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IEEE Guide for the Application of Metal-Oxide Surge Arresters for Alternating-Current Systems

IEEE Power & Energy Society

Sponsored by the
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Approved 19 March 2009

IEEE-SA Standards Board

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Abstract: This guide covers the application of metal-oxide surge arresters to safeguard electric power equipment, with a nominal operating voltage 1000 V and above, against the hazards of abnormally high-voltage surges of various origins. This guide provides information on the characteristics of metal-oxide surge arresters and the protection of substation equipment, distribution systems, overhead lines, and large electrical machines.

Keywords: distribution lines, insulation coordination, lightning, metal-oxide surge arrester, overvoltage, substations, surge arrester, switching surges, transmission lines

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Introduction

This introduction is not part of IEEE Std C62.22-2009, IEEE Guide for the Application of Metal-Oxide Surge Arresters for Alternating-Current Systems.

Abnormally high voltages can occur on power systems from a variety of origins, including lightning and switching. These overvoltages can cause insulation breakdown, resulting in equipment failure and interrupting the continuity of electric supply to users. Proper coordination of surge-protective devices with the insulation strength of the protected equipment is essential to protect the reliability of power systems and equipment. Metal-oxide surge arresters are the predominately used overvoltage protective device on ac power systems.

The application of surge protection devices and their coordination with equipment insulation strengths is a broad and complex subject for which the industry has accumulated a large body of knowledge, experience, and practices. This document provides a concise guide to the application of metal-oxide surge arresters to protect power systems and equipment operating at a nominal voltage of 1000 V and greater. This application guide does not cover the application of low-voltage surge protective devices below 1000 V alternating current (ac). However, it references these devices when applied to the secondary of a transformer because they are part of the transformer protection.

Step-by-step directions toward proper solutions for various applications are provided. In many cases, the prescribed steps are adequate. More complex and special situations requiring study by experienced engineers are described, but specific solutions may not be given. These procedures are based on theoretical studies, test results, and experience.

The clauses of this guide cover the various categories of electric power systems and equipment.

- Clause 4 provides fundamental information on overvoltages, metal-oxide surge arrester characteristics, and equipment insulation.
- Clause 5 covers the application of surge arresters to stations and substations.
- Clause 6 covers application of surge arresters for protection of overhead and underground distribution system equipment, including all distribution transformers, and other electric distribution equipment.
- Clause 7 covers the protection of overhead transmission and distribution line insulation, which is an application unique from station equipment and underground protection because the overhead line insulation is self-restoring.
- Clause 8 covers the protection of large electrical machines, including generators and motors, rated 1000 V and above.

This guide is a revision of IEEE Std C62.22™-1997.[a] Substantial reorganization of the guide has been made to help users focus on their areas of interest. Major additions to this revision include substantially increased information on the characteristics of surge arresters and surge arrester energy discharge considerations. Extensive overhead line protection guidelines have been added.

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

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IEEE Guide for the Application of Metal-Oxide Surge Arresters for Alternating-Current Systems

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1. Scope

This guide covers the application of metal-oxide surge arresters (see IEEE Std C62.11™-2005) to safeguard electric power equipment against the hazards of abnormally high voltage surges of various origins. This application guide does not cover the application of low-voltage surge protective devices below 1000 V alternating current (ac), except when applied to the secondary of a transformer.

~~Such overvoltages may cause ßashovers and serious damage to equipment and thereby jeopardize the supply of power to users. It is essential to prevent this by the proper coordination of surge-protective devices with the insulation strength of the protected equipment.~~

~~This application guide does not cover the application of low-voltage surge protective devices below 1000 V ac. However, it references these devices when applied to the secondary of a transformer since they are part of the transformer protection~~.

