device, rubber gloves, sleeves, and cover-up should be designed, rated, and tested for the voltage across which they are applied.

Example: A worker is working on a 121 kV line-to-line using hot sticks from an insulating aerial device. The clear live tool insulation distance should be equal to or greater than the MAD for Tools in the air gap distance for the line voltage being worked on. The aerial device shall also be rated for 121 kV use.

4.10.5 Composite insulation

Composite insulation systems that use more than one dielectric medium in series to meet the required dielectric strength should not be used unless the series combination has been predetermined to be adequate.

Example: Double gloving with class 1 and class 2 gloves does not make a class 3 glove. The rating would be the higher of the two gloves; in this case, it is a class 2.

Example: Using two class 2 rubber blankets does not make a class 3 blanket. The rating in this case is still class 2.

When air gaps are in series, the resultant dielectric strength can exceed that of the tool or equipment itself, but it cannot be determined from direct addition of the material thickness and air gap sizes.

4.10.6 Principal insulation system used to put workers onto live parts

In this case, the worker normally moves to the end or is located at the end of the device before making contact with the live parts. The device should have a clear live tool insulation distance equal to or greater than the line-to-ground MAD for Tools in the air gap distance for the line voltage being worked on. The worker is considered at floating potential, which is somewhere between ground and the line-to-ground voltage. In positioning the worker, the use of the line-to-line MAD for Tools in the air gap distance for the line voltage being worked on may be required when the worker is exposed to other phases.

Examples:

a) Aerial work devices (bucket trucks)

b) Structure-mounted ladders or platforms, which are moved to place the worker on the live parts

4.10.7 Principal insulation system used to allow workers to move between ground and live parts

In this case, the worker moves between ground potential and the live parts on an insulating platform or ladder. The device should have a clear live tool insulation distance equal to or greater than the line-to-ground MAD for Tools in the air gap distance for the line voltage being worked on with an additional allowance for the area taken up by the worker. The worker is considered at floating potential, which is somewhere between ground and the line-to-ground voltage. The consideration of the line-to-line MAD for Tools in the air gap distance for the line voltage being worked on is required when the worker is exposed to other phase conductors.

4.10.8 Workers at floating potential

When the worker and support equipment are at a floating potential, the line-to-ground and line-to-line MAD for Tools in the air gap distance for the line voltage being worked on from either the live parts or items at ground potential should be maintained.

4.10.9 Workers at live potential (barehand)

The geometry of the live parts changes due to the physical dimensions of the worker and the worker's support devices when a worker is placed on a conductor at live potential. The line-to-ground MAD for Tools in the air gap distance for the line voltage being worked on should be maintained from the worker and the worker's support equipment to the closest item at ground potential. When exposed to other phases, the line-to-line MAD for Tools in the air gap distance for the line voltage being worked on should be maintained from the worker and the worker's support equipment to the closest phase.

Examples:

a) Working from aerial lift devices or platform

b) Working from insulating ladders

c) Working from the conductors

d) Working from helicopter platforms

4.10.10 Insulating barriers

Insulating barriers that are designed and tested to restrict the worker's movement may be used to allow work within the MAD as long as the insulating barrier places the worker at or beyond the MAID.

Example: A worker is performing work on the de-energized side of a 25 kV line-to-line line disconnect switch with the other side energized. An insulating barrier that restricts the worker to the de-energized side of the switch can be installed using live working methods.

4.10.11 Grounded barriers

Grounded barriers that are designed to restrict the worker's movement may be used to allow work within the MAD as long as the grounded barrier places the worker at or beyond the MAD.

Example: A worker is inside of the envelope of the grounded structural members of a tower and can perform work and pass through the area that does not meet the line-to-ground MAD in the air-gap distance,

Example: A worker is climbing a structure with the climbing space positioned so that it restricts the worker to an area that does meet the line-to-ground MAD in the air-gap distance.

4.10.12 Shields

Shields on live working tools (or on other tools) are used during energized-line work to shield the worker from the effects of an electric arc such as the thermal (heat) effects and the fragmentation and pressure-wave blast effects.

5. Tools and equipment

This clause covers the basic insulating tools and equipment used in live work. See Clause 8 for personal protective items such as conductive clothing, flame-resistant clothing, etc.

References or specific guidance concerning the specialized tools and equipment needed for live work are provided. These tools and devices are produced in accordance with certain standards, requirements, or performance factors, including the essential elements of laboratory electrical testing for design, certification, and acceptance testing. Other applicable test methods may also be utilized, but comparison of data between different test procedures may not be practical because of the variations in test conditions.

5.1 Categories of insulating tools and equipment

The insulating tools and equipment used for working on or near energized electric lines or power apparatus can be divided into the categories described in 5.1.1 through 5.1.5.

5.1.1 Principal insulation

5.1.1.1 Personal equipment—rubber gloves and sleeves

The electric stresses are applied essentially across the thickness of the equipment replacing the air gap insulation. The dielectric strength of the equipment depends on the material, its thickness, and its condition. Such equipment is often made of natural rubber and rubber-like materials and may be flexible or rigid.

The following standards should be referenced for further information on these items. Latest revision should be used.

a) Gloves – ASTM D 120 and IEC 60903
b) Sleeves – ASTM D 1051 and IEC 60984
c) Protectors for rubber gloves – ASTM F 696

5.1.1.2 Insulating tools

The electrical stress is applied essentially along the length of the tool or equipment within the air gap insulation. The dielectric strength is defined as the voltage per-unit length (kilovolt/foot or kilovolt/meter) of the insulating part of the tool or equipment. Examples are suspended or supported aerial devices, ladders, platforms, poles, and booms. Such tools and equipment are typically made of solid or hollow insulating materials in single or multiple pieces and sections. The original live working tools were made of wood. In the late 1950s, most of the tool manufacturers switched from wood to fiberglass-reinforced plastic (FRP) materials that have a high dielectric strength and do not absorb moisture as easily. Some of the wood tools are still in use and meet the dielectric testing requirements.

The following standards should be referenced for further information on these items. Latest revision should be used.

a) Aerial devices – ANSI/SIA A92.2 and IEC 61057
b) Live working tools
    1) Poles – ASTM F 711, IEC 60855, and IEC 61235
    2) Saddles and pole clamps – IEC 61236

5.1.2 Supplemental insulation

5.1.2.1 Cover-up

Cover-up that is rated and tested for the voltage at which the work is being performed may be used to replace the air-gap insulation between the worker and the energized parts.

The following standards should be referenced for further information on these items. The latest revision should be used.

a) Flexible insulating materials
    1) Blankets – ASTM D 1048, IEC 61111, and IEC 61112
    2) Line hoses and line hoods – ASTM D 1050
    3) Hand cover-ups – ASTM D 1049

b) Rigid insulating materials, e.g., line guards, line couplers, cross arm guards, pole covers, cutout covers – ASTM F 968 and IEC 61229

5.1.3 Barriers and shields

Barriers and shields are considered as special tools designed to protect workers during energized-line work.

5.1.3.1 Barriers

Barriers are used to maintain MAID between the worker and the energized part or between the worker and ground. They can be used on lines or equipment at any voltage provided proper MAID is observed. Barriers are not relied on for electrical insulation, but act only as physical barriers.

5.1.3.2 Shields

Shields on live work tools are used during energized-line work to shield the worker from an electric arc such as the thermal (heat) effects and the fragmentation and pressure-wave blast effects. The shield is made from a transparent, nonconducting material. Such shields should not be relied on for electrical insulation, but should be used only for protection of workers exposed to electric arcs. Their attachments and performance during use must withstand the fault (electric arc) characteristics. Shields on live work tools can be tested per ASTM F 2522-05.

5.1.4 Other supplemental insulation

The electrical stress is applied essentially along the length of the tool, rope, or equipment within the air gap insulation. The dielectric strength is defined as the voltage per-unit length (kilovolt/foot or kilovolt/meter) of the insulating part of the tool, rope, or equipment.

The following standard should be referenced for further information on insulating rope: ASTM F 1701. The latest revision should be used.

5.1.5 Helicopters

Helicopters used in live work should be equipped for live work and meet the required aviation rules in effect in the area of work.

In addition, in the United States, the Federal Aviation Administration (FAA) regulations apply.

5.2 Equipment rating

5.2.1 Electrical

The methods described in 5.2.1.1 through 5.2.1.5 are used to determine the voltages on which the tools and equipment can be used. Unless otherwise stated, the voltage is the line-to-line voltage.

5.2.1.1 Flexible insulating gloves and sleeves

The standards have assigned classes for the maximum voltage on which flexible insulating gloves and sleeves can be used. Classes start at 00 and include 0, 1, 2, 3, and 4. Double gloving does not increase insulating class above the highest class used. For an example, class 3 gloves over class 1 gloves are rated as class 3. Double insulation can result in damage to the insulation from corona in the air space between the insulation layers.

5.2.1.2 Flexible insulating cover-up materials and blankets

The standards have assigned classes for the maximum voltage on which flexible insulating cover-up materials and blankets can be used. Classes start at 00 and include 0, 1, 2, 3, and 4. Double layers do not increase insulating class above the highest class used.

5.2.1.3 Rigid insulating cover-up

The standards have assigned classes for the maximum voltage on which rigid insulating cover-up can be used. Classes start at 0 and include 1, 2, 3, 4, 5, and 6. Double layers do not increase insulating class above the highest class used.

5.2.1.4 Handheld live working tools

The clear live tool insulation distance is measured longitudinally along the insulated part of the tool from live parts to a location where the worker’s hand or body is in contact with the tool, whichever is shorter.

The clear live tool insulation distance must be equal to or exceed the MAD for Tools in the gap distance determine from *T* for the line voltage being worked on.

5.2.1.5 Load-bearing live working tools

Live working tools are load-bearing when used in a fixed location and not subject to any inadvertent movement. Examples include link sticks, strain poles, conductor support sticks, booms, ladders, platforms, aerial work devices, and rope.

The MTID, also known as the clear live tool insulation distance without inadvertent movement, is measured longitudinally along the insulated part of the load-bearing tool from live parts to the attachment point at the ground end.

The clear live tool insulation distance must be equal to or exceed the MTID in the gap distance determined from *T* for the line voltage being worked on. If the live working tool is used as a support tool, the clear live tool insulation distance is equal to or greater than the line-to-ground MAID for tools in the air gap or the length of the insulator assembles. Examples include link sticks and strain poles.

5.2.2 Mechanical

Equipment that does not have a load rating is described in 5.2.2.1 through 5.2.2.5.

5.2.2.1 Insulating gloves and sleeves

Rubber gloves and sleeves do not have a mechanical load rating. They should not be compressed with any forces greater than normal hand pressure.

5.2.2.2 Insulating cover-up materials and blankets

Insulating cover-up materials and blankets do not have a mechanical load rating. This equipment is designed for brush type contact and not to support load in compression or tension.

5.2.2.3 Rigid insulating cover-ups

Rigid insulating cover-ups do not have a mechanical load rating. This equipment is designed for brush type contact and not to support load in compression or tension.

5.2.2.4 Handheld live working tools

For handheld live working tools, the loads in tension, compressing, and bending should not exceed the force applied by the worker's hands.

5.2.2.5 Load-bearing live working tools

The mechanical load capacity should be obtained from the manufacturer and marked on the tool or otherwise documented for reference, e.g., in the manufacturer's user manual. The load capacity should state whether the tool is designed for tension, compressing, and bending loads. Testing of tools is recommended to verify their load-carrying capacity.

5.3 Electrical current flows

Electric current flowing between the live parts and ground associated with personal protective, cover-up, support, lift, or reach-extending tools and equipment is the vector sum of the following currents:

a) Capacitive current due to the insulating material of the equipment. Capacitive current is the component of the measured current that leads the applied voltage by 90° due to the capacitance of the tool or equipment.

b) Conduction current flowing through the volume of the equipment. Conduction current is the component of the measured current in phase with the applied voltage that is delivered to the volume of the tool or equipment due to the electrical resistance of the material of the tool or equipment.

c) Leakage current along the surface of the equipment. Surface contamination and condition may significantly increase the leakage current when wet. Leakage current is the component of the measured current that flows along the surface of the tool or equipment due to the properties of the tool or equipment surface, including any surface deposits, and is composed of reactive and resistive components.

5.3.1 For ac excitation

The conduction current consists of the capacitive current and the leakage current. For clean, dry tools and equipment in good condition, the leakage current is small, and the capacitive current predominates. Surface deposits can significantly increase the leakage current.

5.3.2 For dc excitation

The capacitive current does not exist. For clean, dry tools and equipment, the leakage current is small. Surface deposits can significantly increase the leakage current. The conduction current is normally negligible.

5.4 Tool and equipment testing

The fundamental reason for testing insulating tools and other equipment used in live working is to verify tool safety.

5.4.1 Design, certification, and production tests

All of the tools and equipment being produced for use on live work should conform to a standard such as the standards published by ASTM, IEC, ANSI, or IEEE. The latest edition of a standard should always be used.

5.4.1.1 Electrical design and certification tests

The purpose of the electrical design and certification tests is to show that the tools or equipment has the electrical strength to withstand the maximum electrical stress in the work location. These tests will show that the tools or equipment being tested can withstand the maximum anticipated TOV.

The appropriate standard will specify the electrical design and certification testing to be done. The tests are normally done on a complete unit, which is considered as the prototype.

5.4.1.2 Mechanical design and certification tests

The appropriate standard will specify the mechanical design and certification testing to be performed. The tests are normally done on a complete unit, which is considered as the prototype. Tools that carry heavy loads such as strain poles and link sticks are tested for safety to establish a rating for the acceptable working loads.

5.4.1.3 Electrical production tests

Unless required by the purchaser’s procurement specifications or standards, most tools and equipment are not electrically tested after their final assemblies. Most of the manufacturers do electrically test the insulating components at the time of the component production.

5.4.1.4 Mechanical production tests

Unless required by the purchaser's procurement specifications or standards, most tools and equipment are not mechanically tested after their final assembly.

5.4.2 User acceptance testing

Since the handling of tools and equipment during shipping cannot be controlled by the manufacturer or the user, testing to determine the electrical and mechanical integrity of tools and equipment is recommended. The appropriate standard for the tool or equipment should be used to determine the acceptance testing requirements.

Tools and equipment such as rubber gloves, sleeves, and blankets should be electrically tested before they are placed in service by the user.

5.4.3 Periodic laboratory testing

Periodic laboratory testing of all insulating tools and equipment is recommended to ensure their electrical and mechanical integrity. See 5.6.

5.4.3.1 Electrical

Electrical testing of the following tools and equipment is recommended:

a) Flexible insulating cover-up

   There are several commercially available test sets that can be used for the periodic laboratory testing of rubber goods. These testers are designed to test rubber goods according to industry standards. Their use is recommended.

b) FRP poles, booms, and other live working tools

   Electrical testing of FRP poles, booms, and other live working tools is further described in 5.5.

5.4.3.2 Mechanical

It is recommended that FRP poles, booms, and other live working tools that support loads be mechanically tested to verify their load-carrying capacity. The test should not be limited to the FRP pole or fiberglass boom, but include the entire assembly. Test loading should not exceed the rating or capacity of the equipment or tool.

Aerial lift devices with insulating booms are mechanically tested with load in the buckets or on the platforms. See ANSI/SIA A92.2 for further details.

There are no existing standards for user mechanical testing of conductor support equipment, such as strain poles and link sticks, which are used in a tension configuration.

To mechanically test the attachment hardware and the insulating part of the equipment, some users place the strain poles and lift sticks in a tensioning assemble to determine whether the elastic limits of the assembly has been exceeded. Measuring points are established, and readings are taken and recorded at 30% and 100% load. An acceptable tool should return to its 30% reading when the load is reduced from 100%.

The readings are recorded for reference on future tests. Test loading should not exceed the rating or capacity of the equipment or tools.

5.4.4 Periodic in-service or field testing

5.4.4.1 Electrical

Electrical testing in the field is limited due to the lack of laboratory equipment.

Portable testers designed for use in the field are commercially available to test the FRP tools. These testers check a small section of the FRP pole, and multiple tests should be made to cover the entire length of the tool.

Some equipment such as aerial work devices and ladders can be equipped with leakage meters to monitor the leakage current. See ASTM F 1236.

5.4.4.2 Mechanical

Periodic in-service mechanical testing is not normally done in the field since laboratory equipment is required for the work

5.5 Testing of FRP live work tools

5.5.1 Introduction

The standards listed in 5.1 provide the basic and essential elements of electrical data and values that are applicable. These standards should be considered in the employment of tools, materials, and equipment in energized operations, and a series of tests should be performed (e.g., design, withstand, and proof voltage). It is recommended that the tests be conducted with applied voltage of the same characteristics as that on which the equipment is being used. For example, if the equipment is being used on 60 Hz, the withstand test should be made with 60 Hz ac. Testing with dc may be done at the discretion of the user.

5.5.2 Tool or equipment current

The preferred criterion is the measurement of tool or equipment current since this is the primary concern related to the use of the sample. Tool or equipment current measurement provides a numerical objective evaluation of the sample quality.

One way to determine the condition of the tools or equipment is to measure the leakage current during testing. In general, the criteria for maximum permissible leakage current as first applied to the insulating aerial lifts and later to tools is 1 $\mu A/kV_{L\text{-}G}$. Therefore, if the applied voltage is 200 kV, the leakage current should not exceed 200 μA.

For insulated tools with small diameters, when tested over 1 ft segments, the leakage current could be much smaller and in the range of 0.05 to 0.25 $\mu A/kV_{L\text{-}G}$ depending on the grading of the electrodes.

The range of leakage normal current for clean, dry insulating tools for one particular test method has been found to vary from 6 to 15 μA depending upon the tool diameter at an applied voltage of 100 kV across

0.3 m (see Figure 7). Current values exceeding these acceptance values may indicate deterioration of insulating qualities. Changes in measured tool or equipment current values may be indications of any or all of the following factors:

a) Contamination
b) Moisture
c) Specimen degradation
d) Instability of the test setup

If the test equipment is not at fault, the tool should be cleaned, dried, refinished as recommended by the manufacturer, and electrically retested. If it is not possible to retest the tool, then the tool should not be used.

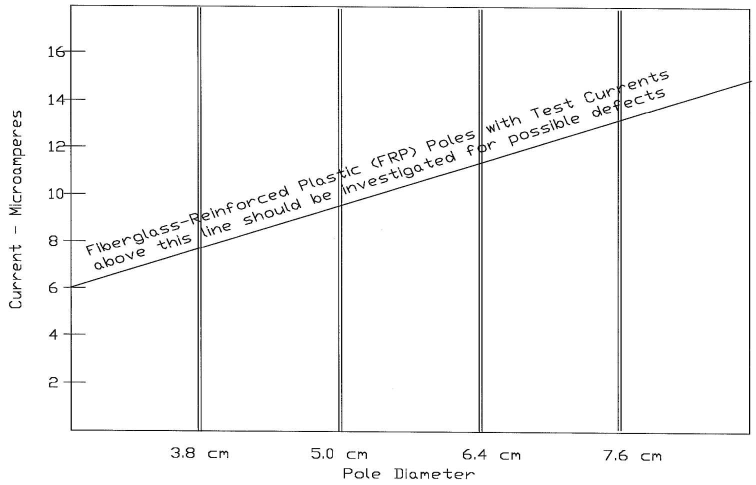


Figure 7—Typical accept/reject values of equipment current for FRP pole of various diameters using 60 Hz, 100 kV per 0.3048 m (1 ft), with the voltage applied between two electrodes in contact with the surface of the pole

5.5.3 Maximum operating voltage

The maximum power frequency operating voltage (V_M) is the voltage to which the tools and equipment could be subjected during routine employment in work operations. For example, for 345 kV systems, the maximum power frequency operating voltage (V_M) is 362 kV. In cases where the bus voltage is unregulated, the user should recognize the possible voltage transformation ratio as well as the maximum voltage that can appear under normal situations from the source line, which can then be reflected through the transformer.

5.5.4 Evaluation of tools and equipment

Tools and equipment should be evaluated using the applicable standard(s), as follows:

a) ASTM F 712 for electrically insulating plastic guard equipment
b) ASTM F 1236 for visual inspection of electrical protective rubber products

c) IEC 60060-1 for high-voltage test techniques (general definitions and test requirements)
d) IEC 60060-2 for high-voltage test techniques (measuring systems)
e) IEC 60060-3 for high-voltage test techniques (measuring devices)
f) IEC 60060-4 for high-voltage test techniques (application guide for measuring devices)
g) IEC 60855 for insulating foam-filled tubes and solid rods
h) IEC 60903 for gloves and mitts of insulating material
i) IEC 60984 for sleeves of insulating material
j) IEC 61057 for aerial devices with insulating boom
k) IEC 61229 for rigid protective covers
l) IEC 61235 for insulating hollow tubes
m) IEC 61236 for saddles, pole clamps (stick clamps) and accessories
n) ANSI/SIA A92.2 for vehicle-mounted elevating and rotating aerial devices

The previously listed documents do not discuss equivalence of withstand voltages for the tools and equipment under ac and impulse voltage stresses. Ongoing research has indicated support for the use of the ratio of 1.3 for testing flexible insulating equipment. For rigid insulating covers, the ratio appears to be affected by the geometrical details of test electrodes used in testing. Research is ongoing to obtain precise values of the ratios. Based on tests for line guards, the 1.3 ratio applies to equipment such as blankets and line hoses. The ratio of withstand voltage (peak) under impulse conditions to the withstand voltage (peak) with ac energization is not equal to 1.0.

IEC 61472 [B21] does not provide a value for the ratio of impulse-to-power-frequency (peak) withstand voltage.

5.6 Typical tests for insulating tools

The fundamental reason for testing insulating tools and other equipment used in live working is to verify tool safety. Basically there are three categories of tests:

a) Design and certification tests. The purpose of design and certification tests is to show that the tools or equipment has the electrical strength to withstand the maximum electrical stress in a work location. These tests must show that the tools or equipment being tested can withstand the maximum anticipated TOV.
b) Periodic tests, referred to as proof test, double rated test, or in-service tests. The purpose of the proof test, double rated test, or in-service test is to demonstrate the safety of the insulating tools or equipment for work and to check for indications of deterioration. These are periodic tests. The test voltage is higher than the maximum use voltage but lower than the certification test voltage. Usually the test voltage is twice the maximum use or rated voltage (L-G) on which the tools or equipment is used.
c) Before-work tests. The purpose of the before-work test is to demonstrate the safety of the insulating tools or equipment for work. The test voltage is usually the phase-to-ground voltage of the system on which the tools or equipment is to be used.

Test requirements and testing methods for specific insulated tools and equipment are provided in standards published by, for example, ASTM and IEC (see Clause 2).

5.7 Worksite procedures

5.7.1 Field care, handling, and storage

When not in use, insulating tools should be stored where they will remain dry and clean and they are not subjected to abuse and excessive ultraviolet light. Wood insulating tools should be stored in a temperature-controlled environment, such as a control room, and should be adequately supported or hung vertically to prevent warping. Insulating tools used for energized-line maintenance should not be laid on the ground because of possible contamination or wetting. They should be placed on clean, dry tarpaulins; on moisture proof blankets; or in tool racks. They may also be leaned against dry supports. When transporting insulating tools, ventilated containers should be provided to prevent damage to the surfaces of the individual tools, or the tools should be mounted on racks in trucks or trailers. These racks should be well padded and constructed so that the tools are held firmly in place to prevent abrasive or bumping action against any surface that would damage the glossy surface of the tools.

5.7.2 Before-work inspection and checking

Insulating tools should be visually inspected before use for indications that they may have been mechanically or electrically overstressed. Tools that show evidence of overstress (such as damaged, bent, worn, or cracked components) should be removed from service and evaluated for repair. Elongated or deformed rivet ends, for instance, indicate that excessive mechanical loading has occurred and has weakened or sheared the bond between the ferrules and the insulating pole. Any moisture penetration reduces the insulating properties of these tools.

The surface of each tool should be inspected before and after each use for contamination such as dirt, creosote, grease, or any other foreign material. If any of the above contaminants exist, the tool surface should be cleaned.

When the insulating member of a tool shows signs of accumulated contamination, surface blisters (delamination), excessive abrasion, nicks, or deep scratches, the tool should be removed from service, cleaned or refinished as recommended by the manufacturer, and retested. If it is not possible to retest the tool, then it should not be used.

When tools have been exposed to excess moisture, their moisture content can be measured with a moisture meter, which is commercially available, or their general condition can be determined on the basis of ac power loss measurements (see 5.7.5).

5.7.3 Cleaning

Before each use, wipe insulating tools with a clean, absorbent paper towel or cloth. This may be followed by wiping with a silicone-treated cloth.

If simple wiping does not remove the contaminant, then apply a solvent or cleaner recommended by the manufacturer of the insulating tool with a clean, absorbent paper towel or cloth and wipe with a silicone-treated cloth, if available.