~~The subject is broad, with many ramiÞcations, and it requires a volume of considerable bulk to explain all possible cases in detail. Clause 5 of this guide covers the basic cases for stations used to supply and switch electric power transmission, subtransmission, or distribution feeders. Information is included in Clause 6 on application of arresters for protection of overhead and underground distribution systems, all distribution transformers, and other electric distribution equipment.~~

~~Step-by-step directions toward proper solutions for various applications are provided. In many cases, the prescribed steps are adequate. More complex and special situations requiring study by experienced engineers are described, but speciÞc solutions may not be given. These procedures are based on theoretical stud- ies, test results, and experience.~~

2. Normative references

The following referenced documents are indispensable for the application of this document. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments or corrigenda) applies.
~~This guide shall be used in conjunction with the following publications. When the following standards are superseded by an approved revision, the revision shall apply.~~

~~ANSI C62.22-1987, American National Standard Guide for the Application of Gapped Silicon-Carbide Surge Arresters for AC Systems.[1]~~

ANSI/IEEE Std C37.06™-2000 American National Standard AC High-Voltage Circuit Breakers Rated on a Symmetrical Current Basis—Preferred Ratings and Related Required Capabilities.[1]

ANSI C84.1-~~1989, American National Standard for~~2006, Electric Power Systems and Equipment – Voltage Ratings (60 ~~Hertz).~~ Hz).

IEC 60034-15:1995~~-01)~~, Rotating Electrical Machines, Part 15: Impulse Voltage Withstand Levels of Rotating
A.C. Machines with Form-Wound Stator Coils~~ (draft revision)~~.[2]

~~IEEE Std 18-1992, IEEE Standard for Shunt Power Capacitors~~

IEC 60071-2-1997, Insulation Coordination—Part 2: Application Guide.

~~IEEE Std 100-1996, The IEEE Standard Dictionary of Electrical and Electronics Terms, Sixth Edition.[3]~~

~~IEEE Std 824-1994, IEEE Standard for Series Capacitors in Power Systems.~~

~~IEEE Std 998-1996, IEEE Guide for Direct Lightning Stroke Shielding of Substations. IEEE Std 1036-~~

~~1992, IEEE Guide for Application of Shunt Power Capacitors.~~

~~IEEE Std 1313.[1]-1996, IEEE Standard for Insulation CoordinationÑDeÞnitions, Principles, and Rules.~~

~~IEEE Std C37.04-1979 (Reaff 1989), IEEE Standard Rating Structure for AC High-Voltage Circuit Breakers~~
~~Rated on a Symmetrical Current Basis (DoD).~~

~~IEEE Std C37.015-1993, IEEE Application Guide for Shunt Reactor Switching.~~

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

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

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

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

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

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~~[4] IEEE Std C57.12.01-1989 has been withdrawn; however, copies can be obtained from Global Engineering, 15 Inverness Way East, Englewood, CO 80112-5704, USA, tel. (303) 792-2181.~~

~~IEEE Std C62.11-1993, IEEE Standard for Metal-Oxide Surge Arresters for Power Circuits.~~

IEEE Std 522™-2004, IEEE Guide for Testing Turn Insulation of Form-Wound Stator Coils for Alternating-Current Electric Machines. [3,4]

~~IEEE Std C62.92.1-1987 (Reaff 1993), IEEE Guide for the Application of Neutral Grounding in Electrical Utility Systems, Part IÑIntroduction.~~

~~IEEE Std C62.92.4-1991 (Reaff 1996), IEEE Guide for the Application of Neutral Grounding in Utility Systems, Part IVÑDistribution.~~

~~IEEE Std C62.92.5-1992 (Reaff 1997), IEEE Guide for the Application of Neutral Grounding in Electric Utility Systems, Part VÑTransmission Systems and Subtransmission Systems.~~

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

IEEE Std 1299/C62.22.1™-1996 (Reaff 2003), IEEE Guide for the Connection of Surge Arresters to Protect Insulated, Shielded Electric Power Cable Systems.

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IEEE Std C57.12.00™-2000, IEEE Standard for Standard General Requirements for Liquid-

Immersed Distribution, Power, and Regulating Transformers.

IEEE Std C57.12.01™-2005, IEEE Standard General Requirements for Dry-Type Distribution and Power Transformers, Including Those with Solid-Cast and/or Resin Encapsulated Windings.

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IEEE Std C62.21™-2003, IEEE Guide for the Application of Surge Voltage Protective Equipment on AC Rotating Machinery 1000 V and Greater.

IEEE Std C62.34™-1996, IEEE Standard for Performance of Low-Voltage Surge-Protective Devices (Secondary Arresters).