5.7.4 Field test equipment

5.7.4.1 Portable live tool tester

Portable live tool testers provide a means for conveniently field-testing insulated tools without auxiliary equipment except for a power supply. It is very important to note that some portable units are designed to test the entire insulated tool's cross-sectional areas for conductivity. To be certain of the tester's capability, the user should check the applicable literature or contact the equipment manufacturer.

Reliance on electrical testing is the prerogative of the user who is responsible for maintaining equipment calibration, application, and interpretation and responsible for the safety of the user.

5.7.5 Use of moisture or dielectric property determination meters

Moisture meters are portable devices that can be used for worksite inspection of insulated tools for indications of excessive moisture or tracking. One model employs a radio frequency (RF) power loss circuit at 10 MHz. By way of roller electrodes, this meter applies an RF field through the sample and measures the power loss as affected by moisture. The meter scale can be set arbitrarily at either of two levels of intensity.

Another dielectric meter employs a measurement of the real part of an RF field transmitted through part of the cross section of the tool. The real part of the transmitted field is related to conductive faults caused by moisture, carbon tracking, or conductive elements in the sample. The response of this meter is adjustable according to the sample diameter and wall thickness. An internal standard is used to set the instrument response to the prescribed level for each tool configuration to be measured.

When using either meter, measurements should be made at several points along the circumference of the insulating tool even for small-diameter tools.

CAUTION

Reliance on moisture and dielectric property determination meter readings should be the prerogative of the user who is responsible for maintaining equipment calibration, application, and interpretation and responsible for the safety of the user.

5.8 Shop or laboratory procedures

All testing should be performed using methods and criteria set forth in the appropriate standards. The following testing standards cover most of the laboratory testing:

a) IEC 60060-1 for high-voltage test techniques (general definitions and test requirements)
b) IEC 60060-2 for high-voltage test techniques (measurement systems)
c) IEC 60060-3 for high-voltage test techniques (measurement system)
d) IEC 60060-4 for high-voltage test techniques (application guide for measuring devices)
e) IEEE Std 62 for oil-filled power transformers, regulators, and reactors

5.8.1 Periodic inspection and testing

5.8.1.1 When to perform shop or laboratory testing

Insulating tools should be shop maintained and tested at an interval dependent on their exposure, manner of use, care they receive, individual company policy, and field inspections. Wood tools should be checked more frequently during periods of high humidity or after exposure to moisture.

The following field observations, if present, should warrant the removal of tools from service and their return to the laboratory or shop for repair and electrical testing:

a) A tingling or fuzzy sensation when the tool is in contact with energized conductor or hardware
b) Failure to pass the electric test or the moisture meter test (see 5.7.5)
c) Deep cuts, scratches, nicks, gouges, dents, or delamination in the stick surface
d) A mechanically overstressed tool showing evidence of damaged, bent, worn, or cracked components
e) A loss or deterioration of the glossy surface
f) A pole inadvertently cleaned with a soap solution (see 5.8.2)
g) Improper storage or improper exposure to weather
h) An electrically overstressed tool showing evidence of electrical tracking, burn marks, or blisters (delamination) caused from heat

5.8.1.2 Inspection procedure

Tools should be carefully inspected and/or tested before returning them to service. Elongated or deformed rivet ends indicate that excessive mechanical loading has occurred and has weakened or sheared the bond between the ferrules and the insulating pole.

Hardware bolts and pins should be replaced only with high-strength material, the same as the original part. Nondestructive testing (e.g., magnetic particle inspection, dye penetrant inspection, ultrasound, and X-ray) should be performed on the mechanical end fittings after a tool has been subject to possible overstressing or vibrating loads for any extended period of time.

5.8.2 Cleaning, waxing, refinishing, and repair

5.8.2.1 Fiberglass-reinforced plastic (FRP) tools

FRP tools should be cleaned and waxed or refinished in accordance with the tool manufacturer's recommendations.

5.8.2.2 FRP tools cleaning and waxing

Waxing is not necessary after every use of the tools, but rather as needed to maintain a glossy surface that may cause any moisture or water to bead on the surface. Before a tool is rewaxed, the pole should always be cleaned with a solvent or cleaner recommended by the tool's manufacturer to avoid a wax build-up. Waxing not only imparts a glossy finish to the surface of the fiberglass, but also adds to the electrical integrity of the tool by providing a protective barrier against dirt, creosote, and other contaminants and against moisture.

5.8.2.3 FRP tools repair or refinishing

In view of various available repair or refinishing processes, the decision is left to the user about the adequacy of the repair process and the quality of workmanship.

Only competent personnel should repair or refinish FRP insulating tools. Light spots are caused by impact blows and may have a noticeable effect on the mechanical strength or electrical properties of the tool. Numerous light spots may show excessive abuse and, coupled with surface contamination, may lower the sparkover voltage or contribute to insulation degradation. If there is no roughness on the surface, there is no need for repair. Small surface ruptures can be seen with the naked eye and should be repaired by competent personnel by removing the damaged fibers and cleaning the void following the manufacturer's recommended procedure for repair.

If there is any indication that the outer layer of material has separated and leaves a void beneath the surface, the tools should be removed from service and refinished as recommended by the manufacturer. Such voids can accumulate moisture or, under electrical stress, become ionized and lead to degradation in the organic materials. The resulting conductive deposits act as an extension of the electrode and cause further progressive degradation.

All repairs and refinishing should be followed by a high-potential dielectric leakage (see 5.7.4 and 5.7.5) or ac power loss test. An insulating tool should not be used unless it is tested.

5.8.2.4 Wood tools

Although the surface of the tool may appear to be perfectly dry and the finish in excellent condition, the wood may have absorbed excessive moisture from the air if the tool has been exposed to high humidity conditions. Therefore, extra precautions should be taken during wet seasons of the year. Treatment in a drying cabinet is recommended if high leakage currents are encountered. In these cases, tools should be dried at 32 °C (90 °F) for approximately 48 h in a 31.6% to 38% relative humidity controlled and ventilated area to provide air circulation and subsequently subjected to a high-potential leakage or ac power loss test. Prompt touch-up is recommended where the finish is worn or damaged to prevent dirt or moisture from entering and becoming absorbed by the wood fibers where it might form dangerous conductive paths.

When general refinishing is required, wood tools should be thoroughly dried to 6% or 7% moisture content. After the old varnish and foreign material have been removed, the surface should be rendered smooth with flint paper and finished with two or three coats of varnish. Finishing includes sanding lightly between coats. Damage to the finish should be repaired according to the manufacturer's recommendations.

Repairs and refinishing should be performed by competent personnel and followed by a high-potential leakage or ac dielectric loss test. Replacement of wood tools with FRP tools is recommended. A tool should not be used unless it is tested.

5.8.3 High-potential ac test method

The entire length of the tool should be divided into test segments for testing. In some cases, the test segments may overlap. One test segment should include the area adjacent to the metal fittings with one electrode making contact to the end fitting. The test contacts may be two helical springs (see Figure 8).

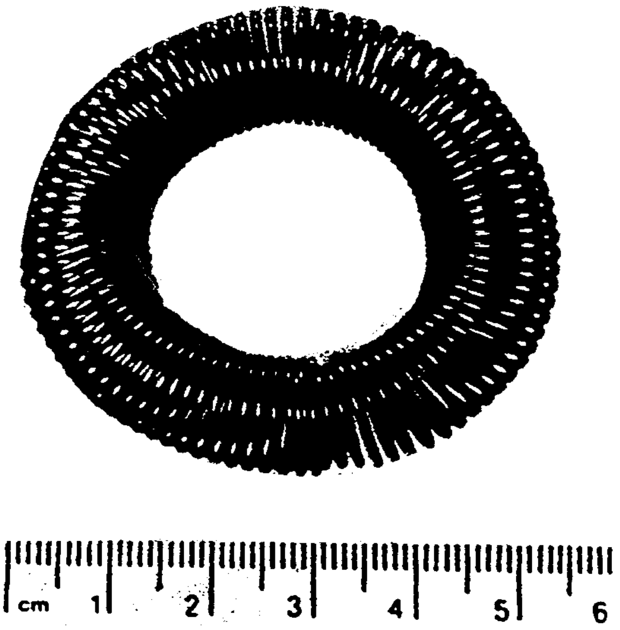


Figure 8—Helical spring electrode for in-service electrical testing of FRP tools (see 5.8.6 for the electrode specification)

The test instructions are as follows:

a) Suspend or support the tool in a horizontal position, using insulating material, approximately 1.2 m above the floor.

b) Orient the tool to the transformer to give the minimum leakage current at a fixed voltage. Maintain this reference location for all subsequent tests.

c) Wrap the spring electrodes around the tool. Spring contact should be maintained around the entire circumference of the tool.

d) Attach the test leads to the springs so that sharp edges extend inside the coiled area of the spring. The power lead of the test set should be routed directly to the nearest electrode. Coil excess lead in the center of the lead maintaining 0.60 m ground distance. Metal conductor spark plug wire may be used for the power lead. Use shielded cable for the ground lead. Attach the inner conductor of the shielded cable to the ground spring and to the ground return meter of the test set. Float the shield on the spring end, and attach the shield to the ground lug on the test set.

e) For fiberglass poles only, spray the test segment with distilled water to thoroughly wet its surface. A clean spray applicator adjusted to a fine mist is suitable for this purpose. Spray water uniformly on the pole until droplets just begin to drip from the bottom surface. Apply potential to the test segment immediately after wetting.

f) For wood poles, inspect them for dryness as they should be dry when tested.

g) Increase the voltage gradually at a rate of 3 kV/s to 75 kV across 30 cm for fiberglass and 50 kV across 30 cm for wood. Maintain this voltage for 1 min minimum. Read the maximum leakage current in the ground return meter.

If the current continues to rise after full voltage is reached, the test should be discontinued, and the pole should be cleaned or refinished and then retested. If the condition is not corrected, the pole should be removed from service.

5.8.4 Current measurements

Current measurement provides an objective evaluation of the specimen's insulating tool quality.

Typical current (leakage) values on new FRP poles using guarded electrodes and tested at 100 kV across 30 cm may be in the range of 5 to 25 μA depending on the diameter of the pole and other factors.

See ASTM F 711, 5.5.2, and Figure 6. This range of values can vary from laboratory to laboratory or from test to test within a given laboratory; therefore, historical data should be established by performing tests exactly the same way from day to day. The electrode's shapes, spacing, pole orientations, lead wires, instruments, etc., should not be varied.

If nonguarded electrodes are used, the current values may be appreciably higher by a factor of 10, 15, or more, depending on the voltage.

Sample current readings should be made when the specimen has clean, uncontaminated surfaces to establish historical data. These data should be used to establish a benchmark range for making a comparison between the in-service tool tested and the acceptance levels established for that particular diameter of pole and specific electrode configuration.

Changes in current may be cause for rejection. Significant changes in current values during a test are indications of any or all of the following conditions: contamination, moisture, specimen degradation, or instability of the test setup. If the test setup is not at fault, the tool should be cleaned, dried, refinished as recommended by the manufacturer, and retested.

If the current decreases when the voltage is maintained across the test specimen, it may be indicative of absorbed moisture drying out during the test. A reading that shows an increase may be indicative of incipient degradation of the specimen.

5.8.5 Wet and dry testing

Experience has shown that insulated tools with contaminated surfaces having failed electrically under humid, moist, or wet conditions may pass 100 kV across 30 cm after the tools have been dried.

It is the surface conditions of the tool that determine the performance under wet conditions. A glossy stick may allow water to bead on the surface whereas a dull surface may allow the water to spread in a sheeting action. Fairly dirty tools that retain surface gloss may show an increase in leakage current, but may sustain 100 kV across 30 cm with an acceptable leakage level. Conversely, fairly clean tools with a dull surface that has been wetted may fail at a low applied voltage. Tests on tools under wet conditions, therefore, verify whether the surface condition of the tool is satisfactory.

Only fiberglass tools should be tested under wet conditions.

5.8.6 Electrode design

Guarded electrodes are required to measure the high-potential leakage current through and along the surface of the test specimen.

Manufacturers use guarded electrodes in design testing of FRP poles without end fittings. See ASTM F 711.

When testing FRP poles with end fittings or operating rods, special electrodes should be designed to slide over the end fittings, or the electrodes should be a clam shell design.

Nonguarded electrodes are not recommended. However, if they are used, they should have a rounded edge contour to reduce the streamers that can occur before sparkover. Such streamers can cause ionic bombardment and cause electrons to rupture the chemical bonds of the stick material leading to degradation of the organic materials of the specimen being tested.

One type of contoured electrode used for in-service testing is a spring toroid that can be formed from 12.7 mm outside diameter (minimum) springs wound from 1.02 mm (18 gauge) stainless steel wire. These should be made with the inside diameter of the toroid slightly less than the pole diameters tested. Such springs are flexible enough to expand and roll over most end fittings. The 12.7 mm outside diameter of the spring gives a rounded contour to reduce the streamers (see Figure 8).

Another type of electrode system, which is less contoured than the one described above, is made using conductor straps or collars, which are easily wrapped around the specimen. Metal rings secured to the ends of the straps serve both to help hold the straps securely in place and as a point to attach the test electrodes.

The cables connecting the electrodes to the instruments should be shielded.

5.8.6.1 Electrode spacing

The spacing of electrodes is determined by the purpose of the test and the voltage chosen. For in-service testing of FRP materials, the voltage should be 75 kV across 30 cm of the pole. Wood poles should be tested at 50 kV across 30 cm spacing. Close spacing of electrodes allows inspection of more minute sections for quality control and thus avoids the averaging effects of wider electrode spacing. For example, 75 kV across 30 cm spacing or an equivalent potential difference such as 37.5 kV across 15 cm spacing has proved to be satisfactory. Testing may also be performed over a greater distance provided the applied voltage and distance are proportionally increased.

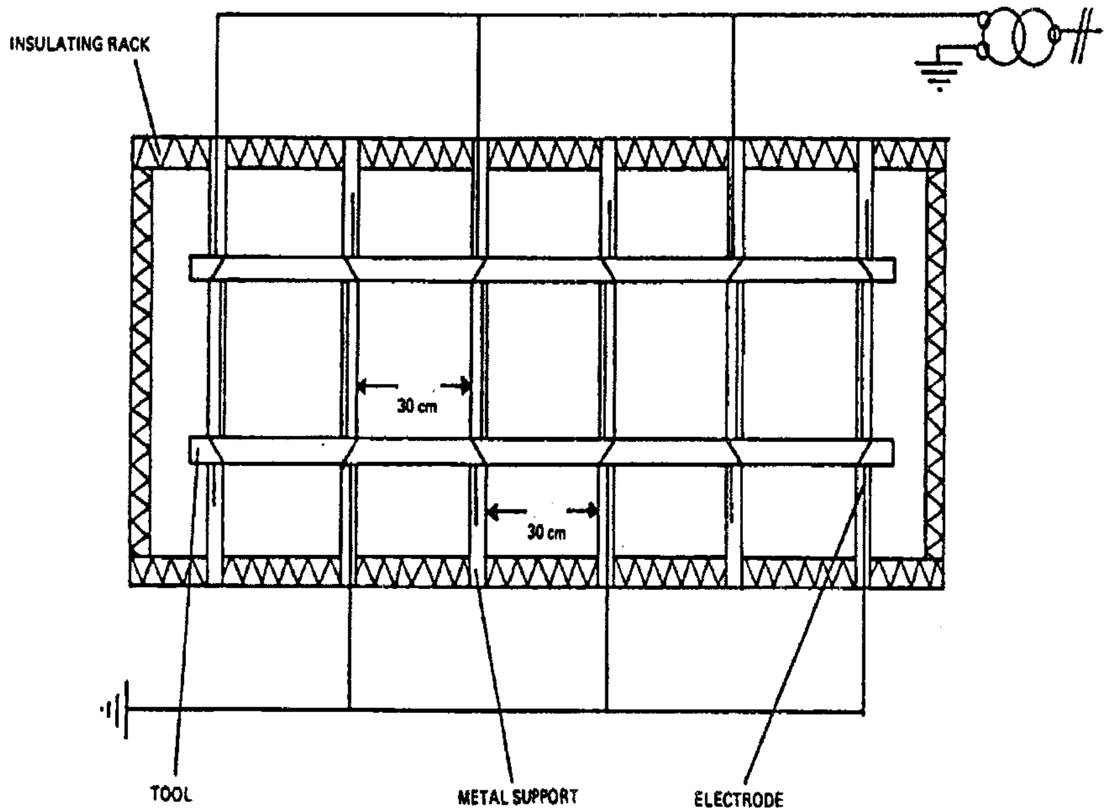
For larger or smaller distances, the relationship may be nonlinear.

Spacing distance of adjacent spring toroids should be measured between the centerlines of the springs.

5.8.6.2 Rack testing

Rack testing is the procedure of placing poles or tools on an insulating lattice structure where line and ground electrodes are attached alternately to the metal supports at a distance of 1 ft along the length of the tool.

This type of testing is intended primarily for high-volume acceptance testing of new poles in the manufacturing process (see Figure 9).



See Appendix B of IEC 60832 [B20].

Figure 9—Typical rack for testing FRP tools

The electrodes, which are impractical to shield, should be of a shape to minimize corona streamers. Typical electrodes are beaded chain, machined clamps, stranded wire, helical springs, or flat braid up to 6.35 cm wide.

Racks may also be used for in-service testing provided that certain disadvantages are recognized. For instance, assembled tools having metal end fittings, handles, or hooks might shorten some of the 30 cm spacing on the rack and thus not allow the voltage to be raised to the appropriate level without premature sparkover. Also it is inconvenient to monitor the current unless a meter is placed in each ground lead. Therefore, the rack is primarily used for testing new FRP poles where 100 kV is impressed across each 30 cm for 5 min and for observing any puncture, surface tracking, or heating (see 29 CFR 1926.951(d) [B40] and 29 CFR 1910.269(j)(1)(i)(3) [B39]). Since new poles have an inherent high gloss, only dry electrical testing is required.

5.8.7 Test voltage supply for high-potential testing

Either ac or dc may be used. Direct current testing is less sensitive to slight changes in the geometry of the test equipment. Also, dc equipment is much lighter, compact, and portable enough to perform insulated tool testing at many different locations. It is a good practice to test equipment to be used on ac lines with ac and equipment to be used on dc lines with dc.

The required test voltage for acceptance testing by users is that which will give a voltage gradient great enough for evaluation of material, but not so great that it leads to material degradation from corona or streamer discharges.

The power supply voltage parameters are dependent on factors such as electrode design and the distance over which the tests are conducted. The required test voltage capacity for in-service testing is that which will give an average voltage gradient of 75 kV across 30 cm of FRP specimen being tested or 50 kV across 30 cm of wood specimen being tested.

The 75 kV across 30 cm and 50 kV across 30 cm parameters are for in-service tests. New poles are tested by the manufacturer at 100 kV across 30 cm and 75 kV across 30 cm, respectively (see 29 CFR 1926.951(D) [B40]. The lower recommended test voltage for wood recognizes that wood tools are more susceptible to cumulative damage by repeated overvoltage tests than FRP tools. However, this lower test voltage does not compromise tool integrity or safety under proper use.

5.8.8 Orientation of equipment and test specimen

The high voltage should be applied to the end of the test specimen nearest to the power supply. The orientation of the high-voltage bus and test specimen should be such that nearby ground planes do not introduce significant capacitive effects.

To reduce the effects of stray currents on the specimen and on the meter indication, the specimen tested, especially on ac circuits, should be parallel to the high-voltage lead or bus, and the high-voltage connection (bus) should be kept as short as possible.

Other factors to be considered are the following:

a) Leads, bushings, and instruments should be shielded to minimize stray currents to any nearby ground planes.
b) Meters or other current-indicating devices should be incorporated to give quantitative data for material evaluation.
c) The power supply should have an adjustable interrupting device (circuit breaker) to protect against leakage currents significantly greater than the highest acceptance level for a given specimen and against damage to the power supply.
d) Interlocks and grounding features should be included for operator protection.

5.8.9 AC power loss (watts loss) test method

5.8.9.1 General

The power loss method is employed to determine the electrical condition of FRP and wood materials using the loss or dissipation of energy in the material compared to a reference based on a new or good condition value.

5.8.9.2 Test equipment

At a minimum, the test set should be capable of applying 2500 V; however, the preferred test voltage is 10 kV or greater. Provision for the measurement of power loss or the loss (leakage) component, $(I)(W)$, of the total specimen current is required. If desired, the average alternating voltage resistance of the specimen can be calculated as follows:

$$R = \frac{V_T}{I_W} \tag{81}$$

$$W = \frac{(V_T)(I_W)}{R} \tag{82}$$

where

R is in ohms
I_W is the watt current, in amperes
W is in watts
V_T is the test voltage, in volts

Measurement sensitivity should be sufficient to distinguish between 10^{10} (10 000M) Ω and 10^{11} (100 000M) Ω resistance.

Capacitance and power factor measurements are not recommended for routine tests of specimens having a capacitance of only a few pico farads. Accurate measurement of these quantities depends on complete specimen shielded systems, which are not feasible for routine tests.

A guard shield to avoid measurement errors should be incorporated in the test equipment, including connections to the specimen. Preferably, the test equipment should be able to make measurements using the ungrounded specimen test method with the guard shield at ground potential (see IEEE Std 62). The power loss test is relatively unaffected by extraneous objects located near the specimen.

Test electrodes are applied in the selected area. Each electrode may be a conducting strap or collar wrapped tightly around the specimen or clamped to it. A metal fitting attached to the specimen is sometimes used as an electrode. A common arrangement is three electrodes with a spacing of 7.5 cm (see Figure 10). The test voltage is applied to the center electrode, and the measurement is made between it and the two other electrodes.

With 10 kV applied across every 7.5 cm section, the 15 cm section under test may be stressed at 20 kV (or the equivalent of 40 kV/30 cm).

For long poles and other specimens of considerable length, measurements may be made at two or more locations along the length using the three electrode method described in Figure 10. An important test location is at both ends of the insulating tool, i.e., the end normally applied to the energized line and the end held by the worker. An alternative method is to use two electrodes separated by a considerable distance although this usually requires a high-voltage test to meet the test equipment sensitivity requirements specified in this clause. When making a two electrode measurement, use of the ungrounded specimen test method (where ground is guard) is recommended.

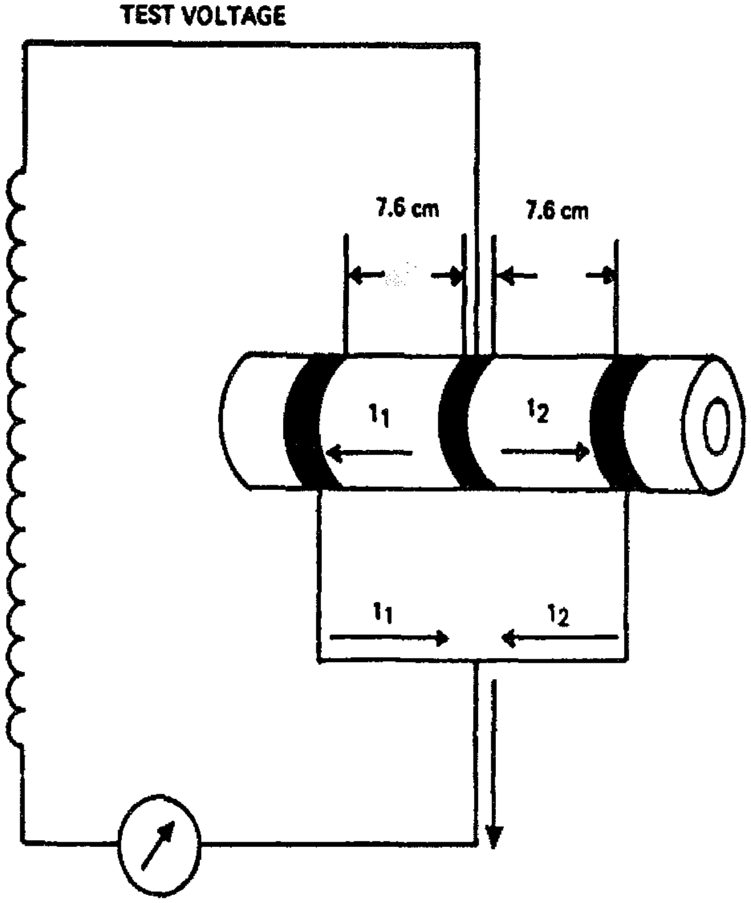


Figure 10—General circuit for power loss (watt loss) testing

5.8.9.3 Power loss (watts loss) method criteria

The criteria for acceptance of tools checked by the power–loss method should be based on power loss values formulated from historical data. Test criteria for specimens made of the same material and similar dimensions are usually determined from statistical analysis. Wood, FRP, and many composite-insulating materials, when clean and dry, have very low losses on the order of 0.01 W at 10 kV with the usual three-electrode test arrangement (ac resistance greater than 10^{10} Ω). When the loss exceeds 0.1 W at 10 kV (resistance of 10^{9} Ω), this usually indicates presence of moisture, dirt, or damage in the tool. Equivalent criteria in terms of leakage current can be derived, if desired.