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

NEMA MG-1-~~1993~~2006, Motors and Generators, Parts 20.35 and 21.38.[5]

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3. Definitions, acronyms, and abbreviations

3.1 Definitions

For the purposes of this guide, the following terms and definitions apply. *The Authoritative Dictionary of IEEE Standards Terms, Seventh Edition* [B74][6] should be referenced for terms not defined in this clause.

3.1.1 arrester: *See*: **surge arrester**.

3.1.2 arrester discharge current: The current that flows through an arrester resulting from an impinging surge.

3.1.3 arrester discharge voltage: The voltage that appears across the terminals of an arrester during the passage of discharge current.

3.1.4 arrester disconnector: A means for disconnecting an arrester in anticipation of, or after, a failure in order to prevent a permanent fault on the circuit and to give indication of a failed arrester.

3.1.5 arrester duty-cycle rating: The designated maximum permissible root-mean-square (rms) value of power-frequency voltage between its line and ground terminals at which it is designed to perform its duty cycle.

3.1.6 basic lightning impulse insulation level (BIL): The electrical strength of insulation expressed in terms of the crest value of a standard lightning impulse under standard atmospheric conditions. BIL may be expressed as either statistical or conventional.

3.1.7 basic switching impulse insulation level (BSL): The electrical strength of insulation expressed in terms of the crest value of a standard switching impulse. The BSL may be expressed as either statistical or con~~-~~ventional.

3.1.8 coefficient of grounding (COG): The ratio, E_{LG}/E_{LL} (expressed as a percentage), of the highest root-mean-square (rms), line-to-ground, power-frequency voltage E_{LG} on a sound phase, at a selected location, during a fault to ground affecting one or more phases to the line-to-line power-frequency voltage E_{LL} that would be obtained at the selected location with the fault removed.

~~[5] NEMA publications are available from the National Electrical Manufacturers Association, 1300 N. 17th St., Ste. 1847, Rosslyn, VA 22209, USA.~~

3.1.9 conventional BIL (basic lightning impulse insulation level): The crest value of a standard lightning impulse for which the insulation shall not exhibit disruptive discharge when subjected to a specific number of applications of this impulse under specified conditions, applicable specifically to non- self-restoring insulations.

3.1.10 conventional BSL (basic switching impulse insulation level): The crest value of a standard switching impulse for which the insulation does not exhibit disruptive discharge when subjected to a specific number of impulses under specified conditions, applicable to non-self-restoring insulations.

3.1.11 conventional withstand voltage: The voltage that an insulation is capable of withstanding with a 0% probability of failure.

3.1.12 coordination of insulation: The selection of insulation strength consistent with expected overvoltages to obtain an acceptable risk of failure.

[6] The numbers in brackets correspond to those of the bibliography in Annex H.

3.1.13 crest value: (of an impulse): The maximum value that an impulse attains. *Syn*: **peak value**.

3.1.14 critical flashover voltage (CFO): The amplitude of voltage of a given wave shape that, under specified conditions, causes flashover through the surrounding medium on 50% of the voltage applications.

3.1.15 deadfront type arrester: An arrester assembled in a shielded housing providing system insulation and conductive ground shield intended to be installed in an enclosure for the protection of underground and padmounted distribution equipment and circuits.

3.1.16 disconnector, surge arrester: *See*: **arrester disconnector**.

3.1.17 disruptive discharge: The sudden and large increase in current through an insulating medium due to the complete failure of the medium under electrical stress.

3.1.18 distribution arrester:

a) **heavy duty class:** An arrester most often used to protect overhead distribution systems exposed to severe lightning currents.

b) **light duty class:** An arrester generally installed on and used to protect underground distribution systems where the major portion of the lightning stroke current is discharged by an arrester located at the overhead line/cable junction.

c) **normal duty class:** An arrester generally used to protect overhead distribution systems exposed to normal lightning currents.

3.1.19 ferroresonance: Sustained oscillations involving a capacitance in series with a nonlinear inductance, characterized by highly distorted waveforms. ~~Can also occur between the capacitance to ground of an ungrounded circuit and voltage transformers with primary windings that are grounded. This phenomenon is also possible in gas- insulated systems~~

3.1.20 flashover: A disruptive discharge around or over the surface of a solid or liquid insulator.

3.1.21 ground flash density (GFD): The number of lightning strokes to ground per square kilometer per year.

3.1.22 impulse: A surge of unidirectional polarity.

3.1.23 insulation level: A combination of voltage values (both power frequency and impulse) that characterize the insulation of an equipment with regard to its capability of withstanding dielectric stresses.

3.1.24 lightning overvoltage: The crest voltage appearing across an arrester or insulation caused by a lightning surge.

3.1.25 lightning surge: A transient electric disturbance in an electric circuit caused by lightning.

3.1.26 liquid-immersed type arrester: An arrester designed for use immersed in an insulating liquid.

3.1.27 maximum continuous operating voltage rating (MCOV): The maximum designated root-mean- square (rms) value of power frequency voltage that may be applied continuously between the terminals of the arrester.

3.1.28 metal-oxide surge arrester (MOSA): A surge arrester utilizing valve elements fabricated from non~~-~~linear resistance metal-oxide materials.

3.1.29 nominal rate of rise (of an impulse) For a wave front, the slope of the line that determines the virtual zero. It is usually expressed in volts or amperes per microsecond.

3.1.30 nominal system voltage: A nominal value assigned to designate a system of a given voltage class.

3.1.31 non-self-restoring insulation: An insulation that loses its insulating properties or does not recover them completely after a disruptive discharge caused by the application of a test voltage; insulation of this kind is generally, but not necessarily, internal insulation.

3.1.32 overvoltage: Abnormal voltage between two points of a system that is greater than the highest value appearing between the same two points under normal service conditions. Overvoltages may be low frequency, temporary, and transient (surge).

3.1.33 peak value: *See*: **crest value.**

3.1.34 riser pole type arrester: An arrester for pole mounting most often used to protect underground distribution cable and equipment.

3.1.35 self-restoring insulation: Insulation that completely recovers its insulating properties after a disruptive discharge caused by the application of an overvoltage; insulation of this kind is generally, but not necessarily, external insulation.

3.1.36 series gap: An intentional gap(s) between spaced electrodes in series with the valve elements across which all or part of the impressed arrester terminal voltage appears.

3.1.37 standard lightning impulse: The wave shape of the standard impulse used is 1.2/50 µs voltage wave (when not in conflict with products standards).

3.1.38 standard switching impulses: The wave shapes of standard impulse tests depend on equipment being tested:

a) For air insulation and switchgear: 250/2500 µs

b) For transformer products: 100/1000 µs

c) For arrester sparkover tests (the tail duration is not critical):

  1) 30 µs to 60 µs /90 µs to 180 µs

  2) 150 µs to 300 µs /450 µs to 900 µs

  3) 1000 µs to 2000 µs /3000 µs to 6000 µs

3.1.39 statistical basic lightning impulse insulation level (BIL): The crest values of a standard lightning impulse for which the insulation exhibits a 90% probability of withstand (or a 10% probability of failure) under specified conditions, applicable specifically to self-restoring insulations.

3.1.40 statistical basic switching impulse insulation level (BSL): The crest value of a standard switching impulse for which the insulation exhibits a 90% probability of withstand (or a 10% probability of failure), under specified conditions, applicable to self-restoring insulations.

3.1.41 statistical withstand voltage: The voltage that an insulation is capable of withstanding with a given probability of failure, corresponding to a specified probability of failure (e.g., 10% or 0.1%).

3.1.42 surge: A transient wave of current, potential, or power in an electric circuit.

3.1.43 surge arrester: A protective device for limiting surge voltages on equipment by discharging or bypassing surge current; it limits the flow of power follow current to ground and is capable of repeating these functions as specified.

3.1.44 switching overvoltage: Any combination of switching surge(s) and temporary overvoltage(s) associated with a single switching episode.

3.1.45 switching surge: A heavily damped transient electrical disturbance associated with switching. ~~System insulation flashover may precede or follow the switching in some cases but not all.~~

3.1.46 system voltage: The root-mean-square (rms) phase-to-phase power frequency voltage on a three-phase alternating-current electric system.

3.1.47 temporary overvoltage (TOV): An oscillatory overvoltage associated with switching or faults (for example, load rejection, single-phase faults) and/or nonlinearities (ferroresonance effects, harmonics) of relatively long duration, which is undamped or slightly damped.