5.8.9.4 Orientation

The orientation of the power loss equipment should be in accordance with the instructions of the test equipment manufacturer.

5.9 Insulating rope

Insulating rope suitable to be used in contact with live parts during live maintenance operation is produced according to ASTM F 1701 and ISO 2307.

5.9.1 General

Insulating ropes should be designed and manufactured to be used in accordance with live working methods and procedures and the instructions for use. There are several types of rope being used as insulated rope that are not manufactured specifically for that purpose. If they pass the electrical and mechanical testing requirements, they may be used as insulating rope.

5.9.2 Instructions for use and care

Each reel of rope or each smallest shipping length should be supplied with manufacturer's written information and instructions for use and care.

These information and instructions should include the following as a minimum:

a) A certificate of testing
b) Any special treatment of the fibers that makes them specially suitable for this application
c) Instructions for cleaning, storage, and transportation
d) Instructions for periodic testing, possible repair, and disposal of the rope

5.9.3 Water absorption

A rope sample should be conditioned by immersing it for 24 h in water at 20 °C. After 7 h of drying in a dry and airy place, the water content should be less than 2%.

5.9.4 Periodic test criteria

Periodic tests may be made to determine the condition of the equipment. The most important activity in this area is to visually inspect all tools and equipment before each use. A visual check by qualified personnel is the best practice because abuse or misuse since the date of the electrical test can radically change the electrical performance of the tool or equipment. Intervals between electrical tests may be established based on criteria such as elapsed time, voltage level, number of times used, condition of use, company user policy, or a combination of these. Even when equipment passes a periodic electrical test, the user should still visually inspect or otherwise check the equipment before use. For example, even though a rubber glove is given a periodic electrical test, there is no assurance that the glove has not been damaged in transportation from the test site to the worksite; therefore, a visual inspection should always be made before use to check for mechanical damage. Refer to ASTM F 1236 about visual inspection.

5.10 Histograms

Histograms of initial tool or equipment current values for acceptance of tools or equipment can be established from production or manufacturing limits. The basic purpose of these histograms is to indicate a trend and to establish reference points for each tool being tested. In the absence of historical information or another equivalent basis, the tool or equipment current values for FRP provided in Figure 6 are applicable.

Plotting of histograms on graph paper gives a good graphic review of the testing of the tool or equipment and shows trends in the performance of the material under test.

5.11 Electrical test references

The following references are recommended for electrical tests:

a) Low frequency: ASTM D 1049
b) Lightning impulse: IEEE Std 4-1995 [B28]
c) Water for wetting: IEC 60625-1 and IEC 60625-2
d) Atmospheric conditions: Temperature of 20 °C + 5 °C ; relative humidity of 35% minimum
e) Correction to standard conditions: lightning and switching surge voltage, IEC 60060-1
f) Shield testing: ASTM F 2522-05

5.12 Marking and identification—general

All equipment should be marked with the manufacturer's name or logo and the date of manufacture (month and year). The user may add an identification number or code to suit the user's record-keeping requirements. All markings and identification should be permanent, i.e., weather-resistant and not susceptible to sunlight, fading, etc. They should be tested, as required, to ensure that they should remain legible for the intended service life of the device.

5.13 Restoration or temporary structures

At times there is a need to install a restoration or temporary structure to support the conductors. Restoration or temporary structures may be installed using live work methods if the required clearance can be maintained.

There are three categories of dedicated equivalent type structures used for restoration or temporary structures:

a) Type I: Structures that are lightweight, modular, and designed specifically for fast line restoration.
b) Type II: Wood pole structures.
c) Type III: Steel pole and lattice structures, including structures designed for permanent installation only.

Restoration structures are generally used under emergency conditions and are frequently obtained from other utilities in a mutual assistance arrangement or secured from a manufacturer. It is, therefore, advantageous that strength of the structure be determined with a minimum of detailed analysis. Most companies have design application tables for Type II and Type III structures.

For Type I structures, IEEE Std 1070 was developed. The purpose of this guide is to provide a generic specification that can be used by electric utilities for acquiring transmission modular restoration structure components. This particular design would then be compatible with the modular restoration structures presently in use within the industry and would greatly enhance the highly successful plan of transmission mutual aid. In addition to the foregoing guide, application guidance for such systems should be available.

Restoration structures can be used for emergency, transient, or permanent installations.

During emergency installation of restoration structures, the following may be considered due to their relatively short exposure time:

a) MAD, including climbing spaces, may be reduced considering the voltage involved and the absence of energized-line maintenance from these structures. MAD reductions involving the public require barriers and or markers to restrict access.
b) Structural loading criteria should be selected appropriately and should be designed to withstand expected loads, including that imposed by line workers and construction equipment. Designing for the requirements of a permanent installation may severely penalize the restoration structures and unnecessarily increase restoration time.
c) Less than optimal electrical and mechanical designs (i.e., overhead ground wire shield angle and conductor clamping) may be acceptable due to limited exposure.

During installation of restoration structures used as transient structures, the installation should meet the requirements for permanent installations, except for structural loading criteria, which should be selected appropriately and should be designed to withstand expected loads, including that imposed by the line workers and construction equipment.

During installation of restoration structures used as permanent structures, the installation should meet the requirements for permanent installations.

Restoration systems can be implemented and ready to use in a matter of hours to restore damaged transmission lines and ensure the stability, reliability, and continuity of service. Utilities should plan for such systems and include periodic training about them. In addition to the basic reusable structural elements, the transmission utility needs to provide a complete system consisting of conductor, insulators, hardware components, and anchoring arrangements.

Planning, training, and periodic drills in the use of the restoration systems are key for utilities and outside contractor personnel. It is vital to keep an on-call pool of trained personnel and critical transmission construction equipment at all times. Equally important in addition to a trained workforce and correct material is to have adequate and proper transportation and communication infrastructure in place to provide a rapid response in the event of an emergency. Although not mandatory, helicopter support is important to provide emergency medical transportation as well as providing quick turnaround for material or personnel.

6. In-service checking and care of insulated tools and equipment

6.1 Introduction

Tools and devices used in energized-line maintenance are usually tested by the manufacturer for certification. Further information can be found in the standards listed below and in “Recommendations for safety” [B25].

a) ANSI/SIA A92.2 for vehicle-mounted elevating and rotating aerial devices
b) ASTM D 120 for rubber insulating gloves
c) ASTM D 1048 for rubber insulating blankets
d) ASTM D 1049 for rubber insulating covers

e) ASTM D 1050 for rubber insulating line hose

f) ASTM D 1051 for rubber insulating sleeves

g) ASTM F 496 for the in-service care of insulating gloves and sleeves

h) ASTM F 968 for electrically insulating plastic guard equipment

Very often the user conducts electrical certification (acceptance) testing of equipment and tools to verify the manufacturer's tests. After the equipment is put into service, periodic testing and in-service checking ensures that the capability of the equipment remains adequate.

The material for tools constructed of FRP is tested by manufacturers in accordance with ASTM F 711. See Clause 5 for testing requirements.

6.2 Scope

This clause covers in-use field care, handling, and storage; periodic inspection and checking; and maintenance and repair of tools and devices.

6.3 Field care, handling, and storage

6.3.1 Insulating tools

When not in use, insulating tools should be stored where they will remain dry and clean and they are not subjected to abuse or direct sunlight. Wood insulating tools should be adequately supported or hung vertically to prevent warping, and they should be stored in a temperature- and humidity-controlled room. Insulating tools used for energized-line maintenance should be placed on clean, dry tarpaulins; on moisture-proof blankets; or on tool racks. They may also be leaned against dry supports. The tools should not be laid on the ground because of possible contamination, damage, or wetting. When transporting insulating tools, ventilated containers should be provided to prevent damage to the surfaces of the individual tools, or the tools should be mounted on racks in trucks or trailers. These racks should be well padded and constructed so that the tools are held firmly in place.

6.3.2 Insulating aerial devices

When parking aerial devices in buildings or maintenance garages where heat sources are present, care should be taken to avoid damage to the insulating portion of the arm from excessive heat. Fiberglass portions can be damaged if the resin is exposed to temperatures of 80 °C (176 °F) or more.

The recommended maximum boom and bucket or platform mechanical loads should not be exceeded.

When moving an aerial device, the boom should be in the rest position, the outriggers should be up, the buckets should be in the normal storage place, and the boom tie-downs should be secured, unless the device is specifically designed to be moved with the boom elevated.

Additionally, the boom hydraulic system should be disengaged; the auxiliary engine, if used, should be shut down; and, in the case of hydraulically leveled buckets, the free-swing valve should be open.

6.3.3 Insulating cover-up equipment

Cover-up equipment should be stored in a clean, dry condition. Tars and oils left in contact for long periods can cause softening of plastics and rubber, which, in turn, can reduce the dielectric strength of the materials. The equipment preferably should be stored in canvas bags or draped with a plastic cloth or tarp to prevent dust and other contaminants from building up on the surfaces. Equipment should not be stored close to heating pipes or in places where they might be exposed to the sunlight for prolonged periods of time.

Protective cover-up equipment should be transported in canvas bags or other protective containers. Materials that might crack or distort cover-up equipment should not be placed or piled on top of these containers.

6.3.4 Rope

6.3.4.1 General

Rope used in energized-line work should be kept clean and dry. It should be stored in clean, dry nonmetallic containers when not in use. The use of a moisture-absorbing agent such as desiccant is suggested. The rope should not be permitted to contact the ground; this goal can be accomplished by paying the rope in and out of the container or by having a tarpaulin or other type of ground cloth on which to put the rope. Rope used in energized-line work should not be used for any other purpose, and it should not be left on the structure overnight.

Hand lines and slings should be stored by tying them in hanks or coils and suspending them from a rack where the air can circulate freely between them. Rope should never be used wet when a voltage is applied across it. Not only can a current pass through the rope, but also this current can cause localized internal heating, resulting in an almost total loss of mechanical strength, which is not easily detected by visual inspection. Inspection can be accomplished by unwrapping the strands to see if there are any fused filaments or threads, which indicate high stress (either electrical or mechanical).

6.3.4.2 Natural fibers

Natural-fiber rope should be stored so that it can remain clean, cool, and dry, as deterioration is accelerated by hot, humid conditions. Care should also be taken so that the rope does not come into contact with acids or caustics or their vapors.

Natural-fiber rope used for conductor-pulling lines, when wet, should not be wound on a drum or reel and allowed to remain there for long periods of time. A minimum safety factor of 5 should be applied to the mechanical strength of natural fiber ropes.

6.3.4.3 Synthetic fibers

Synthetic rope should not be stored under tension because it has a tendency to become permanently elongated. This stretching will reduce its breaking strength. It should also be stored in a dark place, as exposure to sunlight or ultraviolet light tends to reduce the mechanical strength and cause deterioration. A safety factor between 5 and 9 should be applied to synthetic ropes, depending on the material and type of construction. The manufacturer should be consulted for the exact value.

6.3.5 Clothing

6.3.5.1 Conductive clothing

Conductive clothing, including footwear, should be stored separately in a location that is dry and dust-free to prevent contamination by grease, oil, dirt, or water. It should not be exposed to direct sunlight for long periods of time.

Other objects should not be stacked on the suits of clothing because of possible damage to the fine interwoven material that forms the conductive portion of the suit. Such damage may result in hot spots during energized use.

Extra care should be taken when storing the suits of clothing to ensure that they are clean and that no sharp or rough objects, which could rip or tear the materials, are stored with the suits.

Conductive suits and related equipment should be transported in separate containers to prevent damage.

6.3.5.2 Insulated personal equipment

Insulated personal equipment, such as rubber gloves, rubber sleeves, and overshoes, should be stored in clean, dry locations. Care should be taken to prevent damage from rough objects. In addition, insulating equipment, such as gloves, should not be dropped or allowed to slide down a hand line. Rubber insulating gloves should never be used without placing protector gloves over them. A small puncture in the rubber could render any insulating apparel useless. In general, the same care should be given to insulated personal equipment as is given to conductive clothing.

6.3.6 Cable carts

Care should be taken to ensure that the combined weight of the conductor cart, workers, and equipment does not allow the design electrical clearance (particularly at midspan) to be reduced below the design electrical minimum clearances. Care must be taken that the cart movement will not knock off grounding or bonding devices.

6.3.7 Grounding and bonding devices

The effectiveness of these devices depends on the integrity of the electrical contact surfaces, the cable stranding, and the clamping mechanism. Care should be taken to prevent damage to the cable and the clamping mechanism. These devices should be stored separately to avoid kinking the cable. Contact surfaces and threads should always be kept clean. Heavily oxidized or tarnished contact surfaces can present excessive contact resistance. Poor contact surfaces can compromise safety in the event of a line fault. See personal electrical protective equipment in IEEE Std 1048.

These devices should be inspected for strand breakage especially around the areas where the ferrule is crimped to the cable, for tightness of the cable terminal to the clamp body, and for condition of the threads for smooth operation and clean surfaces.

6.4 Periodic inspection and checking

Procedures for periodic electrical testing of tools and devices used in energized-line maintenance are given in Clause 5. The acceptance in-service check values for these devices are provided in various ASTM standards (see Clause 2).

6.4.1 Insulating tools

Insulating tools should be inspected visually by qualified personnel for indications of being mechanically overstressed. Tools that show evidence of being overstressed, such as damaged, bent, worn, or cracked components, should be removed from service and evaluated for repair. Feathered, elongated, or deformed rivet ends indicate that excessive mechanical loading has occurred and has weakened or sheared the bond between the ferrules and the insulating pole.

Hardware, bolts, and pins should be replaced only with high-strength, tempered-steel material, or the same as the original part, or Grade 5. Nondestructive testing should be performed on the mechanical end fittings and saddle clamps after a tool has been subjected to possible overstressing or vibrating loads for any extended periods of time. Magnetic particle inspection, dye penetrant inspection, ultrasound, and X-ray may be used for checking ferrous and nonferrous parts. Should a tool be dropped from an elevated worksite, it should be withdrawn from service, and its integrity should be verified before future use.

When the insulating member of a tool shows signs of accumulated contamination, tracking, surface blisters, excessive abrasion, nicks, or deep scratches, the tool should be removed from service, cleaned or refinished as recommended by the manufacturer, and electrically retested.

Moisture will reduce the insulating properties of insulating tools. When tools have been exposed to excess moisture, their moisture content can be measured with a commercially available moisture meter in accordance with the manufacturer's recommendations.

Jackscrews should be examined for excessive looseness (indicative of worn threads) and freedom from binding. Worn elements should be replaced. Bolt and nut threads should be free of burrs, roughness, or other damage that can seriously erode mating threads, and all threads should be lubricated only with "dry" lubricants.

6.4.2 Insulating aerial devices

6.4.2.1 Inspection before live work

Before equipment is used for live work, it should undergo a comprehensive daily inspection. Items to be checked or inspected daily, or both, should include, but are not limited to, the following:

a) Emergency power system, including battery
b) Hoses, which should not be cut or damaged, and controls, which should move freely
c) Insulating section of boom, which should be wiped down and visually inspected
d) Engine, which should be started and run while the device operates through its normal operating cycle with no one in the bucket. Any unusual noise, malfunctions, oil leaks, erratic movement, or other occurrence that is not normal should be noted.
e) Bucket or platform metal liner and bonding system, which should be placed in contact with energized conductor to record leakage current
f) Hydraulic system, which should be stabilized by elevating the device to its working height

g) Outriggers, which should be on a solid surface

6.4.2.2 Periodic inspection

Comprehensive periodic inspections should be made and records kept on file. Items to be checked, serviced, and repaired should include, but are not limited to, the following:

a) Vehicle and aerial device, for lubrication as specified by the manufacturer
b) Vehicle power take-off mounting, controls, linkage, and leaks
c) Hydraulic pump mounting, hose connection, leaks, and noise level
d) Filters, for cleanliness or replacement
e) Hydraulic lines, for leaks and general condition
f) Mast and turret, for cracks and excessive motion in the bearings
g) Rotation motor and gear box, for oil level, leaks, and drive mechanism
h) Manifold block or rotary connections, for leaks
i) Bucket controls, for free movement and self-centering
j) Oil reservoir, for oil level
k) Outriggers, for mounting, welds, and proper functioning of holding valves
l) Pivot points, for lubrication, proper hose routing, wear, and hose condition
m) Bucket-leveling (platform-leveling) system to ensure that the bucket (platform) levels properly
n) Boom-lift cables, for wear, broken strands, and proper adjustment
o) Booms, for cracks, alignment, and general condition of the insulating sections
p) Boom cylinders, for leaks and properly functioning holding valves
q) Bucket and bucket liners, for surface damage, cuts, and cracks
r) Emergency systems, for proper operation
s) D-ring attachment, for safety
t) Throttle control, for proper cycling and system settings
u) Vacuum prevention system or other devices to preclude the drawing of a vacuum in any oil line for trucks with a reach exceeding 18 m

6.4.3 Insulating cover-up equipment

Cover-up equipment should be inspected for dents, tears, cracks, punctures, burns, tracking, distortion, soft spots, loose or broken appendages, contamination, and dampness. Cover-up equipment that is damaged, as distinguished from being soiled or damp, should not be used, but rather set aside for electrical tests and possible repairs.

Equipment that is damp should be wiped thoroughly with a clean cloth both inside and outside before use. Where wiping internally by hand is impossible because of space, a clean cloth should be thrust through to swab internal surfaces. Covers that are soiled with dust or mud should be wiped with a moist rag and dried.

6.4.4 Insulating rope

Ropes used for energized-line work should be inspected before using to check for deterioration, wear, broken strands, contamination, and condition of eyes and splices. Periodic examination of the inner strands or fibers is also strongly recommended.

6.4.5 Conductive clothing

All conductive clothing should be inspected visually before and after use to check for rips, brown or burnt marks, punctures, or any damage that can prevent complete shielding. A defect in the conductive clothing or its bonding apparatus should be a reason for removing it from service, instituting immediate repairs, if possible, and testing.

Particular care should be given to removing any dirt or gravel that may be embedded in conductive shoes.

For additional information on the use, care, maintenance, and testing of conductive clothing, see IEEE Std 1067.

6.4.6 Cable carts

Cable carts should be checked prior to use to make certain that the wheels, drive mechanisms, safety slings, and bonding traveler wheel are in good condition.

6.5 Maintenance and repair of tools and equipment

6.5.1 Insulating tools

Repair to insulating tool fittings by welding or reshaping should not be done because damage by impact or overstressing may have weakened the member elsewhere. Welding may also damage heat treatment of the part. Tools damaged as a result of any mechanical stress (e.g., falls, overloads) should, therefore, be removed from service (see Clause 5).

6.5.2 Insulating aerial devices

All repair work should be performed by, or under the supervision of, competent workers. A detailed record should be kept of all maintenance and repairs performed on the aerial device. Replacement parts should be as specified by the manufacturer.

After major repair work has been performed on the insulating portion of the aerial device, a certification or periodic test should be made before the device is returned to service.

A thorough inspection of the device should be made if the recommended maximum load of the bucket, platform, or boom has been exceeded (see ANSI/SIA A92.2).

6.5.3 Insulating cover-up equipment (e.g., plastic, fiberglass)

Repairs to cover-up equipment having cracks, tears, or holes are not recommended. The only parts that might be repaired are appendages that are damaged or loose and have no effect on the dielectric strength of the equipment. See the following standards:

a) ASTM F 478 for in-service care of insulating line hose and covers
b) ASTM F 479 for in-service care of insulating blankets
c) ASTM F 496 for in-service care of insulating gloves and sleeves

For instance, a loose rope loop might be repaired using the manufacturer’s recommended repair kit or the scissors bar, or its mounting hardware might be replaced or reattached to the bottom lip of the line guard. Repairs to this equipment should be made according to the manufacturer’s recommendation. ASTM provides proof test withstand voltage and sparkover voltage tests for plastic guards as listed in ASTM F 711.

Repairs to rubber insulating line hose and covers are not recommended. Hose may be used in shorter lengths if the defective portion is cut off (see ASTM F 478). Repairs made in accordance with the manufacturer’s recommendations for rubber blankets are permissible. Severing the defective area from the undamaged portion of the cover-up may salvage blankets with defects too extensive to repair. Repairs and salvaging of blankets should meet the requirements of the ASTM F 479.

6.5.4 Testing repaired equipment

Repairs and refinishing should be done by competent personnel and followed by a dielectric or power loss (power factor) test.

6.5.5 Insulating rope

Damaged ropes should be removed from service. For additional information, see ASTM F 1701.

6.5.6 Clothing

6.5.6.1 Conductive clothing

Body residues and other impurities will cause deterioration of conductive clothing. Clothing should be washed in accordance with the manufacturer’s recommendations.

For additional information on the use, care, maintenance, and testing of conductive clothing, see IEEE Std 1067.

6.5.6.2 Insulated personal equipment

Repairs to insulated personal equipment are not generally recommended. See ASTM F 496 for in-service care of insulating gloves and sleeves.

6.5.7 Cable carts

Damaged or fatigued members should be replaced and bonding circuits periodically checked for continuity.

7. Work methods

7.1 Introduction

This clause covers work methods and equipment usage based on accepted MADs and techniques used by qualified electrical workers when working on energized lines. It should in no way be considered as a training outline or be used by untrained personnel as instructions for doing work on or near energized lines or equipment.

7.2 Categories of energized-line maintenance

Energized overhead line maintenance can be performed using several methods or a combination of them such as:

a) Rubber gloving method
b) Insulating tool method
c) Barehand method

7.2.1 Workers at ground potential

The workers located on the ground, pole, or structure are at ground potential. Work methods could include rubber gloving and insulating tool method.

7.2.2 Workers at floating potential

The workers isolated from grounded objects or energized objects by insulating means, such as an aerial device or an insulating ladder or platform, are at floating potential. Work methods could include rubber gloving, barehand method, or insulating tool method.

7.2.3 Workers at line potential

Workers bonded to the energized device on which work is to be performed and insulated from grounded objects and other energized devices that are at a different potential are at line potential. A common work method is the barehand method.

7.2.4 Other related work procedures

In some case, lines and equipment are de-energized and not grounded in order to perform overhead line maintenance work. Lines and equipment are considered energized until grounds have been installed.

In order to ground the lines and equipment, live work methods are used to install and remove the grounding equipment. The following standards may be referenced to determine the proper work methods:

- IEEE Std 1048 provides guidelines for protective grounding methods for the safety of persons engaged in de-energized and grounded overhead transmission and distribution line maintenance.
- IEEE Std 524 and ASTM F 855 provide general recommendations for the selection of methods, equipment, and tools that have been found practical for the stringing of overhead transmission line conductors and overhead ground wires. The purpose of these guides is to present sufficient details of present-day methods, materials, and equipment and to outline the basic considerations necessary for safety in maintaining control of conductors during stringing operations.

7.3 Precautions when working energized lines

7.3.1 General precautions

7.3.1.1 Energized-line maintenance

Energized-line maintenance should not be started when lightning is visible or thunder is audible at the worksite. Lightning-to-ground radar detection equipment can be used to aid in making decisions.

7.3.1.2 Insulated material and equipment

Insulated material and equipment, such as insulators, arrestors, or capacitors, that are being installed or replaced during live work should be inspected, cleaned, and tested where practical to ensure their electrical and mechanical properties are acceptable.

Ceramic insulators are typically factory tested on an individual basis for electrical properties but not mechanical properties.

Nonceramic insulators are typically factory tested on an individual basis for mechanical properties but not electrical properties.

7.3.1.3 Blocking reclosing

Decisions regarding blocking reclosing during energized-line maintenance work should be consistent with other safety considerations, system conditions (e.g., integrity, coupling), work method, or method of overvoltage control. On distribution lines, the nature of the work being performed usually determines the action to be taken.

7.3.1.4 Equipment inspection

All equipment should be inspected for defects before use.

7.3.1.5 Eye and face protection

Protective glasses or face protection should be worn to protect the eyes and, if required, the face.

7.3.1.6 Line operating voltage

The maximum operating voltage of the circuit should be known before starting work so that proper MADs are maintained.

7.3.1.7 Minimum working distances

Care should be taken to maintain proper MADs, as determined by Clause 4, when using conductive material, including noninsulating ropes or slings, in the vicinity of energized devices. When required, insulating measuring tools should be used for verifying the insulating distance.

7.3.1.8 Tool inspection

Insulating tools should be inspected for condition and indication of damage before and after each job.

7.3.1.9 Worksite inspection

Conductor, adjacent structures, and hardware should be inspected prior to moving an energized conductor. When an energized conductor is being moved, checks should be made to avoid sparkover to trees or other objects located adjacent to the spans.

7.3.1.10 Public safety

Persons not involved in the work operation should be kept clear of the worksite.

7.3.1.11 Mechanical loading

It is important to determine correct locations relative to mechanical loadings that may be added or relative to changes in electrical distances on structures for the placement of transient rigging loads. Care should be taken to verify that tools properly engage conductors or hardware, or both, before transferring a mechanical load to the tool. Tools should not be mechanically overloaded.

7.3.1.12 Floating objects

Care should be taken when handling metallic objects while working near the end of the insulator string as they can become electrically charged and result in unexpected shocks. When passing conductive objects to the worker at floating potential, a hand line or tool, insulated for the voltage involved, should be used so that the insulating value to ground or to other objects at a different potential is not decreased. The possible effect of the conductive part should also be taken into account. To avoid shocks, the worker should first bond to any conductive object being passed to the worker. When returning to a metal structure from an insulating ladder or similar support platform, the worker should drain the charge off the worker's conducting suit or body using a bonding device to prevent the current from flowing through the worker's body.

7.3.1.13 Working in the vicinity of energized conductors

When working within the reach or extended reach of conductors or equipment energized at 72.5 kV or below, the conductors or equipment should be covered, if applicable, with protective cover-up equipment rated for the voltage involved. To avoid inadvertent contact with energized conductors or equipment energized at 46 kV or below, appropriately rated rubber gloves and sleeves should be worn. For line-to-line voltages above 46 kV, workers should maintain MADs at all times.

7.3.2 Precautions when working at line potential

7.3.2.1 Bonding

Bonding should be such that the worker is at the potential of the device on which work is being performed.

If possible, all objects passed to the worker should be brought to the line worker's potential before the line worker touches them.

7.3.2.2 Bundled conductors

When working with bundled conductors, the worker should bear in mind that a heavy fault current will pull the subconductors together with violent force.

7.3.2.3 Exposure to other conductors or objects

When other conductors or objects are within the MADs of the conductor or device being maintained at line potential, the worker should safeguard themselves with protective cover-up equipment, if such equipment is available and rated for the voltages involved, or move the conductors or objects to avoid inadvertent contact with other potentials or ground by the worker or the equipment being used.

7.4 Requirements when working energized lines

7.4.1 General requirements

7.4.1.1 Worker training

Line workers doing energized-line work should successfully complete a training course and demonstrate competency. Records of training and work experience should be maintained.

7.4.1.2 Electric fields

Whenever workers are exposed to electric fields, shielding should be considered as described in Clause 8.

7.4.1.3 Rules and procedures

A set of written work rules should be provided for safety in implementing energized-line maintenance. All personnel should be familiar with these rules. Procedures should be continuously examined and updated to take advantage of new equipment and lessons learned during use of present procedures and work methods. Frequent, well-developed on-the-job or tailgate discussions of the aspect of each energized-line work program or job by the working personnel should be conducted. Communication by all participants should be encouraged constantly, both during the discussions and during the progress of the work program. Every effort should be made to provide logical, understandable answers or reasons for all questions, and all proposals should be readily received and discussed, with immediate action initiated on any approved changes. A high degree of intra-crew discussion and participation fosters a highly trained, well-adjusted, energized-line crew.

If an unexpected condition arises during the course of the work that requires a change in the preestablished work procedures, the work should be suspended pending additional planning.

The leader of the crew should be responsible for seeing that detailed plans are worked out in advance and for determining the location of all grounded and energized parts near the proposed work. MADs for personnel and their supporting insulating devices (considering movements during the work) should be determined in advance and strictly observed.

7.4.1.4 Use of PPAG

When PPAGs are used, they should be installed on an adjacent structure or as close as practical, but should not exceed 2 mi from structure being maintained.

7.4.2 Guidelines for the rubber gloving method

7.4.2.1 General guidelines

The following guidelines are recommended for the rubber gloving method:

a) References to voltages in the following subclauses are phase-to-phase on multiphase circuits. When exposure is limited to phase-to-ground voltage only, gloves rated for that voltage can be used with special precautions as listed in Part 4 of NESC [B1].
b) Rubber and synthetic gloves and sleeves are available for use on voltages through 36 kV. See also Clause 5.
c) Rubber gloves and sleeves when required should be donned before the workers are within reach or extended reach of MAD and removed only after moving out of reach or extended reach of MAD.
d) Energized or neutral conductors, ground wires, messengers, guy wires, etc., in the proximity of the work to be performed should be covered with approved protective equipment. This equipment should be installed and removed from a position below the conductor. Protective covering should be applied to the nearest or lowest conductor first and removed in reverse order.
e) When working in proximity to fuses, lightning arrestors, etc., procedures may require that the equipment be bypassed or disconnected for the duration of the work.
f) Rubber protective equipment should not normally be left installed on a conductor overnight.

7.4.2.2 Field inspection

Rubber gloves and sleeves should be inspected for cracks, bruises, and other damage or defects at least daily while in use. Gloves should be given an air test or water test at the beginning of the work period and at any time their condition is suspect.

7.4.2.3 Field care, use, and storage

Rubber gloves should never be stored or worn inside out, nor worn without glove protectors. Class 0 and class 00 rubber gloves may be used without protectors under certain conditions (see ASTM F 496). Gloves should be stored in their natural shape. Rubber sleeves and blankets should not be folded or creased, but should be stored flat or in an approved roll-up.

All rubber protective equipment should be protected from mechanical damage and exposure to harmful chemicals, heat, ozone, oil, grease, etc. Harsh chemicals, oil, grease, etc., should be removed as soon as practicable by wiping or by using a mild detergent and a thorough rinse to remove all traces of the detergent. The gloves or sleeves should be checked for any damage. If there is any indication of damage, they should be returned to an approved testing facility for an electrical proof test. Thorough rinsing is important to prevent damage.

7.4.2.4 Typical work guidelines

The typical work requirements contained in this subclause should be used only as a guide to developing work procedures. Further guidelines may be found in NESC [B1], OSHA regulation, state and local codes, and other national standards.

a) When working with voltages from 600 V up to 7500 V

   With the use of proper protective equipment (e.g., line hoses, blankets), this voltage level may be worked directly from wood poles and other grounded structures.

b) When working with voltages from 7501 V up to 36 000 V

   For voltages up to 15 000 V, installation of line hose, blankets, and other protective equipment can be performed from the structure using the rubber gloving or insulating tool method. For voltages above 15 000 V, line hose, blankets, etc., may be installed with live line tools or using the rubber gloving method from an insulating device. Additional insulating devices should be used when using the rubber gloving method to reduce the leakage current in the worker. Sleeves are used when there is no positive assurance that the arms cannot violate the phase-to-phase or phase-to-ground MAD for the voltage involved. Work in damp or foggy weather is often limited by the boom leakage current or the atmospheric humidity.

7.5 Insulating equipment used in energized-line work

7.5.1 Insulating aerial devices

Vehicle-mounted devices are used to position the worker in contact with or near energized lines or equipment and provide electrical insulation between the energized equipment and the ground potential at the vehicle location. Examples of vehicle-mounted devices include aerial ladders, articulating boom platforms, extendable boom platforms, vertical towers, and telescoping boom platforms.

7.5.2 Insulating ladder

A single- or multiple-section insulating ladder is used for personnel support during energized-line work. This ladder may be structure-mounted, base-supported, or cable-supported by a crane or similar device.

7.5.3 Insulating tower or cargo boom

An insulating tower or cargo boom is used, in conjunction with support platforms such as boatswain's chair, basket or bucket, or tree trimmer's saddle, to position the worker.

7.5.4 Structure-mounted insulating work platform

A fiberglass board, when attached to the pole or structure, provides an insulating horizontal surface that electrically isolates the worker from the structure to which it is attached.

7.6 Noninsulating equipment used in energized-line work

7.6.1 Conductor carts

A conductor cart is a cart suspended from the conductor used as a work platform.

7.6.2 Helicopters

Helicopters can be used to lower and raise workers and tools and to place line workers in a work position.

7.7 Insulating devices used in energized-line work

7.7.1 Insulating tools

Insulating tools made of FRP are used for work on energized devices while the worker is at ground potential or at a floating potential.

7.7.2 Insulating rope

Insulating rope is used in rigging to support platforms for positioning personnel, controlling conductors, and raising or lowering tools and equipment whenever work is being done on, or within the MAD of, the energized lines or devices. It can be used alone or in series with an insulating tool or an insulator.

7.7.3 Protective cover-up

Protective cover-up equipment is used to insulate energized lines and devices from the worker and reduce MAD. When the worker is at the conductor potential, the cover-up equipment may be used to insulate the worker from ground potential.

7.8 Methods for positioning personnel

7.8.1 Minimum working distances

7.8.1.1 Insulated ladders

The following guidelines are recommended for the MAD for insulated ladders:

a) When a worker is using an insulated ladder to access the worksite, the MAD from the worker to the ground should not be less than the distances specified in Clause 4.

b) The MAID of the ladder should be adjusted to account for the area usually occupied by the worker.

c) When a worker is using an insulating ladder to access an energized conductor, the worker's body length plus extended reach must be deducted from the MAID. An average lineman with extended reach measures 2.4 m (7.75 ft). As the lineman moves up and down the ladder, the clear insulating air space on ether side of the lineman must be equal or greater than MAID.

7.8.1.2 Insulating aerial devices

The MAD between any grounded part of the insulating aerial device and any energized device should not be less than that specified in Clause 4.

7.8.1.3 Bonding

The following guidelines are recommended for the MAD when bonding:

a) When bonding to any energized device, the line-to-ground MAD from the worker and all energized parts should not be less than the distance specified in Clause 4.

b) When bonding to an energized phase, the line-to-line MAD to another energized phase of the same circuit should not be less than the distance required by Clause 4.

c) When bonding to an energized pole of a dc line, the pole-to-pole and pole-to-ground MAD should not be less than the distances specified in Clause 4.

7.8.2 Aerial devices

7.8.2.1 Vehicle-mounted elevating and rotating aerial devices

The following guidelines are recommended for vehicle-mounted elevating and rotating aerial devices:

a) All aerial devices should meet the criteria for design, testing, installation, maintenance, use, training, and operation as specified in ANSI/SIA A92.2.

b) Before the boom of an aerial device is elevated, the outriggers on the truck should be extended, and if required, the aerial device should be properly grounded.

c) The boom should be operated through its full range to ensure all functions are operating correctly.

d) The floor of the aerial device buckets or platform should be kept clean of dirt or material. This is especially important when conductive liners or metal platforms require good contact for conductive footwear worn by workers.

e) When working aloft, workers should stand on the bottom of the bucket or platform.

f) Workers on the ground should minimize contact with the aerial device chassis while the lift is near or in contact with energized devices.

g) The aerial device, including buckets or platform and upper insulating boom, should not be overstressed by attempting to lift or support weights in excess of the manufacturer's rating. To protect the fiberglass parts, none of the parts of the bucket, platform, or upper arm should be used as a support point for prying or lifting.

h) The fiberglass of buckets should not be considered to have any insulating value unless designed, maintained, and operated in accordance with the appropriate standard: CSA C225, ANSI/SIA A92.2, or IEC 61057.

i) When it is necessary to move between an insulating aerial device or ladder and a structure or conductor, workers should be attached in accordance with IEEE Std 1307.

j) When state or local regulations require, a removable insulating liner should be used and tested.

7.8.2.2 General precautions

The following precautions are recommended for all aerial devices:

a) Before the platform is elevated, the outriggers on the unit, if so equipped, should be extended and adjusted to stabilize and level the unit.

b) The body and chassis of the unit should be properly grounded when required. Grounding through the outriggers is not sufficient.

c) Before moving the insulating platform into the work position, all controls both at ground level and on the support platform should be operational.

d) For scissors-type platforms with hydraulic lines to the controls at the support platform level, all arms supporting the platform should be raised to their maximum height and left in the raised position for 5 min.

e) Workers within the MAD of the support platform, in contact with or near energized lines, should not make contact with the support platform.

7.8.2.3 General requirements for aerial devices performing barehand work

The following guidelines are recommended for aerial devices performing barehand work:

a) Bonds
    1) Bonding leads should be equipped with (or terminated with) pull-away clamps or have a pull-away section that allows for separation in an emergency situation.
    2) Bond leads should remain firmly attached to the energized device throughout the work operation.

b) One qualified person should be nearby whenever the aerial device is aloft in the event that it is necessary to operate the controls from the lower unit.

c) Aerial buckets with hydraulic lines at the bucket position should be equipped with atmospheric check valves on hydraulic lines at the bucket position to admit air into the lines in the event of a line leak, which would normally cause a partial vacuum to form in the hydraulic line. If a partial vacuum were allowed to form along the entire length of the insulating boom section when the bucket is in contact with a conductor, a sparkover could occur because the dielectric strength of partial vacuum is lower than that of the hydraulic fluid. The atmospheric check valves should be functionally tested using the manufacture's recommended procedures and intervals.

7.8.3 Structure-mounted ladders for barehand work

7.8.3.1 General precautions

The following precautions are given for structure-mounted ladders for barehand work:

a) The structure end of the ladder should be firmly secured to an anchorage point on the structure capable of supporting at least twice the potential impact load of a worker's fall (determined by a qualified person), or 22.2 kN.

b) The ladder should not be secured to a defective component or to a component that will be taken apart or moved.

c) Before the worker mounts the ladder, the worker should first assure that all rigging has been checked. When transferring to and from the ladder, continuous attachment should be required. Refer to IEEE Std 1307.

7.8.3.2 General requirements

The following guidelines are recommended for structure-mounted ladders for barehand work:

a) Before a worker mounts the ladder, it should be tested electrically by placing the ladder in contact with the line to be worked on and monitored for 3 min. Personnel should stay clear of the ladder and base while the ladder is being moved into position.

b) The ladder should be moved to a safe position prior to allowing the worker to mount or dismount.

c) Controlling the movement of the ladder should be done with insulating tools or insulating rope, or both.

7.8.3.3 Minimum working distance

The MAID specified in Clause 4, plus an additional distance for inadvertent movement (ergonomic), should be maintained between the worker and any grounded part.

7.8.4 Base-supported ladders for live-line work

7.8.4.1 General precautions

The equipment being used as a fixed-base support should provide a sturdy, safe prop for the length of ladder and weight to be supported.

7.8.4.2 General requirements

The following guidelines are recommended for base-supported ladders for live-line work:

a) The equipment being used as a fixed-base support for the ladder should be grounded.

b) Insulating devices, when needed to assure either the MAD or the insulating tool length requirements, should be used to move the ladder to the energized device.

c) The ladder should be checked electrically each time the base is relocated when barehand work is being performed.

7.8.4.3 Minimum working distance

A distance of 2.4 m (7.75 ft) should be added to the MAID to allow for the length of ladder occupied by the person.

7.8.5 Cable-supported ladders for live-line work

7.8.5.1 General precautions

The following precautions are recommended for cable-supported ladders for live-line work:

a) The lifting device should be of enough capacity to handle the ladder load without any risk of an operating deficiency.

b) The ladder should be supported and secured for safety of operation at all expected angles and positions.

c) The equipment should be inspected by the supervisor and operator following setup, and any noted or suspected deficiencies should be corrected.

d) Insulating devices (e.g., link sticks, insulating rope) should be used between the cable and the ladder whenever possible to facilitate the current testing or to improve the insulating quality of the setup, if needed.

7.8.5.2 General requirements

The following guidelines are recommended for cable-supported ladders for live-line work:

a) The equipment being used as the lift device should have both power-raising and power-lowering facilities. Brake type lowering should not be used.

b) When workers are on the ladder, all movements of the lifting device should be directed or controlled from aloft.

c) One person capable of operating all controls should be near the lifting device when workers are on the ladder to allow rapid response to movement needs, to warn other persons not to walk under the worksite, and to keep them clear from the lifting device when the ladder is elevated.

d) Link sticks or ladders should be solidly attached to the lifting cable. Open-load hooks should not be used.

7.8.5.3 Minimum working distance

Noninsulating portions of the equipment should not be closer to energized devices than the MADs. Depending on the work location, additional distances may be specified by the person in charge so that minimum distances are not violated.

7.8.6 Insulating cargo booms for live-line work

7.8.6.1 General precautions

The following precautions are recommended for cargo booms for live-line work:

a) The cargo boom should be erected at a suitable location on the structure to facilitate moving the worker or equipment to the desired location.

b) The specific support platform to be used should be properly attached to the cargo boom, and all component parts should have a large enough factor of safety for the load to be carried.

7.8.6.2 Minimum working distance

The following guidelines are recommended for the MAD on cargo booms for live-line work:

a) The minimum insulation distance between the worker and any grounded part should not be less than the distance specified in Clause 4.

b) When bonding to any energized device, the MAD from the worker and all energized parts should not be less than the distance specified in Clause 4.

c) When bonding to an energized phase, the minimum distance to another energized phase of the same circuit should not be less than the distance required by Clause 4.

7.8.7 Conductor carts used in energized (barehand) work

7.8.7.1 General precautions

The following precautions are recommended for conductor carts used in energized work:

a) A worker using a conductor cart should not make contact with the cart during its installation on the conductor until it is at the same potential as the worker. Contact can be made either by allowing the cart to be pulled by other workers against the conductor to which the worker is bonded or by the worker's reaching out and hooking the cart with the worker's bonding wand.

b) An insulating rope tag (e.g., rope, rope with link stick) should be tied to the cart to control its motion during hoisting and at other times as required.

c) After the trolley wheels are on the conductor, safeties should be installed across the wheel attachment to prevent the cart from dropping if a wheel should jump off the conductor.

d) When transferring from an insulating ladder to a cart attached to the conductor, the worker should make sure that the safety strap, which is fastened to the ladder, and the conductive clothing bond are of sufficient length to permit transfer from the ladder to the cart.

e) When the cart is being mounted on bundled conductors, the rigid side of the cart support should be mounted on the conductor away from the worker on the insulating ladder, and the hinged side of the cart support should then be mounted on the conductor near the worker.

7.8.7.2 General requirements

The following guidelines are recommended for conductor carts used in energized work:

a) Suitable bonding should be maintained.

b) For cable carts propelled by internal-combustion engines, care should be taken in handling fuel. A fire extinguisher should be in the cart at a readily accessible position and as far away from the engine and fuel as possible.

7.8.7.3 Minimum working distance

Care should be taken during the installation of the cart on the conductor so that the minimum distances indicated in Clause 4 are not violated.

The weight of the cart and the worker should be such that when installed on the conductor, they do not alter the sag of the conductor to the extent that they violate the distances indicated in Clause 4.

7.8.8 Helicopter performed barehand procedures

7.8.8.1 General requirements

When performing barehand live-line techniques with a helicopter, the guidelines below should be followed:

a) The pilot and the line worker should be checked out on the particular job to be done.

b) All applicable MADs should be discussed.

c) Constant communications between pilot and line worker should be provided.

d) The crew and line worker should be dressed in equivalent conductive clothing.

e) The pilot, in consultation with the line worker, should be responsible for all decisions regarding safe flying conditions.

f) A regulator-approved work platform should be provided for the line worker.

g) Pull-away bonding clamps should be used.

h) The worker should be fastened to the helicopter or work platform, or both, by an approved safety harness and lanyard.

i) A conductive wand should be used to bring the platform and the helicopter to line potential.

7.9 Insulator cleaning

Cleaning contaminated insulators on energized lines can be done by using various methods. See “Applications of insulators” [B29] and IEEE Std 957.

8. Work in the vicinity of energized lines and devices

8.1 Introduction

This clause suggests ways to provide protection for workers during energized-line maintenance or while working in the vicinity of other energized lines.

8.2 Physiological aspects of live-line work

8.2.1 Electric fields

An electric field exists in the space between energized transmission line conductors and between the conductors and ground. Electric field strength is generally expressed in kilovolts/meter.

For example, a worker standing on the ground under an energized transmission conductor, a worker on a pole working on an energized conductor with live-line tools, or a worker in a bucket of an aerial device working on an energized conductor are all within an electric field of much different strengths.

Guidelines for evaluating electric field exposure have been developed by the International Committee on Electromagnetic Safety for non-ionizing radiation (see Bridges [B2]).

The IEEE guidelines are based on the severity of a shock for isolated individuals standing upright in a uniform field of 20 kV/m. This limit is of minimal safety risk for a person of average weight and size. For workers in a structure, equal shock severity would be at a 31.7 kV/m field.

Table 7 shows the calculated unperturbed electric field in kilovolts/meter and the short-circuit current at various locations on the tower for the average size lineman in fields from the various operating voltages.

Table 7—Electric field exposure

Position	Voltage (kV)	Configuration	Average field (kV/m)	Short-circuit current (μA)
Climbing	230	Flat	10.0	110
	345	Flat	16.0	117
	500	Delta	27.3	300
	765	Flat	19.5	210
Tower bridge	230	Flat	6.0	70
	345	Flat	10.8	120
	500	Delta	26.1	290
	765	Flat	19.5	210
Tower arm	230	Flat	7.7	80
	345	Flat	13.2	140
	500	Delta	25.0	270
	765	Flat	28.6	310

The short-circuit current is well below the 1 mA (1000 ųA) limit for perception. However, a transient shock should be perceptible when an isolated person contacts a grounded object. For this reason, conductive shoes are sometimes used when working in a field over 10 kV/m.

The field from a delta configuration is generally higher than for a flat configuration.

One of the most common manifestations of an electric field on a person is an electric shock. Such a shock may be a transient or steady state, or both. A nonbonded worker assumes a potential other than that of adjacent objects, and the worker may receive a perceptible transient shock and may also receive a perceptible steady-state shock.

Transient shocks occur as contact is made or broken with an object at different potentials from the worker, as there is a short-duration transfer of energy. The shock energy level as used by this guide is 4.6 mA.

The steady-state (power frequency) shock perception level is 0.6 to 1.1 mA. The let-go level is considered in the range of 10 to 15 mA. These values are valid for ac transmission. Either bonding the worker to adjacent objects or shielding the worker from the electric field can mitigate both types of shock.

8.2.2 Studies

The results of a comprehensive literature survey on the effects of electric fields on power workers describe contrasting sets of research findings. Research results have failed to provide conclusive evidence that human exposure to present levels of electric fields from high-voltage overhead power lines, as normally encountered, have any harmful biological effects.

8.2.3 Mitigation of electric field effects on workers

Electric field effects (i.e., perceptible shocks) are readily mitigated by shielding or bonding.

8.2.3.1 Shielding

The electric field strength inside a conductive shield is a function of the field strength and the degree of shielding. The proximity to the line, its voltage, and the resultant strength of the electric field should determine the shielding required. When using barehand methods on energized lines of 230 kV and higher, full shielding may be necessary. Full shielding may not be necessary at lower voltages or when using other work methods at higher voltages. Any sensation or discomfort experienced by the worker can serve as a useful indicator of when shielding is desirable and what degree of shielding is needed.

8.2.3.1.1 Forms of shielding from electric fields

The following are forms of shielding:

a) Conductive clothing. Conductive clothing, including footwear, socks, gloves, and a suit, is a very effective form of shielding and is widely accepted, particularly in barehand work (see IEEE Std 935 and IEC 60895).

b) Conductive screens and liners. At extra-high voltages, conductive liners are often used in conjunction with insulating buckets to provide additional grading of the electric field. At lower voltages (242 kV and below), conductive screens and liners can be used to mitigate electric field effects and, if properly employed, can be as effective as conductive clothing. The design of the conductive liner should be in accordance with the shielding requirements of ANSI/SIA A92.2.

c) Metallic structures. Metallic structures provide shielding when the worker remains within the structure's geometry.

d) Work location. The relative body current at a position normally employed on the tower to perform live work is higher than the values obtained with complete bucket shielding. A worker doing barehand work from a bucket provided with enough shielding is subjected to approximately the same or less electric field as a counterpart working with conventional tools from the tower. The use of a conductive suit greatly reduces the exposure to the electric field in both cases as can be seen in Table 8 for work on 345 kV. The types of shielding employed in the comparisons in column 2 of Table 8 ranged from none to conductive suit through four types of screen as follows:

    1) Type A: Complete bucket shielding with a rear shield wall and overhead canopy
    2) Type B: Complete bucket shielding with a rear shield wall and no overhead canopy
    3) Type C: Complete bucket shielding only
    4) Type D: Partial bucket shielding

Table 8—Worker exposure and body current

Position of worker	**Type of shielding**	**Body current (μA)**	
		At 138 kV	**At 345 kV**
On tower (see NOTE)	None	125	395
In bucket	A	70	130
In bucket	B	155	300
In bucket	C	320	Not measured
In bucket	D	375	Not measured
In bucket	Suit	Not measured	50
NOTE—Worker on tower approximately 240 cm from conductor at 138 kV and 320 cm from the conductor at 345 kV.			

8.2.3.2 Bonding

Bonding is used to bring personnel and conductive objects in the worksite to the same potential. Conductors employed in bonding are not intended to carry line or fault current. Bond leads are used extensively during barehand work to conduct charging current and thereby eliminate transient contact shocks between the worker and conductive objects in the worksite. The worker in the bucket is bonded to a conductor by a bond lead, which in turn is connected to the bucket bonding or shielding system.

The use of conductive footwear is recommended. When the worker is wearing a conductive suit, all the components of the suit should also be bonded together. These bond leads should be installed so that they minimize the probability of carrying line or fault current.

8.2.3.3 Magnetic fields

Unlike electric fields that are present whenever a voltage is applied on a conductor, magnetic fields are present only when current flows in a conductor. Accepted shielding methods employed to mitigate the effects of electric fields are not effective in shielding a worker from magnetic fields. Researchers have also been investigating the possible long-term health effects of magnetic fields on people. Research results continue to be inconclusive, and no definitive evidence of health risk has been found.

8.3 Flame-resistant clothing

Workers should be protected from the thermal effects of an electric arc; an assessment needs to be made to determine the level of the thermal exposure.

8.4 RF field protection

The RF field protection material is based on “RF protection of personnel” [B8].

8.4.1 RF exposure

The U.S. Federal Communications Commission (FCC) conducted scientific studies (see FCC 96-326 [B13] and FCC OET Bulletin 65 [B14]) and produced reports and recommendations that have resulted in the promulgation of Occupational Safety and Health Administration (OSHA) regulations to cover worker exposure to RF fields (see 29 CFR 1910.268 [B38] and 29 CFR 1910.97 [B37]). Utilities are obligated to develop plans, training, policies, and work practices to protect their workers from RF fields. It is incumbent upon utilities to evaluate the risks and needs to equip their workers with protective equipment, such as RF detectors and shielding apparel.

8.4.2 RF safety program

Electric utilities that have personnel working near wireless communications antennas attached to electric power line structures and other facilities are required to protect their personnel from possible hazards arising from working in the presence of high-intensity RF fields. It is advantageous to develop a written RF safety program.

Written RF safety programs demonstrate an electric utility’s efforts to comply with RF regulations and serve as a reference for workers. A comprehensive RF safety program should include elements such as engineering practices, administrative controls, work practices and procedures, use of protective equipment, and addressing situations where external (to the utility) personnel and equipment are located on utility property. Other items that need to be considered are RF exposure limits, RF safety compliance steps, power frequency electric and magnetic field immunity of RF personal monitors, and RF protective clothing.

8.4.3 RF personal monitors for electric and magnetic fields from transmission lines

Most of the RF personal monitors available on the market were originally developed for telecommunications use and were not designed for an environment at transmission line towers where a power frequency electric and magnetic field strengths are present. In the power frequency environment, the potential interference from the electric and magnetic fields on the RF personal monitors can be observed in at least two possible modes:

a) False alarm while the RF radiation is below the maximum permissible exposure limit
b) Alarm inhibition while the RF radiation is above the maximum permissible exposure limit

In order to confirm proper operation of an RF personal monitor when used by a worker performing tasks (e.g., inspection, maintenance) to energized transmission lines, the monitor should be certified for immunity to power frequency electric field strength up to 100 kV/m.

The recommended conservative value of magnetic flux density for immunity testing of RF personal monitors is 5 Gauss. The purpose of the immunity test is simply to show that at 5 Gauss, the magnetic field is not affecting the performance of the monitors.

8.5 Precautions when performing live work

8.5.1 Precautions

8.5.1.1 Minimum working distance

The following factors are among those that should be considered when establishing the MAD for a particular work operation:

a) The potential hazard of the work, including electrical, mechanical, or physical hazards
b) The skills and knowledge of the worker doing the work
c) The possible use of protective cover-up equipment
d) The fact that the live equipment may be the energized conductor or device itself, any hardware attached to it, any conducting tool or material touching it, the metal component at the end of an energized line tool, or any equipment with voltage induced from an alternate source

8.5.1.2 Safety of all workers

Precautions should be taken to maximize the safety of all workers.

8.5.1.2.1 Voltage and current induced into objects in vicinity of energized components

Voltage and current induced into objects in the vicinity of energized components may influence the risk of inadvertent movement by the worker and should be considered in developing work practices and procedures.

a) When conducting shoes or boots are worn while working in the vicinity of energized equipment, to eliminate the annoying, although harmless, discharging of the body capacitive charge to the grounded structure, the worker should not make contact with a source of low-voltage potential.
b) Consideration of the amount of insulation provided at the worksite should include an analysis of the minimum number of healthy insulators (see “Minimum number of good insulators” [B24]). If the work method provides for the shunting of insulators at the hot or cold ends of the string, the analysis should not include the damaged or shunted insulators.
c) Conductor support tools, such as link sticks, strain carriers, and insulator cradles, may be used provided that the tool insulation distance is at least as long as the insulator string or the applicable MAD. When installing this equipment, the employee should maintain the MAD.

8.5.2 General requirements

Whenever field strengths are sufficient to require it, conductive clothing should be worn by workers at ground level and on any grounded extra-high voltage structure.

8.6 Step and touch voltages

8.6.1 Introduction

When induced current flows or a ground fault occurs on a transmission or distribution tower or metal structure, the voltage rise near these structures, with respect to ground, may cause higher step or touch voltages. The degree of the voltage rise in the touch and step potential depends upon the magnitude of the fault current available at the work location, the earth (ground) resistance, and the duration of the exposure. While the probability of a line-to-ground fault during the work period has not increased in recent years, the magnitude of available fault current has in many cases increased appreciably, with the result that the exposure from step and touch voltage should no longer be considered as negligible.

8.6.2 Voltage gradient distribution

The dissipation of the voltage or voltage drop from the ground electrode is called the *ground voltage gradient*, or simply, the *voltage gradient*. The voltage drop depends on the ground resistivity. Figure 11 depicts a typical voltage gradient distribution curve and shows that the voltage decreases rapidly with the distance from the electrode and that most of the voltage drop is concentrated near the electrode. The graph assumes soil of uniform resistivity.

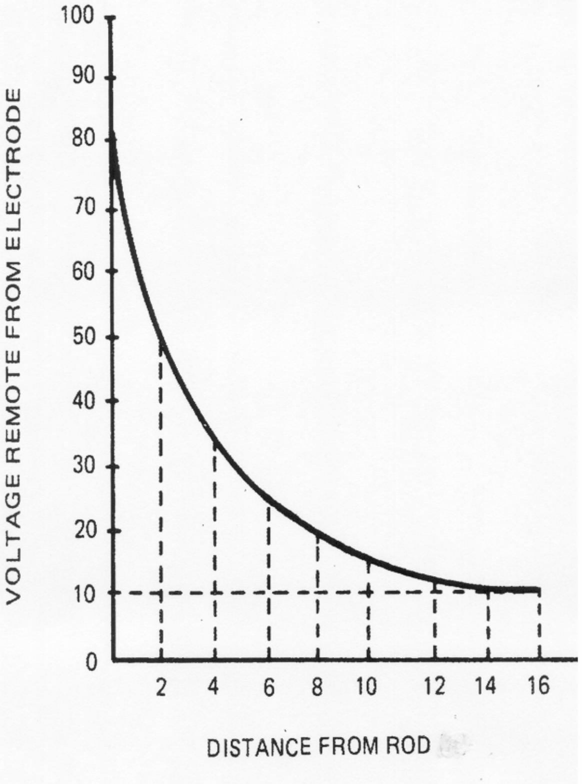


Figure 11 —Typical voltage gradient distribution curve

This figure is a graphical representation of an actual data plot, and the plot should not be used to obtain data for calculation.

Step and touch voltages are illustrated in Figure 12. In the event of a fault to ground, transferred voltages can occur on any metal component connected to station grounds, transmission, and distribution, including station fences, cable sheaths, pipes, and rails.

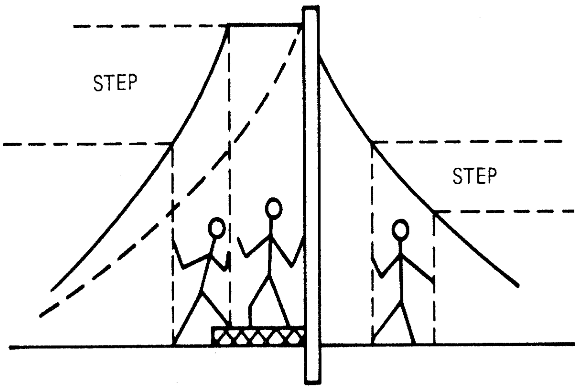


Figure 12—Protection of the workers from step and touch voltages

8.6.3 Protection of the worker from ground voltage gradients

The use of a metal mat connected to the electrode should protect a worker standing on it from any step or touch voltage. However, if the worker is standing with one foot on the conducting mat and one foot on the ground, the worker should be exposed to a step voltage, which is at least equivalent to the touch voltage, as illustrated in Figure 12.

8.7 Mechanical equipment

8.7.1 Methods

Three basic methods are used, separately or in combination, to provide personal protection for the public and workers standing near vehicles working near energized facilities (see "Factors in sizing protective grounds" [B12] and "Methods for protecting workers" [B34]).

8.7.1.1 Grounding equipotential zones

All mechanical equipment is electrically interconnected by temporary protective grounding equipment and grounded to a system neutral, system ground, and/or grids that provide negligible potential difference across the zone.

8.7.1.2 Insulation

Workers are insulated by gloves, footwear, insulating booms, insulating mats, insulating platforms, etc., suitable for the voltage resulting from maximum fault currents and the voltage available at the worksite.

8.7.1.3 Isolation

Isolation may be provided by physical restraints such as barricades or barriers. No one should be inside the isolating perimeter unless protected by one of the above methods. Isolation, if properly used, provides a positive means of protecting the public. With respect to the step voltage potential, the isolation distance may vary from a few meters to 9 m or more depending on the available fault current and voltage.

NOTE 1— If the system neutral or system ground is not available and ground rods are used in conjunction with methods in 8.7.1.1, 8.7.1.2, and 8.7.1.3, the perimeter of the ground rods should be isolated as specified in 8.7.1.4.

NOTE 2— It has been shown in tests that the use of ground rods can produce step and touch voltages around equipment connected to ground rods.

8.7.1.4 Isolation method

If the isolation method is combined with the use of ground rods, the location of the isolation perimeter should consider the location of the ground rods. The voltage gradient in the ground radiating from the ground rod may be large when accidental contact is made, and the ground connection should also be isolated. Barricading these points should be considered.

The protection system chosen should be adequate for the exposure that exists.

8.7.2 Operations near energized lines or equipment

8.7.2.1 Observer

If the equipment operator cannot accurately determine that the MAD is being maintained, a worker should observe the approach distance to exposed energized lines or equipment and give timely warnings before the MAD is reached.

8.7.2.2 Condition of the mechanical equipment

Such factors as the task to be performed, length of the boom, stability of the ground supporting the mechanical equipment, wind and other weather conditions, skill of the operator, responsiveness of the mechanical equipment's controls, and type of winch line, wire or rope should be considered to determine whether an additional distance should be added to the MAD.

8.7.2.3 Working within the MAD

When mechanical equipment is operated within the MAD, each worker should be protected from the hazards that might arise from accidental mechanical equipment contact with the exposed energized lines and equipment by the use of at least one of the procedures listed below. The measures used and the associated safe work practices should minimize the risk that workers will be exposed to hazardous differences in potential.

a) The exposed energized lines and equipment exposed to contact should be covered with insulating protective material rated for the voltage involved.
b) The mechanical equipment should be insulated for the voltage involved. The un-insulated portions of the mechanical equipment should not approach the exposed energized lines and equipment any closer than the MAD.

c) A safety zone should be developed around the mechanical equipment, but should not be used without the use of one or both of the procedures listed above.

IEEE Std 524 indicates a different method of bonding depending on the type of aerial device in use.

8.7.2.4 General requirements

The following guidelines are recommended for operations near energized lines or equipment:

a) The MAD for conductive booms should exist between the boom, attachments and load, and the energized conductors or devices.

b) The minor controlled adjustments of the boom or winch should not encroach on the MAD for conductive booms.

c) When it is necessary to operate the controls at ground or vehicle level, operators should protect themselves by standing on one of the following:
   1) The metallic platform installed for this specific purpose
   2) The deck of the vehicle
   3) A portable conducting mat electrically attached to the vehicle, or
   4) An insulating platform rated for the voltage involved

Annex A

(informative)

Bibliography

[B1] Accredited Standards Committee C2-2007, National Electrical Safety Code® (NESC®), Part 4.[12, 13]

[B2] Bridges, J. E., "Environmental considerations concerning the biological effects of power frequency (50 Hz or 60 Hz) electric fields," *IEEE T&D*, vol. PAS-97, no. 1, pp. 19–32, Jan./Feb. 1978.

[B3] CIGRÉ Brochure 151, "Guidelines for Insulation Coordination in Live Working," CIGRÉ Working Group 33.07, Feb. 2000.[14]

[B4] CIGRÉ/SC 33, "Phase-to-Phase Insulation Coordination," *ELECTRA*, no. 64, 1979.

[B5] CIGRÉ Working Group 13.02 Report, "Switching Overvoltages in EHV and UHV Systems with Special Reference to Closing and Reclosing Transmission Lines."

[B6] CIGRÉ Working Group 33.10 and IEEE Task Force on TOV Report, "Temporary Overvoltages: Causes, Effects and Evaluation. "

[B7] Elek, A., and Simpson, J. W., "Safe clearance and protection against shocks during live-line work," *AIEE Transaction on Power Apparatus and Systems*, vol. 80, pt. III, pp. 897–902, Feb. 1962.

[B8] Engineering in the Safety, Maintenance and Operation of Lines (ESMOL) Subcommittee, Transmission and Distribution Committee, IEEE Power and Energy Society, "RF protection of personnel working in the vicinity of wireless communications antennas attached to electric power line structures," *2003 ESMO Conference Proceedings*.

[B9] EPRI, *Transmission Line Reference Book: 345 kV and Above*, (*Red Book*). Second Edition, 1982.[15]

[B10] EPRI document, "Full-Scale AC and Switching Impulse Tests of Helicopter-Based Live Work: 230 kV Vertical Phase Configuration with Jumper Loop," Palo Alto, CA, PSE&G and PG&E, 2007.

[B11] Esmeraldo, P. C. V., and Fonseca, C. S., "Evaluation of the Phase-to-Phase Overvoltage Characteristics due to Switching Surges for Application on Risk of Failure Statistical Methods in Non-Conventional Power Design," Paper 34.01, *6th ISH*, New Orleans, 1989.

[B12] "Factors in sizing protective grounds," *IEEE Transactions on Power Delivery PES*, 94 SM 607-2 PWRD, vol. 10, no. 3, pg. 1549, July 1995.

[B13] FCC 96-326, ET Docket 93-62, Report and Order: Federal Communication Commission's Guidelines for Evaluating the Environmental Effects of Radiofrequency Radiation, Aug. 1996, http://www.fcc.gov/oet/dockets/et93-62/.

---

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

[13] The NESC is available from the Institute of Electrical and Electronics Engineers, 445 Hoes Lane, P.O. Box 1331, Piscataway, NJ 08855-1331, USA (http://standards.ieee.org/).

[14] CIGRÉ publications can be obtained from the International Council on Large Electric Systems, 21 rue d'Artois, 75 008 Paris, France (http://www.cigre.org/gb/publications/brochures.asp).

[15] EPRI publications are available from the Electric Power Research Institute, 3420 Hillview Avenue, PO Box 10412, Palo Alto, CA 94303-0813 (http://www.epri.com).

[B14] FCC OET Bulletin 65, Evaluating Compliance with FCC Guidelines for Human Exposure to Radiofrequency Electromagnetic Fields, Edition 97-01, Aug. 1997, http://www.fcc.gov/oet/info/documents/bulletins/.

[B15] Gallet, G., and Leroy, G., "Expression for positive switching impulse strength suggesting a highest permissible voltage for ac systems," IEEE Conference Paper C73-408, *IEEE Transaction on Power Apparatus and Systems*, vol. PAS-92, no. 6, pg. 1808, Nov./Dec. 1973.

[B16] Gallet, G., et al., "General expression for positive switching impulse strength valid up to extra line air gaps," *IEEE Transaction on Power Apparatus and Systems*, vol. PAS-94, pp. 1989–1993, Nov./Dec. 1975.

[B17] Gallet, G., Hutzler, B., and Riu, J-P., "Analysis of the switching impulse strength of phase-to-phase air gaps," *IEEE Transactions on Power Delivery*, vol. PAS-97, no. 2, Mar./Apr. 1978.

[B18] Gela, G., Lux, A. E., Kientz, H., Gillies, D. A., Mitchell, J. D., and Lyons, P. F., "Application of Portable Protective Gaps for Live Line work on Compact 550 kV Transmission Lines," *IEEE Transactions on Power Delivery*, vol. 11, no. 3, pp. 1419–1429, July 1996.

[B19] Hileman, A., *Insulation Coordination for Power System*. New York: Marcel Dekker, 1999.

[B20] IEC 60832, Live working—Insulating sticks and attachable devices.[16]

[B21] IEC 61472, Live Working—Minimum Approach Distances for AC Systems in the Voltage Range 72,5 kV to 800 kV—A Method of Calculation.

[B22] IEEE 100™, *The Authoritative Dictionary of IEEE Standards Terms*, Seventh Edition, New York, Institute of Electrical and Electronics Engineers, Inc.[17, 18]

[B23] IEEE Committee Report, "Live-line maintenance methods," *IEEE T&D*, vol. PAS-92, pp. 1642–1648, Sept./Oct. 1973.

[B24] IEEE Committee Report, "Minimum number of good (healthy) insulator units in a string for live work," PE-020PRD, 2002. .

[B25] IEEE Committee Report, "Recommendations for safety in live-line maintenance," *IEEE T&D*, vol. PAS-87, no. 2, pp. 346–352, Feb. 1968.

[B26] IEEE Modeling and Analysis of System Transients Working Group, "Digital Computation of Electromagnetic Transients in Power Systems: Current Status," *Modeling Analysis of System Transients Using Digital Programs*, TP-133-0, pp. 1-1 to 1-19.

[B27] IEEE Modeling and Analysis of System Transients Working Group, "Modeling Guidelines for Switching Transients," *Modeling Analysis of System Transients Using Digital Programs*, TP-133-0, pp. 4-1 to 4-24.

[B28] IEEE Std 4-1995, IEEE Standard Techniques for High-Voltage Testing.

---

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

[17] IEEE publications are available from the Institute of Electrical and Electronics Engineers, 445 Hoes Lane, Piscataway, NJ 08854, USA (http://standards.ieee.org/).

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

[B29] IEEE Std 1654™-2009, IEEE Guide for RF Protection of Personnel Working in the Vicinity of Wireless Communications Antennas Attached to Electric Power Line Structures.[19]

[B30] IEEE Working Group Report, "Applications of insulators in a contaminated environment," *IEEE T&D*, vol. PAS-98, no. 5, pp. 1676–1695, Sept./Oct. 1979.

[B31] Kolcio, N., "Field measurements of leakage current in insulating gloves," *IEEE Trans. Power Apparatus Systems*, vol. PAS-104, no. 9, Sept., 1985.

[B32] Kolcio, N., Halladay, J. A., Allen, G. D., and Fromholtz, E. N., "Transient overvoltages and overcurrents on 12.47 kV distribution lines: Computer modeling results," 92 WPM 273-3 PWRD, IEEE Transaction Paper, *Winter Power Meeting*, New York City, 1992.

[B33] Kolcio, N., Halladay, J. A., Allen, G. D., and Fromholtz, E. N., "Transient overvoltages and overcurrents on 12.47 kV distribution lines: Field test results," *IEEE Transactions on Power Delivery*, ITPDE 5, vol. 7, no. 3, July 1992.

[B34] "Methods for protecting workers and the public adjacent to electric utility vehicle," *IEEE Transactions on Power Delivery PES*, 94 SM 606-4 PWRD, vol. 10, no. 2, pg. 950, Apr. 1995.

[B35] Risk, F. A. M., "Critical switching impulse strength of phase-to-phase air insulation," *IEEE Transaction on Power Delivery*, vol. 8, no. 3, pp. 1492–1506, July 1993.

[B36] Task Force 15.07.04.01, Engineering in the Safety, Maintenance and Operation of Lines (ESMOL) Subcommittee, Transmission and Distribution Committee, IEEE Power and Energy Society, "The Use of Portable Protective Air Gaps in Live Line Maintenance," *IEEE Transactions on Power Delivery*, vol. 16, no. 4, pp. 806–811, Oct. 2001.

[B37] 29 CFR 1910.97, Occupational Health and Environment Control, Subpart G, Non Ionizing Radiation, Mar. 1996, http://www.osha/OshSta_data/1910_0097.html.[20]

[B38] 29 CFR 1910.268, Special Industries, Subpart R, Telecommunications, June 1998, http://www.osha.gov/OshStd_data/1910_0268.html.

[B39] 29 CFR 1910.269, Occupational Safety and Health Standards, Subpart R, Special Industries—Electric Power Generation, Transmission, and Distribution.

[B40] 29 CFR 1926.951, Safety and Health Regulations for Construction, Subpart V, Power Transmission and Distribution—Tools and protective equipment.

[B41] Vaisman, R., et al, "Switching impulse strength of compact transmission lines," *IEEE Transactions on Power Delivery*, vol. 8, no. 3, pp. 1570–1578, July 1993.

---

[19] As this standard goes to press, IEEE Std 1654-2009 is approved but not yet published. The draft standard is, however, available from the IEEE. Anticipated publication date is July 2009. Contact the IEEE Standards Department at (732) 562-3800 for status information.

[20] CFR publications are available from the Superintendent of Documents, U.S. Government Printing Office, P.O. Box 37082, Washington, DC 20013-7082, USA (http://www.gpoa.gov/).

Annex B

(informative)

Sample distance calculations

This annex offers examples of the derivation of MAID, MTID, MAD, MAD for Tools, and MHAD using the equations from Clause 4 and the tables in Annex D.

B.1 Work at and below 72.5 kV

B.1.1 Given

Live work is to be performed on the center phase of a three-phase vertical configuration transmission line operating at a line-to-line voltage of 46.0 kV located at 4400 ft above sea level. The distances are to be in feet.

B.1.2 Data required

The following needs to be determined before live work can be done:

a) Line-to-ground MAID and line-to-line MAID is needed to determine whether sufficient space is available for the work methods to be used.

b) Line-to-ground MTID and line-to-line MTID is needed to determine the minimum clear insulation distance for the conductor support tools.

c) Line-to-ground MAD is needed to determine the minimum distance that workers at ground potential must keep from the live parts and workers at floating and live potential must keep from the items at ground potential.

d) Line-to-line MAD is needed to determine the minimum distance that workers at floating and live potential must keep from the live parts of other energized phases.

e) Line-to-ground MAD for Tools is needed to determine the minimum clear insulation distance for tools.

B.1.3 From tables in Annex D

For line-to-line voltages of 46 kV, use 45.01 to 48.00 kV from Table D.1.

a) Line-to-ground MAID = $D_{\mathrm{FT}} = 0.57$ ft

b) Line-to-line MAID = $D_{\mathrm{FT}} = 1.08$ ft

c) Line-to-ground MTID = For $V_{L\text{-}L} < 72.5$ kV MAID = MTID $D_{\mathrm{FT}} = 0.57$ ft

d) Line-to-line MTID = For $V_{L\text{-}L} < 72.5$ kV MAID = MTID $D_{\mathrm{FT}} = 1.08$ ft

e) Line-to-ground MAD $D_{\mathrm{FT}} = 2.57$ ft

f) Line-to-line MAD $D_{\mathrm{FT}} = 3.08$ ft

g) Line-to-ground MAD for Tools = For $V_{L\text{-}L} < 72.5$ kV MAD = MAD for Tools $D_{\mathrm{FT}} = 2.57$ ft

B.1.4 From calculation

$V_{L\text{-}L} = 46.0$ (Given)

$V_{L\text{-}G} = 46.0/1.732 = 26.558$ (Equation (63))

$T = 3.0$ 4.7.4.1

$TOV_{L\text{-}G\ Peak} = \sqrt{2}(V_{L\text{-}G})(T) = (1.414)(26.558)(3) = 112.7$ Equation (1)

$TOV_{L\text{-}L\ Peak} = \sqrt{2}(V_{L\text{-}L})(T) = (1.414)(46.000)(3) = 195.2$ Equation (2)

M = 2.0 ft (Table 6) 4.7.7

B.1.4.1 Find line-to-ground MAID

$D_{\mathrm{FT}} = \mathrm{Roundup}[3.28\times((((TOV_{L\text{-}G\ Peak}-36.7)/5.6)+2.75)/100)],2\ \mathrm{Places}$ Equation (4)

$D_{\mathrm{FT}} = \mathrm{Roundup}[3.28\times((((112.7-36.7)/5.6)+2.75)/100)],2\ \mathrm{Places}$

$D_{\mathrm{FT}} = \mathrm{Roundup}[3.28\times(((76.0/5.6)+2.75)/100)],2\ \mathrm{Places}$

$D_{\mathrm{FT}} = \mathrm{Roundup}[3.28\times((13.57+2.75)/100)],2\ \mathrm{Places}$

$D_{\mathrm{FT}} = \mathrm{Roundup}[3.28\times(16.321/100)],2\ \mathrm{Places}$

$D_{\mathrm{FT}} = \mathrm{Roundup}[3.28\times(0.16321)],2\ \mathrm{Places}$

$D_{\mathrm{FT}} = \mathrm{Roundup}[0.53532],2\ \mathrm{Places}$

$D_{\mathrm{FT}} = 0.54$ ft

B.1.4.2 Find line-to-line MAID

$D_{\mathrm{FT}} = \mathrm{Roundup}[3.28\times((((TOV_{L\text{-}LPeak}-63.6)/5.15)+5.65)/100)],2\ \mathrm{Places}$ Equation (8)

$D_{\mathrm{FT}} = \mathrm{Roundup}[3.28\times((((195.2-63.6)/5.15)+5.65)/100)],2\ \mathrm{Places}$

$D_{\mathrm{FT}} = \mathrm{Roundup}[3.28\times(((131.6/5.15)+5.65)/100)],2\ \mathrm{Places}$

$D_{\mathrm{FT}} = \mathrm{Roundup}[3.28\times((25.553+5.65)/100)],2\ \mathrm{Places}$

$D_{\mathrm{FT}} = \mathrm{Roundup}[3.28\times(31.2033/100)],2\ \mathrm{Places}$

$D_{\mathrm{FT}} = \mathrm{Roundup}[3.28\times(0.3121)],2\ \mathrm{Places}$

$D_{\mathrm{FT}} = \mathrm{Roundup}[1.02347],2\ \mathrm{Places}$

$D_{\mathrm{FT}} = 1.03$ ft

B.1.4.3 Find line-to-ground MTID

For $V_{L\text{-}L} < 72.5$ kV MAID = MTID 4.5.2.1

$D_{\mathrm{FT}} = 0.54$ ft

B.1.4.4 Find line-to-line MTID

For $V_{L\text{-}L} < 72.5$ kV MAID = MTID 4.5.2.1

$D_{\mathrm{FT}} = 1.03$ ft

B.1.4.5 Find line-to-ground MAD

D_{FT} = Roundup[(3.28×(((($TOV_{L\text{-}G\ Peak}$–36.7)/5.6)+2.75)/100)+M)],2 Places Equation (6)

D_{FT} = Roundup[(3.28×((((112.7–36.7)/5.6)+2.75)/100)+2.0)],2 Places

D_{FT} = Roundup[(3.28×(((76.0/5.6)+2.75)/100)+2.0)],2 Places

D_{FT} = Roundup[(3.28×((13.57+2.75)/100)+2.0)],2 Places

D_{FT} = Roundup[(3.28×(16.321/100)+2.0)],2 Places

D_{FT} = Roundup[(3.28×(0.16321)+2.0)],2 Places

D_{FT} = Roundup[(0.53532+2.0)],2 Places

D_{FT} = Roundup[2.53532],2 Places

D_{FT} = 2.54 ft

B.1.4.6 Find line-to-line MAD

D_{FT} = Roundup[(3.28×(((($TOV_{L\text{-}LPeak}$–63.6)/5.15)+5.65)/100))+M],2 Places Equation (8)

D_{FT} = Roundup[(3.28×((((195.2–63.6)/5.15)+5.65)/100))+2.0],2 Places

D_{FT} = Roundup[(3.28×(((131.6/5.15)+5.65)/100))+2.0],2 Places

D_{FT} = Roundup[(3.28×((25.553+5.65)/100))+2.0],2 Places

D_{FT} = Roundup[(3.28×(31.2033/100))+2.0],2 Places

D_{FT} = Roundup[(3.28×(0.3121))+2.0],2 Places

D_{FT} = Roundup[(1.02347)+2.0],2 Places

D_{FT} = Roundup[3.02347],2 Places

D_{FT} = 3.03 ft

B.1.4.7 Find line-to-ground MAD for Tools

For $V_{L\text{-}L}$ < 72.5 kV MAD = MAD for Tools 4.5.4.1

D_{FT} = 2.54 ft

B.2 Work above 72.5 kV

B.2.1 Given

Live work is to be performed on the center phase of a three-phase vertical configuration transmission line operating at a line-to-line voltage of 348 kV located at 4400 ft above sea level. An engineering evaluation has determined that T = 2.8.

B.2.2 Data required

The following needs to be determined before live work can be done:

a) Line-to-ground MAID and line-to-line MAID is needed to determine whether sufficient space is available for the work methods to be used.

b) Line-to-ground MTID is needed to determine the minimum clear insulation distance for the conductor support tools.

c) Line-to-ground MAD is needed to determine the minimum distance that workers at ground potential must keep from the live parts and workers at floating and live potential must keep from the items at ground potential.

d) Line-to-line MAD is needed to determine the minimum distance that workers at floating and live potential must keep from the live parts of other energized phases.

B.2.3 Using the tables in Annex D

The crew use feet and not meters for their measurement; therefore, the feet tables in Annex D will be used.

For line-to-line voltages of 348 kV, use 242.1 to 362.0 kV from Annex D.

From 362 kV in Table D.11 in Annex D, using T = 2.8

- Line-to-ground MAID = 6.66 ft
- Line-to-ground MTID = 7.25 ft
- Line-to-ground MAD = 7.66 ft
- Line-to-ground MAD for Tools = 8.25 ft
- Line-to-line MAID = 12.03 ft
- Line-to-line MAD = 13.03 ft

Since the altitude is greater than 3000 ft, find A from Table 5 4.7.6.2

A = 1.05

a) Line-to-ground MAID corrected for altitude

D_{FT} = (Line-to-ground MAID) × A Equation (77)

D_{FT} = (Line-to-ground MAID) × 1.05

$D_{\mathrm{FT}} = 6.66\ \mathrm{ft} \times 1.05$

$D_{\mathrm{FT}} = 6.99\ \mathrm{ft}$

b) Line-to-ground MTID corrected for altitude

D_{FT} = (Line-to-ground MTID) × A Equation (78)

D_{FT} = (Line-to-ground MTID) × 1.05

$D_{\mathrm{FT}} = 7.25\ \mathrm{ft} \times 1.05$

$D_{\mathrm{FT}} = 7.61\ \mathrm{ft}$

c) Line-to-ground MAD corrected for altitude

D_{FT} = ((Line-to-ground MAD) × (A) Equation (79)

D_{FT} = (Line-to-ground MAID corrected for altitude) + 1.0

$D_{\mathrm{FT}} = 6.96\ \mathrm{ft} +1.0$

$D_{\mathrm{FT}} = 7.99\ \mathrm{ft}$

d) Line-to-ground MAD for Tools corrected for altitude

D_{FT} = ((Line-to-ground MTID) × A) + M Equation (80)

D_{FT} = (Line-to-ground MTID corrected for altitude) + 1.0

$D_{\mathrm{FT}} = 7.61\ \mathrm{ft} + 1.0$

$D_{\mathrm{FT}} = 8.61\ \mathrm{ft}$

e) Line-to-line MAID corrected for altitude

D_{FT} = (Line-to-line MAID) × A Equation (81)

D_{FT} = (Line-to-line MAID) × 1.05

$D_{\mathrm{FT}} = 12.03\ \mathrm{ft} \times 1.05$

$D_{\mathrm{FT}} = 12.6315 = 12.64\ \mathrm{ft}$

f) Line-to-line MAD corrected for altitude

D_{FT} = ((Line-to-line MAID) × A) + M Equation (78)

D_{FT} = (Line-to-line MAID corrected for altitude) + 1.0

$D_{\mathrm{FT}} = 12.64\ \mathrm{ft} +1.0$

$D_{\mathrm{FT}} = 13.64$ ft

B.2.4 Using the formulas in Clause 4

The crew use feet and not meters for their measurement; therefore, the resulting distances in meters will be converted to feet.

Given

$V_{L\text{-}L} = 348$
$T = 2.8$ (Phase-to-ground)
Worksite altitude 4400 ft above sea level

Find the value of "a" to use

$V_{L\text{-}G} = V_{L\text{-}L}/1.732 = 348/1.732 = 200.92$ kV   Equation (63)

$V_{Peak} = 1.414(V_{L\text{-}G})(T) = 1.414 \times 200.92 \times 2.8 = 795.486$ kV   Equation (54)

Since V_{Peak} is greater than 630 kV, "a" must be calculated.

"a" for the line-to-ground work

For V_{Peak} from 635.1 to 915.0 kV

$\mathrm{a} = ((V_{Peak})\text{-}635) \times 0.00000714$ Equation (56)

$\mathrm{a} = (795.5\text{-}635) \times 0.00000714 = 160.5 \times 0.00000714$

$\mathrm{a} = 0.0011395$

Since the altitude is greater than 3000 ft, find A from Table 5 (feet).

A = 1.05 (from Table 5, feet)   4.7.6.2

M = 1.0 ft (from Table 6)   4.7.7

$C_1 = 0.01$ 4.7.1.3

$C_2 = 1.1$ or 110% of C_1 4.7.2.2

Calculation using the above

a) **MAID in feet for line-to-ground work**

$D_{\mathrm{FT}} = [(C_1 + \mathrm{a}) \times (T) \times (V_{L\text{-}G}) \times (\mathrm{A})]$ rounded up to 2 decimal places   Equation (18)

$D_{\mathrm{FT}} = [((0.01) + 0.0011395) \times (2.8) \times (200.9) \times (1.05)]$

$D_{\mathrm{FT}} = [(0.0111395) \times (2.8) \times (200.9) \times (1.05)]$

$D_{\mathrm{FT}} = [6.579501] = 6.58$

b) **MTID in feet for line-to-ground work**

$D_{\mathrm{FT}} = [(((C_1)\times(C_2)+\mathrm{a})\times(T)\times(V_{L\text{-}G})\times(\mathrm{A})]$ rounded up to 2 decimal places Equation (20)

$D_{\mathrm{FT}} = [(((0.01)\times(1.1))+0.0011395)\times(2.8)\times(200.9)\times(1.05)]$

$D_{\mathrm{FT}} = [((0.011+0.0011395)\times(2.8)\times(200.9)\times(1.05)]$

$D_{\mathrm{FT}} = [(0.0121395)\times(2.8)\times(200.9)\times(1.05)]$

$D_{\mathrm{FT}} = [7.170147] = 7.17$

c) **MAD in feet for line-to-ground work**

$D_{\mathrm{FT}} = [((C_1+\mathrm{a})\times(T)\times(V_{L\text{-}G})\times(\mathrm{A}))+\mathrm{M}]$ rounded up to 2 decimal places Equation (22)

$D_{\mathrm{FT}} = [((0.01+0.0011365)\times(2.8)\times(200.9)\times(1.05))+1.0]$

$D_{\mathrm{FT}} = [(0.0111395)\times(2.8)\times(200.9)\times(1.05))+1.0]$

$D_{\mathrm{FT}} = [6.579501+1.0]$

$D_{\mathrm{FT}} = 7.579501 = 7.58$

d) **MAD for Tools in feet for line-to-ground work**

$D_{\mathrm{FT}} = [(((C_1)\times(C_2))+\mathrm{a})\times(T)\times(V_{L\text{-}G})\times(\mathrm{A}))+\mathrm{M}]$
rounded up to 2 decimal places Equation (24)

$D_{\mathrm{FT}} = [(((0.01)\times(1.1)+0.0011365)\times(2.8)\times(200.9)\times(1.05))+1.0]$

$D_{\mathrm{FT}} = [(((0.011+0.0010675)\times(2.8)\times(200.9)\times(1.05))+1.0]$

$D_{\mathrm{FT}} = [((0.0121395)\times(2.8)\times(200.9)\times(1.05))+1.0]$

$D_{\mathrm{FT}} = [7.170147+1.0]$

$D_{\mathrm{FT}} = 8.170147 = 8.17$

e) **MAID in feet for line-to-line work**

$D_{\mathrm{FT}} = 3.281\times[8/[(4875/[(((1.35)(T))+0.45))(V_{L\text{-}L})]-1]\times(\mathrm{A})]$
rounded up to 2 decimal places Equation (30)

$D_{\mathrm{FT}} = 3.281\times[8/(4875/[(((1.35)\times(2.8))+0.45))\times(348)])-1]\times(1.05)]$

$D_{\mathrm{FT}} = 3.281\times[8/(4875/[((3.78)+0.45))\times(348)])-1]\times(1.05)]$

$D_{\mathrm{FT}} = 3.281\times[8/(4875/[(4.23)\times(348)])-1]\times(1.05)]$

$D_{\mathrm{FT}} = 3.281\times[8/(4875/[1472.04])-1]\times(1.05)]$

$D_{\mathrm{FT}} = 3.281\times[8/(3.3117)-1]\times(1.05)]$

$D_{\mathrm{FT}} = 3.281\times[8/2.3117]\times(1.05)]$

$D_{\mathrm{FT}} = 3.281\times[3.4606]\times(1.05)]$

$D_{\mathrm{FT}} = 11.922134 = 11.93$

f) **MAD in feet for line-to-line work**

$D_{\mathrm{FT}} = [3.281\times[8/[(4875/[(((1.35)(T))+0.45))(V_{L\text{-}L})]\text{-}1]\times(\mathrm{A})]]+\mathrm{M}$
rounded up to 2 decimal places Equation (34)

$D_{\mathrm{FT}} = [3.281\times[8/(4875/[(((1.35)\times(2.8))+0.45))\times(348)])\text{-}1]\times(1.05)]]+1.0$

$D_{\mathrm{FT}} = [3.281\times[8/(4875/[((3.78)+0.45))\times(348)])\text{-}1]\times(1.05)]]+1.0$

$D_{\mathrm{FT}} = [3.281\times[8/(4875/[(4.23)\times(348)])\text{-}1]\times(1.05)]]+1.0$

$D_{\mathrm{FT}} = [3.281\times[8/(4875/[1472.04])\text{-}1]\times(1.05)]]+1.0$

$D_{\mathrm{FT}} = [3.281\times[8/(3.3117)\text{-}1]\times(1.05)]]+1.0$

$D_{\mathrm{FT}} = [3.281\times[8/2.3117]\times(1.05)]]+1.0$

$D_{\mathrm{FT}} = [3.281\times[3.4606]\times(1.05)]]+1.0$

$D_{\mathrm{FT}} = [11.922134]+1.0$

$D_{\mathrm{FT}} = 12.922134 = 12.93$

The calculated distances for MAID and MAD are lower for 348 kV than the table values, which are based on 362 kV.

Annex C

(informative)

Sample PPAG calculations

The two calculation examples in this annex are for the PPAG described in 4.8.2.1.

Normally the PPAGs are installed only on one phase adjacent to the worksite. The reduced T_{PPAG}, $MAID_{L\text{-}G}$, and $MAD_{L\text{-}G}$ values apply only to the phase on which the PPAG is installed.

The $MAID_{L\text{-}L}$ and $MAD_{L\text{-}L}$ values will also be lower, but sufficient data do not exist to determine them. The $MAID_{L\text{-}L}$ and $MAD_{L\text{-}L}$ values for the worksite T with the PPAG should be used.

If there is a requirement to lower the line-to-ground and line-to-line MAID and MAD, PPAGs are required on all the phases involved.

C.1 Finding line-to-ground MAID and the MAD obtained by using PPAG

To find the line-to-ground MAID and the MAD that can be obtained by using a PPAG, the steps are as follows:

a) Select the appropriate (statistical) withstand voltage of the PPAG based on system requirements and the acceptable probability of gap sparkover. This is the line-to-ground peak voltage that the user is willing to accept. Line-to-ground peak voltages above this level will in all probability cause the gap to spark over and fault the line.

b) From PPAG test data, select a gap distance that provides a (statistical) withstand voltage (85% of gap V_{50}) equal to or greater than the one selected in step a).

c) Use the gap's (statistical sparkover) +2σ sparkover voltage (110% of gap V_{50}) to determine the line-to-ground peak voltage ($V_{PPAG\ L\text{-}G\ Peak}$) at which the gap will spark over.

d) The per-unit value of the PPAG can be determined using the following formula:

$$T_{PPAG} = \frac{V_{PPAG\_L-GPeak}}{V_{L-G\_Peak}}$$

To determine worksite per unit, most of PPAG users add 0.2 p.u. to the PPAG p.u. to give an additional margin of safety.

$$T_{WorkSite} = T_{PPAG} + 0.2$$

e) The line-to-ground MAID and MAD can be obtained by calculation or the Annex D tables, using the $T_{WorkSite}$.

Example: Assume a 500 kV line subject to 2.4 p.u. TOV and operating at a 550 kV maximum operating voltage. The altitude of the worksite is less than 3000 ft above sea level. The user is willing to accept the risk of limiting the maximum per-unit TOV to 125% of the maximum operating voltage during the time that the PPAG is installed on the line. Therefore, the minimum statistical withstand peak voltage of the PPAG is

Given

$V_{L\text{-}L} = 550$
$T = 1.25$

Then

$$V_{L\text{-}G\ Peak} = (V_{L\text{-}L})(\surd 2)(T)/\surd 3$$

$$V_{L\text{-}G\ Peak} = (550)(1.414)(1.25)/1.732$$

$$V_{L\text{-}G\ Peak} = 972.125/1.732$$

$$V_{L\text{-}G\ Peak} = 561.27$$

f) Using test data obtained from the particular protective gap tool geometry, bundle geometry, and varying gap distances to select a gap distance that has a V_{50} equal to or greater than

$$V_{50} = V_{L\text{-}G\ Peak}/(3\sigma)$$

$$V_{50\,=}\ 561.27/0.85 = 660.31$$

Example: If tests on a particular protective gap with a 4.0 ft gap spacing had a $V_{50\ \mathrm{Gap}}$ equal to 665 $\mathrm{kV}_{\mathrm{L\text{-}G\ Peak}}$, select this gap spacing.

g) The protective gap's (statistical sparkover) +2σ voltage is as follows:

$$V_{PPAG\ L\text{-}G\ Peak} = V_{50\ Gap}/{+2\sigma}$$

$$V_{PPAG\ L\text{-}G\ Peak} = 665/1.10$$

$$V_{PPAG\ L\text{-}G\ Peak} = 732$$

h) $T_{PPAG} = V_{PPAG\ L\text{-}G\ Peak}\,/\,V_{L\text{-}G\ Peak}$

$T_{PPAG} = 732/((550\times 1.414)/1.732)$

$T_{PPAG} = 732/449 = 1.63$ rounded up to 1.7

i) Using a safety factor of 0.2 p.u.

$$\mathrm{T}_{\mathrm{WORKSITE}} = \mathrm{T}_{\mathrm{PPAG}} + 0.02 = 1.7 + 0.2 = 1.9$$

j) From Annex D tables for 550 kV (feet), using $T = 1.9$

Line-to-ground MAID = 6.98 ft

Line-to-ground MTID = 7.58 ft

Line-to-ground MAD = 7.98 ft

Line-to-ground MAD for Tools = 8.58 ft

Annex D

(informative)

Distance tables

D.1 General information for using the tables in this annex

a) The data used to formulate these tables was obtained from test data taken with atmospheric conditions that are defined as temperatures above freezing, wind speed under 15 mph, unsaturated air, normal barometer (30 in of mercury at sea level), uncontaminated air, and clean and dry insulators. If these atmospheric conditions do not exist, extra care must be taken.

b) Voltages used in the ac tables are line-to-line voltages from a solidly grounded wye connection source. For other configurations, see 4.7.5.7.

c) Tables are calculated with an altitude correction of A = 1. For worksite altitudes greater than 900 m above sea level, the distance value must be corrected for altitude. See 4.7.6 and Table 5.

D.2 Adjusting *T* for use in tables when actual line voltage is lower than voltage on which table has been calculated

The tables in this annex are calculated using the highest voltage in the voltage class. When using the tables to determine distance and the actual line voltage is significantly less than the voltage on which the table has been calculated, the value of *T* can be adjusted.

Example: Adjusting a *T* of 2.23 based on the line $V_{L\text{-}L}$ of 288 kV and highest voltage in the table range is 362 kV:

— $T_{Table} = ((T_{Line}) \times (V_{L\text{-}L}\ \text{Line}))/(V_{L\text{-}L}\ \text{Table})$ rounded up to 1 decimal place

— *T* for 362 kV = (*T* for 285 kV) × (288/362) = (2.23) × (0.80) = 1.78

— *T* for 362 kV is rounded up to 1 decimal place = 1.8

Table D.1—For energized work between 50 V and 72.5 kV

Voltage line-to-line (kV)	**Line-to-ground work**				**Line-to-line work**			
	MAID (m)	**MAD (m)**	**MAID (ft)**	**MAD (ft)**	**MAID (m)**	**MAD (m)**	**MAID (ft)**	**MAD (ft)**
0.050 to 0.300	Avoid contact	Avoid contact	Avoid contact	Avoid contact	Avoid contact	Avoid contact	Avoid contact	Avoid contact
0.301 to 0.750	0.02	0.32	0.07	1.07	0.02	0.32	0.07	1.07
0.751 to 5.00	0.02	0.63	0.07	2.07	0.02	0.63	0.07	2.07
5.01 to 7.50	0.02	0.63	0.07	2.07	0.02	0.63	0.07	2.07
7.51 to 9.00	0.02	0.63	0.07	2.07	0.02	0.63	0.07	2.07
9.01 to 12.00	0.02	0.63	0.07	2.07	0.04	0.65	0.11	2.11
12.01 to 15.00	0.03	0.64	0.10	2.10	0.06	0.67	0.19	2.19
15.01 to 18.00	0.05	0.66	0.14	2.14	0.09	0.70	0.27	2.27
18.01 to 21.00	0.06	0.67	0.18	2.18	0.11	0.72	0.35	2.35
21.01 to 24.00	0.07	0.68	0.22	2.22	0.14	0.75	0.43	2.43
24.01 to 27.00	0.09	0.70	0.27	2.27	0.16	0.77	0.51	2.51
27.01 to 30.00	0.10	0.71	0.31	2.31	0.19	0.80	0.60	2.60
30.01 to 33.00	0.11	0.72	0.35	2.35	0.21	0.82	0.68	2.68
33.01 to 36.00	0.12	0.73	0.40	2.40	0.23	0.84	0.76	2.76
36.01 to 39.00	0.14	0.75	0.44	2.44	0.26	0.87	0.84	2.84
39.01 to 42.00	0.15	0.76	0.48	2.48	0.28	0.89	0.92	2.92
42.01 to 45.00	0.16	0.77	0.53	2.53	0.31	0.92	1.00	3.00
45.01 to 48.00	0.18	0.79	0.57	2.57	0.33	0.94	1.08	3.08
48.01 to 51.00	0.19	0.80	0.61	2.61	0.36	0.97	1.16	3.16
51.01 to 54.00	0.20	0.81	0.65	2.65	0.38	0.99	1.24	3.24
54.01 to 57.00	0.22	0.83	0.70	2.70	0.41	1.02	1.33	3.33
57.01 to 60.00	0.23	0.84	0.74	2.74	0.43	1.04	1.41	3.41
60.01 to 63.00	0.24	0.85	0.78	2.78	0.46	1.07	1.49	3.49
63.01 to 66.00	0.26	0.87	0.83	2.83	0.48	1.09	1.57	3.57
66.01 to 69.00	0.27	0.88	0.87	2.87	0.51	1.12	1.65	3.65
69.01 to 72.50	0.28	0.89	0.92	2.92	0.54	1.15	1.74	3.74

Table D.2—Meters, 121 kV, line-to-line: For work between 72.6 and 121 kV

T (p.u.)	**Line-to-ground work**					**Line-to-line work**		
	MAID (m)	**MTID (m)**	**MAD (m)**	**MAD for Tools (m)**	**MHID (m)**	**MAID (m)**	**MAD (m)**	**MHID (m)**
1.5	0.32	0.36	0.62	0.66	0.69	0.56	0.86	0.94
1.6	0.35	0.38	0.65	0.68	0.71	0.59	0.89	0.98
1.7	0.37	0.40	0.67	0.70	0.73	0.62	0.92	1.02
1.8	0.39	0.43	0.69	0.73	0.76	0.66	0.96	1.05
1.9	0.41	0.45	0.71	0.75	0.78	0.69	0.99	1.09
2.0	0.43	0.47	0.73	0.77	0.80	0.72	1.02	1.13
2.1	0.45	0.50	0.75	0.80	0.83	0.76	1.06	1.16
2.2	0.47	0.52	0.77	0.82	0.85	0.79	1.09	1.20
2.3	0.49	0.54	0.79	0.84	0.87	0.83	1.13	1.24
2.4	0.52	0.57	0.82	0.87	0.90	0.86	1.16	1.28
2.5	0.54	0.59	0.84	0.89	0.92	0.90	1.20	1.31
2.6	0.56	0.61	0.86	0.91	0.94	0.93	1.23	1.35
2.7	0.58	0.64	0.88	0.94	0.97	0.97	1.27	1.39
2.8	0.60	0.66	0.90	0.96	0.99	1.00	1.30	1.43
2.9	0.62	0.68	0.92	0.98	1.01	1.04	1.34	1.47
3.0	0.64	0.71	0.94	1.01	1.04	1.07	1.37	1.51
3.1	0.67	0.73	0.97	1.03	1.06	1.11	1.41	1.55
3.2	0.69	0.75	0.99	1.05	1.08	1.15	1.45	1.59
3.3	0.71	0.78	1.01	1.08	1.11	1.18	1.48	1.63
3.4	0.73	0.80	1.03	1.10	1.13	1.22	1.52	1.67
3.5	0.75	0.82	1.05	1.12	1.15	1.26	1.56	1.71

Table D.3—Feet, 121 kV, line-to-line: For work between 72.6 and 121 kV

T **(p.u.)**	**Line-to-ground work**					**Line-to-line work**		
	MAID (ft)	**MTID (ft)**	**MAD (ft)**	**MAD for Tools (ft)**	**MHID (ft)**	**MAID (ft)**	**MAD (ft)**	**MHID (ft)**
1.5	1.05	1.16	2.05	2.16	2.26	1.82	2.82	3.11
1.6	1.12	1.23	2.12	2.23	2.33	1.93	2.93	3.22
1.7	1.19	1.31	2.19	2.31	2.41	2.04	3.04	3.34
1.8	1.26	1.39	2.26	2.39	2.49	2.15	3.15	3.46
1.9	1.33	1.47	2.33	2.47	2.57	2.25	3.25	3.58
2.0	1.40	1.54	2.40	2.54	2.64	2.36	3.36	3.70
2.1	1.47	1.62	2.47	2.62	2.72	2.48	3.48	3.82
2.2	1.54	1.70	2.54	2.70	2.80	2.59	3.59	3.94
2.3	1.61	1.77	2.61	2.77	2.87	2.70	3.70	4.07
2.4	1.68	1.85	2.68	2.85	2.95	2.81	3.81	4.19
2.5	1.75	1.93	2.75	2.93	3.03	2.93	3.93	4.32
2.6	1.82	2.00	2.82	3.00	3.10	3.04	4.04	4.45
2.7	1.89	2.08	2.89	3.08	3.18	3.16	4.16	4.57
2.8	1.96	2.16	2.96	3.16	3.26	3.27	4.27	4.70
2.9	2.03	2.23	3.03	3.23	3.33	3.39	4.39	4.83
3.0	2.10	2.31	3.10	3.31	3.41	3.51	4.51	4.96
3.1	2.17	2.39	3.17	3.39	3.49	3.63	4.63	5.09
3.2	2.24	2.46	3.24	3.46	3.56	3.75	4.75	5.23
3.3	2.31	2.54	3.31	3.54	3.64	3.87	4.87	5.36
3.4	2.38	2.62	3.38	3.62	3.72	4.00	5.00	5.49
3.5	2.45	2.69	3.45	3.69	3.79	4.12	5.12	5.63

Table D.4—Meters, 145 kV, line-to-line: For work between 121.1 and 145 kV

T **(p.u.)**	**Line-to-ground work**					**Line-to-line work**		
	MAID (m)	**MTID (m)**	**MAD (m)**	**MAD for Tools (m)**	**MHID (m)**	**MAID (m)**	**MAD (m)**	**MHID (m)**
1.5	0.39	0.43	0.69	0.73	0.76	0.68	0.98	1.08
1.6	0.41	0.45	0.71	0.75	0.78	0.72	1.02	1.12
1.7	0.44	0.48	0.74	0.78	0.81	0.76	1.06	1.16
1.8	0.46	0.51	0.76	0.81	0.84	0.80	1.10	1.21
1.9	0.49	0.54	0.79	0.84	0.87	0.84	1.14	1.25
2.0	0.52	0.57	0.82	0.87	0.90	0.88	1.18	1.30
2.1	0.54	0.59	0.84	0.89	0.92	0.92	1.22	1.35
2.2	0.57	0.62	0.87	0.92	0.95	0.97	1.27	1.39
2.3	0.59	0.65	0.89	0.95	0.98	1.01	1.31	1.44
2.4	0.62	0.68	0.92	0.98	1.01	1.05	1.35	1.49
2.5	0.64	0.71	0.94	1.01	1.04	1.10	1.40	1.54
2.6	0.67	0.73	0.97	1.03	1.06	1.14	1.44	1.58
2.7	0.69	0.76	0.99	1.06	1.09	1.18	1.48	1.63
2.8	0.72	0.79	1.02	1.09	1.12	1.23	1.53	1.68
2.9	0.75	0.82	1.05	1.12	1.15	1.27	1.57	1.73
3.0	0.77	0.85	1.07	1.15	1.18	1.32	1.62	1.78
3.1	0.80	0.88	1.10	1.18	1.21	1.37	1.67	1.83
3.2	0.82	0.90	1.12	1.20	1.23	1.41	1.71	1.88
3.3	0.85	0.93	1.15	1.23	1.26	1.46	1.76	1.94
3.4	0.87	0.96	1.17	1.26	1.29	1.51	1.81	1.99
3.5	0.90	0.99	1.20	1.29	1.32	1.56	1.86	2.04

Table D.5—Feet, 145 kV, line-to-line: For work between 121.1 and 145 kV

T (p.u.)	Line-to-ground work					Line-to-line work		
	MAID (ft)	**MTID (ft)**	**MAD (ft)**	**MAD for Tools (ft)**	**MHID (ft)**	**MAID (ft)**	**MAD (ft)**	**MHID (ft)**
1.5	1.26	1.39	2.26	2.39	2.49	2.22	3.22	3.54
1.6	1.34	1.48	2.34	2.48	2.58	2.35	3.35	3.68
1.7	1.43	1.57	2.43	2.57	2.67	2.48	3.48	3.83
1.8	1.51	1.66	2.51	2.66	2.76	2.61	3.61	3.97
1.9	1.60	1.75	2.60	2.75	2.85	2.75	3.75	4.12
2.0	1.68	1.85	2.68	2.85	2.95	2.88	3.88	4.27
2.1	1.76	1.94	2.76	2.94	3.04	3.02	4.02	4.42
2.2	1.85	2.03	2.85	3.03	3.13	3.16	4.16	4.58
2.3	1.93	2.12	2.93	3.12	3.22	3.30	4.30	4.73
2.4	2.01	2.22	3.01	3.22	3.32	3.44	4.44	4.89
2.5	2.10	2.31	3.10	3.31	3.41	3.59	4.59	5.04
2.6	2.18	2.40	3.18	3.40	3.50	3.73	4.73	5.20
2.7	2.27	2.49	3.27	3.49	3.59	3.88	4.88	5.36
2.8	2.35	2.58	3.35	3.58	3.68	4.02	5.02	5.52
2.9	2.43	2.68	3.43	3.68	3.78	4.17	5.17	5.69
3.0	2.52	2.77	3.52	3.77	3.87	4.32	5.32	5.85
3.1	2.60	2.86	3.60	3.86	3.96	4.47	5.47	6.02
3.2	2.68	2.95	3.68	3.95	4.05	4.63	5.63	6.19
3.3	2.77	3.04	3.77	4.04	4.14	4.78	5.78	6.36
3.4	2.85	3.14	3.85	4.14	4.24	4.94	5.94	6.53
3.5	2.94	3.23	3.94	4.23	4.33	5.09	6.09	6.70

Table D.6—Meters, 169 kV, line-to-line: For work between 145.1 and 169 kV

T (p.u.)	Line-to-ground work					Line-to-line work		
	MAID (m)	**MTID (m)**	**MAD (m)**	**MAD for Tools (m)**	**MHID (m)**	**MAID (m)**	**MAD (m)**	**MHID (m)**
1.5	0.45	0.50	0.75	0.80	0.83	0.80	1.10	1.21
1.6	0.48	0.53	0.78	0.83	0.86	0.85	1.15	1.26
1.7	0.51	0.56	0.81	0.86	0.89	0.90	1.20	1.32
1.8	0.54	0.59	0.84	0.89	0.92	0.95	1.25	1.37
1.9	0.57	0.63	0.87	0.93	0.96	1.00	1.30	1.43
2.0	0.60	0.66	0.90	0.96	0.99	1.05	1.35	1.48
2.1	0.63	0.69	0.93	0.99	1.02	1.10	1.40	1.54
2.2	0.66	0.72	0.96	1.02	1.05	1.15	1.45	1.59
2.3	0.69	0.76	0.99	1.06	1.09	1.20	1.50	1.65
2.4	0.72	0.79	1.02	1.09	1.12	1.25	1.55	1.71
2.5	0.75	0.82	1.05	1.12	1.15	1.31	1.61	1.77
2.6	0.78	0.86	1.08	1.16	1.19	1.36	1.66	1.83
2.7	0.81	0.89	1.11	1.19	1.22	1.41	1.71	1.89
2.8	0.84	0.92	1.14	1.22	1.25	1.47	1.77	1.95
2.9	0.87	0.95	1.17	1.25	1.28	1.52	1.82	2.01
3.0	0.90	0.99	1.20	1.29	1.32	1.58	1.88	2.07
3.1	0.93	1.02	1.23	1.32	1.35	1.64	1.94	2.13
3.2	0.96	1.05	1.26	1.35	1.38	1.70	2.00	2.19
3.3	0.99	1.08	1.29	1.38	1.41	1.75	2.05	2.26
3.4	1.02	1.12	1.32	1.42	1.45	1.81	2.11	2.32
3.5	1.05	1.15	1.35	1.45	1.48	1.87	2.17	2.39

Table D.7—Feet, 169 kV, line-to-line: For work between 145.1 and 169 kV

T **(p.u.)**	**Line-to-ground work**					**Line-to-line work**		
	MAID (ft)	**MTID (ft)**	**MAD (ft)**	**MAD for Tools (ft)**	**MHID (ft)**	**MAID (ft)**	**MAD (ft)**	**MHID (ft)**
1.5	1.47	1.61	2.47	2.61	2.71	2.62	3.62	3.98
1.6	1.57	1.72	2.57	2.72	2.82	2.77	3.77	4.15
1.7	1.66	1.83	2.66	2.83	2.93	2.93	3.93	4.33
1.8	1.76	1.94	2.76	2.94	3.04	3.10	4.10	4.50
1.9	1.86	2.04	2.86	3.04	3.14	3.26	4.26	4.68
2.0	1.96	2.15	2.96	3.15	3.25	3.42	4.42	4.86
2.1	2.05	2.26	3.05	3.26	3.36	3.59	4.59	5.05
2.2	2.15	2.37	3.15	3.37	3.47	3.76	4.76	5.23
2.3	2.25	2.47	3.25	3.47	3.57	3.93	4.93	5.42
2.4	2.35	2.58	3.35	3.58	3.68	4.10	5.10	5.61
2.5	2.44	2.69	3.44	3.69	3.79	4.27	5.27	5.80
2.6	2.54	2.80	3.54	3.80	3.90	4.45	5.45	5.99
2.7	2.64	2.90	3.64	3.90	4.00	4.63	5.63	6.19
2.8	2.74	3.01	3.74	4.01	4.11	4.81	5.81	6.39
2.9	2.83	3.12	3.83	4.12	4.22	4.99	5.99	6.59
3.0	2.93	3.22	3.93	4.22	4.32	5.18	6.18	6.79
3.1	3.03	3.33	4.03	4.33	4.43	5.36	6.36	7.00
3.2	3.13	3.44	4.13	4.44	4.54	5.55	6.55	7.21
3.3	3.22	3.55	4.22	4.55	4.65	5.74	6.74	7.42
3.4	3.32	3.65	4.32	4.65	4.75	5.94	6.94	7.63
3.5	3.42	3.76	4.42	4.76	4.86	6.13	7.13	7.85

Table D.8—Meters, 242 kV, line-to-line: For work between 169.1 and 242 kV

T (p.u.)	Line-to-ground work					Line-to-line work		
	MAID (m)	MTID (m)	MAD (m)	MAD for Tools (m)	MHID (m)	MAID (m)	MAD (m)	MHID (m)
1.5	0.64	0.71	0.94	1.01	1.04	1.20	1.50	1.65
1.6	0.69	0.75	0.99	1.05	1.08	1.27	1.57	1.73
1.7	0.73	0.80	1.03	1.10	1.13	1.35	1.65	1.81
1.8	0.77	0.85	1.07	1.15	1.18	1.43	1.73	1.90
1.9	0.81	0.90	1.11	1.20	1.23	1.50	1.80	1.98
2.0	0.86	0.94	1.16	1.24	1.27	1.59	1.89	2.07
2.1	0.90	0.99	1.20	1.29	1.32	1.67	1.97	2.16
2.2	0.94	1.04	1.24	1.34	1.37	1.75	2.05	2.25
2.3	0.98	1.08	1.28	1.38	1.41	1.84	2.14	2.35
2.4	1.03	1.13	1.33	1.43	1.46	1.92	2.22	2.44
2.5	1.07	1.18	1.37	1.48	1.51	2.01	2.31	2.54
2.6	1.11	1.22	1.41	1.52	1.55	2.10	2.40	2.64
2.7	1.15	1.27	1.45	1.57	1.60	2.19	2.49	2.74
2.8	1.20	1.32	1.50	1.62	1.65	2.28	2.58	2.84
2.9	1.24	1.36	1.54	1.66	1.69	2.38	2.68	2.94
3.0	1.28	1.41	1.58	1.71	1.74	2.47	2.77	3.05
3.1	1.33	1.46	1.63	1.76	1.79	2.57	2.87	3.16
3.2	1.37	1.50	1.67	1.80	1.83	2.67	2.97	3.27
3.3	1.43	1.57	1.73	1.87	1.90	2.77	3.07	3.38
3.4	1.49	1.64	1.79	1.94	1.97	2.87	3.17	3.49
3.5	1.56	1.70	1.86	2.00	2.04	2.98	3.28	3.61

Table D.9—Feet, 242 kV, line-to-line: For work between 169.1 and 242 kV

T (p.u.)	Line-to-ground work					Line-to-line work		
	MAID (ft)	**MTID (ft)**	**MAD (ft)**	**MAD for Tools (ft)**	**MHID (ft)**	**MAID (ft)**	**MAD (ft)**	**MHID (ft)**
1.5	2.10	2.31	3.10	3.31	3.41	3.91	4.91	5.40
1.6	2.24	2.46	3.24	3.46	3.56	4.16	5.16	5.68
1.7	2.38	2.62	3.38	3.62	3.72	4.41	5.41	5.95
1.8	2.52	2.77	3.52	3.77	3.87	4.67	5.67	6.23
1.9	2.66	2.93	3.66	3.93	4.03	4.93	5.93	6.52
2.0	2.80	3.08	3.80	4.08	4.18	5.19	6.19	6.81
2.1	2.94	3.23	3.94	4.23	4.33	5.46	6.46	7.10
2.2	3.08	3.39	4.08	4.39	4.49	5.73	6.73	7.40
2.3	3.22	3.54	4.22	4.54	4.64	6.01	7.01	7.71
2.4	3.36	3.69	4.36	4.69	4.79	6.29	7.29	8.02
2.5	3.50	3.85	4.50	4.85	4.95	6.58	7.58	8.34
2.6	3.64	4.00	4.64	5.00	5.10	6.87	7.87	8.66
2.7	3.78	4.15	4.78	5.15	5.25	7.17	8.17	8.99
2.8	3.92	4.31	4.92	5.31	5.41	7.47	8.47	9.32
2.9	4.06	4.46	5.06	5.46	5.56	7.78	8.78	9.66
3.0	4.20	4.62	5.20	5.62	5.72	8.10	9.10	10.01
3.1	4.34	4.77	5.34	5.77	5.87	8.42	9.42	10.36
3.2	4.48	4.92	5.48	5.92	6.02	8.75	9.75	10.72
3.3	4.67	5.13	5.67	6.13	6.24	9.08	10.08	11.09
3.4	4.88	5.36	5.88	6.36	6.47	9.42	10.42	11.46
3.5	5.09	5.58	6.09	6.58	6.70	9.76	10.76	11.84

Table D.10—Meters, 362 kV, line-to-line: For work between 242.1 and 362 kV

T **(p.u.)**	**Line-to-ground work**					**Line-to-line work**		
	MAID (m)	**MTID (m)**	**MAD (m)**	**MAD for Tools (m)**	**MHID (m)**	**MAID (m)**	**MAD (m)**	**MHID (m)**
1.5	0.96	1.06	1.26	1.36	1.39	1.81	2.11	2.32
1.6	1.02	1.13	1.32	1.43	1.46	1.93	2.23	2.45
1.7	1.09	1.20	1.39	1.50	1.53	2.05	2.35	2.59
1.8	1.15	1.27	1.45	1.57	1.60	2.18	2.48	2.73
1.9	1.22	1.34	1.52	1.64	1.67	2.31	2.61	2.87
2.0	1.28	1.41	1.58	1.71	1.74	2.45	2.75	3.02
2.1	1.34	1.48	1.64	1.78	1.81	2.59	2.89	3.17
2.2	1.42	1.56	1.72	1.86	1.89	2.73	3.03	3.33
2.3	1.52	1.66	1.82	1.96	2.00	2.87	3.17	3.49
2.4	1.62	1.77	1.92	2.07	2.11	3.02	3.32	3.66
2.5	1.72	1.87	2.02	2.17	2.22	3.18	3.48	3.83
2.6	1.82	1.98	2.12	2.28	2.33	3.34	3.64	4.00
2.7	1.93	2.10	2.23	2.40	2.45	3.50	3.80	4.18
2.8	2.03	2.21	2.33	2.51	2.57	3.67	3.97	4.36
2.9	2.15	2.33	2.45	2.63	2.69	3.84	4.14	4.56
3.0	2.26	2.45	2.56	2.75	2.81	4.02	4.32	4.75
3.1	2.38	2.57	2.68	2.87	2.94	4.20	4.50	4.95
3.2	2.50	2.70	2.80	3.00	3.08	4.39	4.69	5.16
3.3	2.62	2.83	2.92	3.13	3.21	4.59	4.89	5.38
3.4	2.75	2.96	3.05	3.26	3.35	4.79	5.09	5.60
3.5	2.88	3.10	3.18	3.40	3.50	5.00	5.30	5.83

Table D.11—Feet, 362 kV, line-to-line: For work between 242.1 and 362 kV

T **(p.u.)**	**Line-to-ground work**					**Line-to-line work**		
	MAID (ft)	**MTID (ft)**	**MAD (ft)**	**MAD for Tools (ft)**	**MHID (ft)**	**MAID (ft)**	**MAD (ft)**	**MHID (ft)**
1.5	3.14	3.45	4.14	4.45	4.55	5.92	6.92	7.61
1.6	3.35	3.68	4.35	4.68	4.78	6.32	7.32	8.05
1.7	3.56	3.91	4.56	4.91	5.01	6.72	7.72	8.50
1.8	3.77	4.14	4.77	5.14	5.24	7.15	8.15	8.96
1.9	3.98	4.37	4.98	5.37	5.47	7.58	8.58	9.43
2.0	4.19	4.60	5.19	5.60	5.70	8.02	9.02	9.92
2.1	4.39	4.83	5.39	5.83	5.93	8.47	9.47	10.42
2.2	4.65	5.11	5.65	6.11	6.22	8.94	9.94	10.93
2.3	4.97	5.45	5.97	6.45	6.56	9.42	10.42	11.46
2.4	5.29	5.79	6.29	6.79	6.92	9.91	10.91	12.00
2.5	5.62	6.14	6.62	7.14	7.28	10.42	11.42	12.56
2.6	5.96	6.50	6.96	7.50	7.65	10.94	11.94	13.13
2.7	6.30	6.87	7.30	7.87	8.03	11.47	12.47	13.72
2.8	6.66	7.25	7.66	8.25	8.43	12.03	13.03	14.33
2.9	7.03	7.63	8.03	8.63	8.83	12.59	13.59	14.95
3.0	7.40	8.03	8.40	9.03	9.24	13.18	14.18	15.59
3.1	7.79	8.43	8.79	9.43	9.66	13.78	14.78	16.26
3.2	8.18	8.85	9.18	9.85	10.10	14.40	15.40	16.94
3.3	8.59	9.28	9.59	10.28	10.55	15.04	16.04	17.65
3.4	9.01	9.72	10.01	10.72	11.01	15.70	16.70	18.37
3.5	9.43	10.16	10.43	11.16	11.47	16.39	17.39	19.12

Table D.12—Meters, 420 kV, line-to-line: For work between 362.1 and 420 kV

T (p.u.)	Line-to-ground work					Line-to-line work		
	MAID (m)	**MTID (m)**	**MAD (m)**	**MAD for Tools (m)**	**MHID (m)**	**MAID (m)**	**MAD (m)**	**MHID (m)**
1.5	1.11	1.22	1.41	1.52	1.55	2.17	2.47	2.72
1.6	1.19	1.31	1.49	1.61	1.64	2.33	2.63	2.89
1.7	1.26	1.39	1.56	1.69	1.72	2.48	2.78	3.06
1.8	1.34	1.47	1.64	1.77	1.80	2.65	2.95	3.24
1.9	1.43	1.57	1.73	1.87	1.90	2.81	3.11	3.42
2.0	1.54	1.68	1.84	1.98	2.02	2.98	3.28	3.61
2.1	1.65	1.81	1.95	2.11	2.15	3.16	3.46	3.81
2.2	1.77	1.93	2.07	2.23	2.28	3.35	3.65	4.01
2.3	1.89	2.06	2.19	2.36	2.41	3.54	3.84	4.22
2.4	2.02	2.19	2.32	2.49	2.55	3.73	4.03	4.44
2.5	2.15	2.33	2.45	2.63	2.69	3.94	4.24	4.66
2.6	2.28	2.47	2.58	2.77	2.84	4.15	4.45	4.89
2.7	2.42	2.62	2.72	2.92	2.99	4.37	4.67	5.13
2.8	2.56	2.76	2.86	3.06	3.14	4.59	4.89	5.38
2.9	2.70	2.92	3.00	3.22	3.30	4.83	5.13	5.64
3.0	2.85	3.07	3.15	3.37	3.47	5.07	5.37	5.91
3.1	3.01	3.24	3.31	3.54	3.64	5.32	5.62	6.19
3.2	3.17	3.41	3.47	3.71	3.82	5.59	5.89	6.47
3.3	3.33	3.58	3.63	3.88	4.00	5.86	6.16	6.78
3.4	3.50	3.76	3.80	4.06	4.18	6.14	6.44	7.09
3.5	3.68	3.94	3.98	4.24	4.38	6.44	6.74	7.42

Table D.13—Feet, 420 kV, line-to-line: For work between 362.1 and 420 kV

T (p.u.)	Line-to-ground work					Line-to-line work		
	MAID (ft)	**MTID (ft)**	**MAD (ft)**	**MAD for Tools (ft)**	**MHID (ft)**	**MAID (ft)**	**MAD (ft)**	**MHID (ft)**
1.5	3.64	4.01	4.64	5.01	5.11	7.12	8.12	8.93
1.6	3.88	4.27	4.88	5.27	5.37	7.62	8.62	9.48
1.7	4.13	4.54	5.13	5.54	5.64	8.14	9.14	10.05
1.8	4.37	4.81	5.37	5.81	5.91	8.67	9.67	10.63
1.9	4.67	5.13	5.67	6.13	6.23	9.22	10.22	11.24
2.0	5.03	5.52	6.03	6.52	6.63	9.78	10.78	11.86
2.1	5.41	5.92	6.41	6.92	7.05	10.37	11.37	12.50
2.2	5.79	6.33	6.79	7.33	7.47	10.97	11.97	13.17
2.3	6.19	6.75	7.19	7.75	7.91	11.59	12.59	13.85
2.4	6.61	7.19	7.61	8.19	8.37	12.24	13.24	14.56
2.5	7.03	7.64	8.03	8.64	8.83	12.91	13.91	15.30
2.6	7.46	8.10	8.46	9.10	9.31	13.60	14.60	16.06
2.7	7.91	8.57	8.91	9.57	9.81	14.31	15.31	16.84
2.8	8.38	9.06	9.38	10.06	10.32	15.06	16.06	17.66
2.9	8.86	9.56	9.86	10.56	10.84	15.83	16.83	18.51
3.0	9.35	10.08	10.35	11.08	11.38	16.62	17.62	19.39
3.1	9.86	10.61	10.86	11.61	11.94	17.45	18.45	20.30
3.2	10.39	11.16	11.39	12.16	12.52	18.32	19.32	21.25
3.3	10.93	11.73	11.93	12.73	13.12	19.21	20.21	22.24
3.4	11.49	12.31	12.49	13.31	13.74	20.15	21.15	23.26
3.5	12.06	12.91	13.06	13.91	14.36	21.12	22.12	24.33

Table D.14—Meters, 550 kV, line-to-line: For work between 420.1 and 550 kV

T (p.u.)	Line-to-ground work					Line-to-line work		
	MAID (m)	**MTID (m)**	**MAD (m)**	**MAD for Tools (m)**	**MHID (m)**	**MAID (m)**	**MAD (m)**	**MHID (m)**
1.5	1.50	1.64	1.80	1.94	1.98	3.10	3.40	3.74
1.6	1.65	1.80	1.95	2.10	2.14	3.34	3.64	4.01
1.7	1.80	1.97	2.10	2.27	2.31	3.59	3.89	4.28
1.8	1.96	2.14	2.26	2.44	2.49	3.86	4.16	4.57
1.9	2.13	2.31	2.43	2.61	2.67	4.13	4.43	4.87
2.0	2.30	2.50	2.60	2.80	2.86	4.42	4.72	5.19
2.1	2.49	2.69	2.79	2.99	3.06	4.72	5.02	5.52
2.2	2.68	2.89	2.98	3.19	3.27	5.03	5.33	5.86
2.3	2.87	3.09	3.17	3.39	3.49	5.36	5.66	6.23
2.4	3.08	3.31	3.38	3.61	3.71	5.71	6.01	6.61
2.5	3.29	3.53	3.59	3.83	3.95	6.08	6.38	7.02
2.6	3.51	3.76	3.81	4.06	4.19	6.47	6.77	7.44
2.7	3.74	4.00	4.04	4.30	4.45	6.87	7.17	7.89
2.8	3.98	4.25	4.28	4.55	4.70	7.31	7.61	8.37
2.9	4.22	4.50	4.52	4.80	4.97	7.77	8.07	8.87
3.0	4.47	4.76	4.77	5.06	5.25	8.26	8.56	9.41

Table D.15—Feet, 550 kV, line-to-line: For work between 420.1 and 550 kV

T (p.u.)	Line-to-ground work					Line-to-line work		
	MAID (ft)	**MTID (ft)**	**MAD (ft)**	**MAD for Tools (ft)**	**MHID (ft)**	**MAID (ft)**	**MAD (ft)**	**MHID (ft)**
1.5	4.90	5.38	5.90	6.38	6.49	10.17	11.17	12.29
1.6	5.39	5.90	6.39	6.90	7.03	10.96	11.96	13.16
1.7	5.90	6.44	6.90	7.44	7.59	11.78	12.78	14.06
1.8	6.43	7.00	7.43	8.00	8.17	12.64	13.64	15.00
1.9	6.98	7.58	7.98	8.58	8.78	13.54	14.54	15.99
2.0	7.55	8.18	8.55	9.18	9.40	14.48	15.48	17.02
2.1	8.15	8.81	9.15	9.81	10.06	15.46	16.46	18.11
2.2	8.77	9.46	9.77	10.46	10.74	16.50	17.50	19.24
2.3	9.41	10.14	10.41	11.14	11.45	17.58	18.58	20.44
2.4	10.08	10.84	11.08	11.84	12.19	18.73	19.73	21.70
2.5	10.79	11.58	11.79	12.58	12.96	19.93	20.93	23.02
2.6	11.51	12.34	12.51	13.34	13.76	21.20	22.20	24.42
2.7	12.26	13.12	13.26	14.12	14.59	22.55	23.55	25.90
2.8	13.04	13.93	14.04	14.93	15.44	23.97	24.97	27.46
2.9	13.83	14.76	14.83	15.76	16.32	25.47	26.47	29.12
3.0	14.65	15.61	15.65	16.61	17.22	27.07	28.07	30.88

Table D.16—Meters, 800 kV, line-to-line: For work between 550.1 and 800 kV

T (p.u.)	Line-to-ground work					Line-to-line work		
	MAID (m)	**MTID (m)**	**MAD (m)**	**MAD for Tools (m)**	**MHID (m)**	**MAID (m)**	**MAD (m)**	**MHID (m)**
1.5	2.64	2.85	2.94	3.15	3.23	5.48	5.78	6.35
1.6	2.93	3.15	3.23	3.45	3.55	6.00	6.30	6.93
1.7	3.23	3.47	3.53	3.77	3.88	6.56	6.86	7.55
1.8	3.55	3.81	3.85	4.11	4.24	7.17	7.47	8.22
1.9	3.89	4.16	4.19	4.46	4.61	7.84	8.14	8.95
2.0	4.24	4.52	4.54	4.82	5.00	8.57	8.87	9.75
2.1	4.61	4.90	4.91	5.20	5.40	9.36	9.66	10.63
2.2	4.99	5.30	5.29	5.60	5.82	10.24	10.54	11.59
2.3	5.39	5.71	5.69	6.01	6.25	11.21	11.51	12.66
2.4	5.80	6.13	6.10	6.43	6.71	12.29	12.59	13.84
2.5	6.22	6.57	6.52	6.87	7.17	13.49	13.79	15.17

Table D.17—Feet, 800 kV, line-to-line: For work between 550.1 and 800 kV

T (p.u.)	Line-to-ground work					Line-to-line work		
	MAID (ft)	**MTID (ft)**	**MAD (ft)**	**MAD for Tools (ft)**	**MHID (ft)**	**MAID (ft)**	**MAD (ft)**	**MHID (ft)**
1.5	8.65	9.34	9.65	10.34	10.62	17.96	18.96	20.85
1.6	9.59	10.32	10.59	11.32	11.64	19.67	20.67	22.74
1.7	10.59	11.38	11.59	12.38	12.75	21.52	22.52	24.77
1.8	11.65	12.48	12.65	13.48	13.91	23.53	24.53	26.98
1.9	12.75	13.63	13.75	14.63	15.13	25.71	26.71	29.38
2.0	13.91	14.83	14.91	15.83	16.40	28.09	29.09	32.00
2.1	15.11	16.08	16.11	17.08	17.72	30.70	31.70	34.87
2.2	16.36	17.38	17.36	18.38	19.10	33.58	34.58	38.04
2.3	17.66	18.72	18.66	19.72	20.52	36.76	37.76	41.54
2.4	19.01	20.11	20.01	21.11	22.01	40.30	41.30	45.43
2.5	20.40	21.56	21.40	22.56	23.54	44.26	45.26	49.78

Table D.18—DC pole-to-ground work

$V_{p\text{-}g}$ (kV)	*T* (p.u.)	MAID (m)	MTID (m)	MAD (m)	MAD for Tools (m)	MAID (ft)	MTID (ft)	MAD (ft)	MAD for Tools (ft)
250	1.5	0.81	0.89	1.11	1.19	2.66	2.92	3.66	3.92
250	1.6	0.87	0.95	1.17	1.25	2.83	3.12	3.83	4.12
250	1.7	0.92	1.01	1.22	1.31	3.01	3.31	4.01	4.31
250	1.8	0.98	1.07	1.28	1.37	3.19	3.51	4.19	4.51
400	1.5	1.30	1.43	1.60	1.73	4.25	4.67	5.25	5.67
400	1.6	1.38	1.52	1.68	1.82	4.53	4.98	5.53	5.98
400	1.7	1.52	1.66	1.82	1.96	4.97	5.45	5.97	6.45
400	1.8	1.65	1.81	1.95	2.11	5.41	5.92	6.41	6.92
500	1.5	1.75	1.92	2.05	2.22	5.74	6.28	6.74	7.28
500	1.6	1.93	2.11	2.23	2.41	6.33	6.90	7.33	7.90
500	1.7	2.12	2.30	2.42	2.60	6.94	7.54	7.94	8.54
500	1.8	2.31	2.51	2.61	2.81	7.57	8.21	8.57	9.21
600	1.5	2.31	2.51	2.61	2.81	7.57	8.21	8.57	9.21
600	1.6	2.56	2.76	2.86	3.06	8.38	9.06	9.38	10.06
600	1.7	2.81	3.03	3.11	3.33	9.22	9.94	10.22	10.94
600	1.8	3.09	3.32	3.39	3.62	10.12	10.88	11.12	11.88
750	1.5	3.30	3.55	3.60	3.85	10.83	11.62	11.83	12.62
750	1.6	3.68	3.94	3.98	4.24	12.06	12.90	13.06	13.90
750	1.7	4.07	4.35	4.37	4.65	13.35	14.25	14.35	15.25
750	1.8	4.49	4.78	4.79	5.08	14.71	15.66	15.71	16.66

Table D.19—DC pole-to-pole work

$V_{p\text{-}p}$ (kV)	*T* (p.u)	MAID (m)	MTID (m)	MAD (m)	MAD for Tools (m)	MAID (ft)	MTID (ft)	MAD (ft)	MAD for Tools (ft)
500	1.5	1.35	1.49	1.65	1.79	4.43	4.87	5.43	5.87
500	1.6	1.42	1.56	1.72	1.86	4.65	5.11	5.65	6.11
500	1.7	1.50	1.65	1.80	1.95	6.19	6.79	7.19	7.79
500	1.8	1.58	1.73	1.88	2.03	6.67	7.30	7.67	8.30
800	1.5	2.73	2.94	3.03	3.24	10.72	11.57	11.72	12.57
800	1.6	2.90	3.13	3.20	3.43	11.71	12.61	12.71	13.61
800	1.7	3.09	3.32	3.39	3.62	12.74	13.70	13.74	14.70
800	1.8	3.28	3.52	3.58	3.82	13.81	14.83	14.81	15.83
1000	1.5	3.94	4.21	4.24	4.51	15.49	16.55	16.49	17.55
1000	1.6	4.21	4.49	4.51	4.79	16.98	18.11	17.98	19.11
1000	1.7	4.49	4.78	4.79	5.08	18.52	19.72	19.52	20.72
1000	1.8	4.77	5.07	5.07	5.37	20.12	21.39	21.12	22.39
1200	1.5	5.37	5.70	5.67	6.00	21.14	22.41	22.14	23.41
1200	1.6	5.75	6.08	6.05	6.38	23.20	24.55	24.20	25.55
1200	1.7	6.14	6.49	6.44	6.79	25.34	26.78	26.34	27.78
1200	1.8	6.54	6.90	6.84	7.20	27.56	29.09	28.56	30.09
1500	1.5	7.93	8.33	8.23	8.63	31.19	32.78	32.19	33.78
1500	1.6	8.50	8.92	8.80	9.22	34.29	35.99	35.29	36.99
1500	1.7	9.08	9.52	9.38	9.82	37.52	39.32	38.52	40.32
1500	1.8	9.69	10.14	9.99	10.44	40.87	42.78	41.87	43.78

Annex E

(informative)

Determining maximum anticipated per-unit TOV (*T*)

E.1 Determining TOV magnitude due to switching transients

There are numerous references that discuss how to determine the TOVs that are the result of switching transients. Most notable are "Digital Computation" [B26], "Modeling Guidelines" [B27], Hileman [B19], the EPRI *Red Book* [B9], and IEEE Std 1313.2. The methods presented in these references can be used to provide reasonable results when using an electromagnetic transients program to simulate a system.

E.2 Determining *T* at worksite

The *T* at the worksite is defined by the 2% statistical switching overvoltage, i.e., V_2. The distribution of switching overvoltages is obtained using a transient program, e.g., electromagnetic transients program, where the switching device, e.g., circuit breaker, is closed and/or reclosed with random switching times. In order to achieve satisfactory results, at least 100 statistical simulations are required. Industry consensus is to use 200 to 400 statistical simulations. The resulting overvoltages from each of the simulations are then statistically analyzed to obtain a probability distribution that approximates the results. Several distribution functions have been used; however, the Gaussian or normal distribution is most frequently used. From statistical analysis of the data, the mean, μ, and the standard deviation, σ, can be computed. Using the data from the statistical analysis, V_2 can be found by using Equation (E.1).

$$V_2 = \mu + 2.054\sigma \tag{E.1}$$

where

μ is the mean switching overvoltage
σ is the standard deviation of the switching overvoltages

When controls are used to mitigate switching surges (e.g., surge arresters, closing resistors), the distribution is not strictly Gaussian, and other distributions have been used (see Hileman [B19]).

There are some subtle differences between performing studies for power system insulation coordination purposes and studies performed to compute *T* for live work. For example, in live work, circuit breaker restrikes can be ignored (see IEC 61472 [B21]). This is based on the fact that the combined probability of a circuit breaker restriking while a worker is working on or near an energized line is extremely low. If devices other than circuit breakers are being utilized on the subject line while live work is being performed, then the probability of restrike must be considered. If reclosing is blocked, the overvoltages due to reclosing into a trapped charge can be ignored. If restriking of the switching device is included, then the resulting overvoltages are essentially the same as those of reclosing into a trapped charge. The only difference is the probability of occurrence. Generally, when detailed engineering studies are performed for a particular system voltage, the worst-case line(s) are analyzed. The results are then used for that voltage level across the entire system.

Example calculation: Based on field tests and computer simulations, it has been noted that the TOVs on lines without switching controls or surge arresters are higher than those at voltage levels where TOV mitigation is part of the design. Thus, the following 230 kV system is presented as a worst-case scenario for all voltage levels.

A single-line diagram of an example system is shown in Figure E.1.

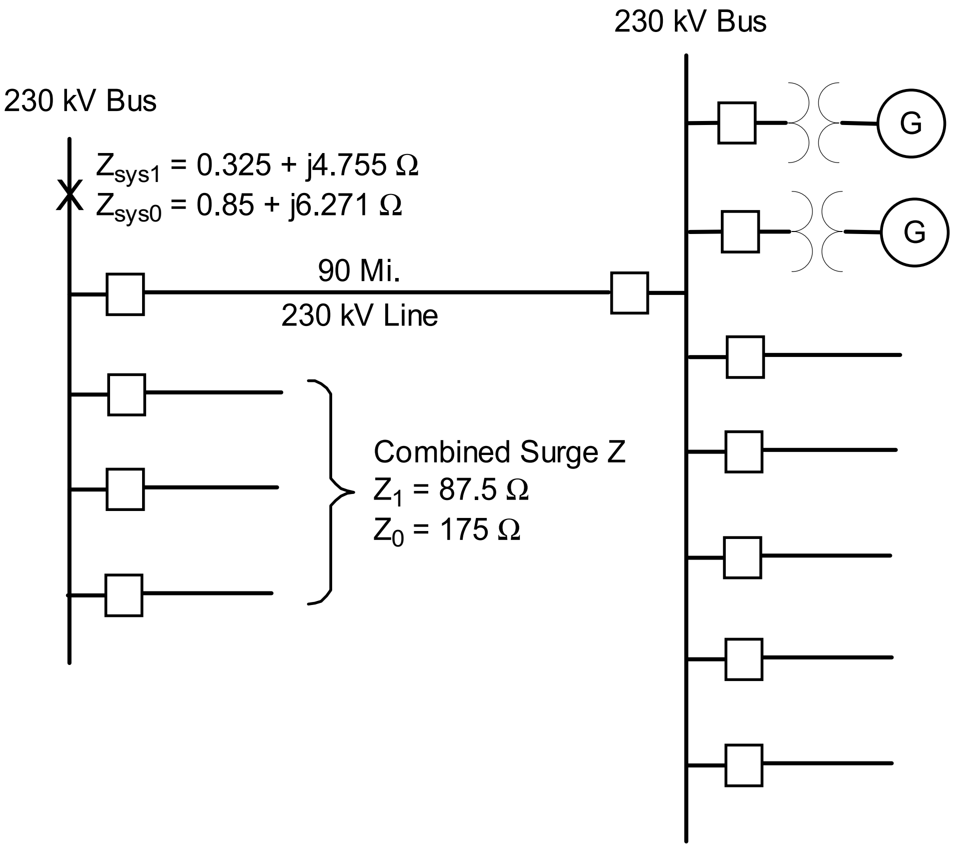


Figure E.1—Single-line diagram of example system

The goal here is to determine the worst-case TOV that might occur at any worksite location along the 90 mi line. Generally speaking, the worst-case TOV will occur when the line is energized from the weakest end of the line (source with largest impedance), and the maximum overvoltage will occur at the end of the line. However, this is not always the case, and other factors should be taken into consideration, e.g., line length, amount of shunt compensation (see "Modeling Guidelines" [B27], Hileman [B19], the EPRI *Red Book* [B9], IEEE Std 1313.2, and IEC 61472 [B21]). In this example, it is assumed that the worst-case TOVs will occur when the line is energized from the end of the line that does not have generation connected to it. The resulting single-line diagram of the system studied is shown in Figure E.2.

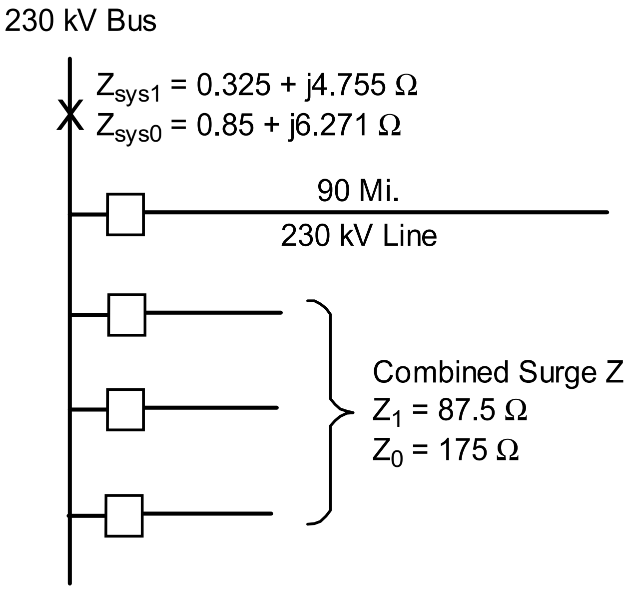


Figure E.2—Single-line diagram of study system

For this study, it is assumed that the receiving end of the line is open and the line is energized with a power circuit breaker (no closing resistors). Also, note that no tapped load is present on the line. The configuration and parameters for the 230 kV line are given in Figure E.3 and Table E.1.

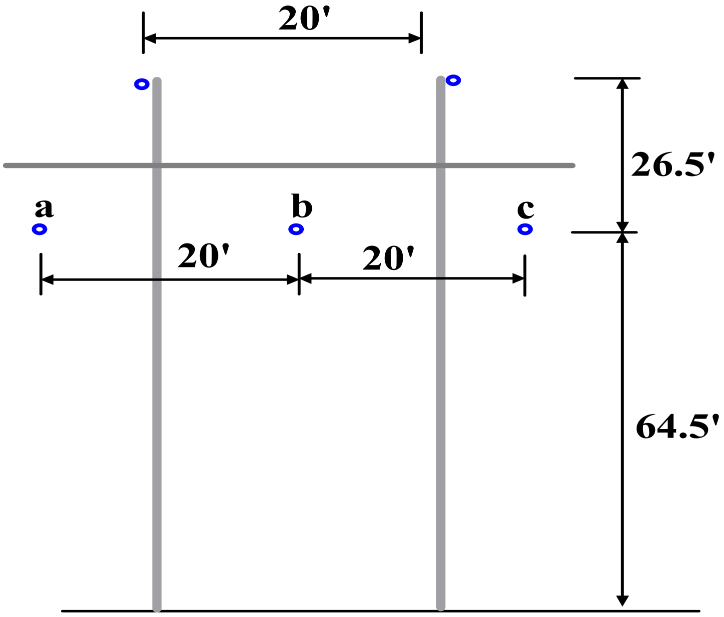


Figure E.3—Line configuration

Table E.1—Line parameters for example line

Phase conductors: 1351 ACSR 54/19 Rdc = 0.0686 Ω.mi Dia. = 1.424 in T/D = 0.38	Shield wires: 3/8" HSS Rdc = 6.59 Ω.mi Dia. = 0.36 in T/D = 0.50
Length: 90 mi	Rho: 100 Ω-m

The system shown in Figure E.2 was modeled using the electromagnetic transients program. No closing resistors or surge arresters were employed in this system.

Case 1 – Reclosing disabled: When reclosing is disabled, the worst-case TOV will occur when the line is energized. The resulting overvoltage is greatly dependant upon the closing angle of the breaker, i.e., the magnitude of the system voltage at the instant the breaker pole closes. In order to determine the worst-case voltage, 2000 statistical breaker closings were performed.

From the statistical analysis, the following parameters were determined:

$$\mu = 362.21 \text{ kV}$$

$$\sigma = 55.71 \text{ kV}$$

Using these statistical values, the 2% statistical overvoltage was computed using Equation (E.1).

$$E_2 = \mu + (2.054)(\sigma) = 476.6 \text{ kV} \tag{E.2}$$

Using the results of Equation (E.2), the line-to-ground TOV was computed.

$$T = \frac{E_2}{E_{Peak}} = \frac{476.6kV}{\frac{(242kV)(\sqrt{2})}{\sqrt{3}}} = 2.41 \text{ p.u.} \tag{E.3}$$

The following statistical parameters were determined for the line-to-line TOVs:

$$\mu = 544.4 \text{ kV}$$
$$\sigma = 74.4 \text{ kV}$$

Using these statistical values, the 2% statistical overvoltage was computed using Equation (E.1).

$$E_2 = \mu + 2.054\sigma = 697.2 \text{ kV} \tag{E.4}$$

Using the results of Equation (E.4), the line-to-line TOV was computed on the line-to-ground base.

$$T_{L\text{-}L} = \frac{E_2}{E_{peak}} = \frac{697.2 \text{ kV}}{\sqrt{2}\,\frac{242 \text{ kV}}{\sqrt{3}}} = 3.53 \text{ p.u.} \tag{E.5}$$

For comparison, $T_{L\text{-}L}$ was computed using Equation (48) and was found to be equal to 3.70 p.u.

Case 2 – Reclosing enabled: The worst-case TOV will occur when the line is reenergized (reclosed) with full trapped charge on all three phases (no fault applied). For this simulation, it was assumed that the reclose delay was 1 s. Using a shunt admittance of 10.5×10^{-9} mhos/mi [see Equation (E.7)], the resulting line-to-ground voltages 1 s after energization was found to be –90.4 kV, 105.5 kV, and –91.5 kV for phase *a*, *b*, and *c*, respectively. These values were then used in the simulations as initial conditions for the transmission line model.

From the statistical analysis, the following parameters were determined from the 1000 simulations:

$\mu = 392.3$ kV
$\sigma = 97.3$ kV

Using these statistical values, the 2% statistical overvoltage was computed using Equation (E.1).

$$E_2 = \mu + 2.054\sigma = 592.2 \text{ kV} \tag{E.6}$$

Using the results of Equation (E.6), the TOV was computed.

$$T_{L\text{-}G} = \frac{E_2}{E_{peak}} = \frac{592.2 \text{ kV}}{\sqrt{2}\,\dfrac{242 \text{ kV}}{\sqrt{3}}} = 3.0 \text{ p.u.} \tag{E.7}$$

The following statistical parameters were determined for the line-to-line TOVs:

$\mu = 562.4$ kV
$\sigma = 124.1$ kV

Using these statistical values, the 2% statistical overvoltage was computed using Equation (E.1).

$$E_2 = \mu + 2.054\sigma = 817.3 \text{ kV} \tag{E.8}$$

Using the results of Equation (E.8), the line-to-line TOV was computed on the line-to-ground base.

$$T_{L\text{-}L} = \frac{E_2}{E_{peak}} = \frac{817.3 \text{ kV}}{\sqrt{2}\,\dfrac{242 \text{ kV}}{\sqrt{3}}} = 4.13 \text{ p.u.} \tag{E.9}$$

For comparison, $T_{L\text{-}L}$ was computed using Equation (48) and was found to be equal to 4.50 p.u.

E.3 Large system studies

Large power systems can consist of hundreds of transmission lines at a particular voltage level. Because of the amount of time involved in these types of system studies, it is impractical to study each line to determine *T*. Generally, a number of worst-case lines will be studied, and the resulting *T* will be used for the entire system at that particular voltage level. This method of determining *T* is acceptable and provides conservative results as long as the worst-case scenarios are chosen correctly.