3.1.48 transmission-line arrester: A surge arrester installed on a transmission line, usually for the purpose of protecting transmission-line insulation.

3.1.49 traveling wave: The resulting wave when an electrical variation in a circuit such as a transmission line takes the form of translation of energy along a conductor, such energy being always equally divided between current and potential forms.

3.1.50 unit operation: Discharge of a surge through an arrester while the arrester is energized.

3.1.51 valve arrester: An arrester that includes one or more valve elements.

3.1.52 valve element: A resistor that, because of its nonlinear current-voltage characteristic, limits the voltage across the arrester terminals during the flow of discharge current and contributes to the limitation of follow current at normal power-frequency voltage.

3.1.53 virtual duration of wave front: (of an impulse) The virtual value for the duration of the wave front is as follows:

a) For voltage waves with wave front durations less than 30 µs, either full or chopped on the front, crest, or tail, 1.67 times the time for the voltage to increase from 30% to 90% of its crest value.

b) For voltage waves with wave front durations of 30 µs or more, the time taken by the voltage to increase from actual zero to maximum crest value.

c) For current waves, 1.25 times the time for the current to increase from 10% to 90% of crest value.

3.1.54 virtual zero point: (of an impulse) The intersection with the time axis of a straight line drawn through points on the front of the current wave at 10% and 90% crest value or through points on the front of the voltage wave at 30% and 90% crest value.

3.1.55 wave front: (of an impulse) That part of an impulse that occurs prior to the crest value.

3.1.56 wave shape: (of an impulse test wave) The graph of an impulse test wave as a function of time**.**

3.1.57 wave shape designation: (of an impulse)

a) The wave shape of an impulse (other than rectangular) of a current or voltage is designated by a combination of two numbers. The first, an index of the wave front, is the virtual duration of the wave front in microseconds. The second, an index of the wave tail, is the time in microseconds from virtual zero to the instant at which one-half of the crest value is reached on the wave tail. Examples are 1.2/50 and 8/20 waves.

b) The wave shape of a rectangular impulse of current or voltage is designated by two numbers. The first designates the minimum value of current or voltage that is sustained for the time in microseconds designated by the second number. An example is the 75 A · 2000 µs wave.

3.1.58 wave tail: (of an impulse) That part between the crest value and the end of the impulse.

3.1.59 withstand voltage: The voltage that an insulation is capable of withstanding with a given probability of failure. In terms of insulation, this is expressed as either conventional withstand voltage or statistical with–stand voltage.

3.2 Acronyms and abbreviations

BIL	basic lightning impulse insulation level
BSL	basic switching impulse insulation level
CFO	critical flashover voltage
COG	coefficient of grounding
CVT	capacitor voltage transformer
CWW	chopped wave withstand
dc	direct current
EHV	extra high voltage
FACTS	flexible alternating current transmission systems
FOR	flashover rate of lines (flashovers per 100 km per year)
FOW	front of wave (protective level)
FW	full wave (lightning test)
FWW	front of wave withstand
GFD	ground flash density (flashes to ground per square kilometer per year)
GIS	gas-insulated substation
GTO	gate turnoff transistor
HVDC	high-voltage direct current
IGBT	insulated gate bipolar transistor
IV	induced voltage
LPL	lightning protective level
MCOV	maximum continuous operating voltage
MOSA	metal-oxide surge arrester
MTBF	mean time between failure
PM	protective margin

PR	protective ratio
SPL	switching protective level
SVC	static VAR compensator
TCSC	thyristor controlled series capacitors
TLA	transmission-line arrester
TOV	temporary overvoltage
TRV	transient recovery voltage
UPFC	universal power flow controller
VAR	volt-ampere reactive

3. Definitions, acronyms, and abbreviations

3.1 Definitions

For the purposes of this guide, the following terms and definitions apply. *The Authoritative Dictionary of IEEE Standards Terms, Seventh Edition* [B74][6] should be referenced for terms not defined in this clause.

3.1.1 arrester: *See*: **surge arrester**.

3.1.2 arrester discharge current: The current that flows through an arrester resulting from an impinging surge.

3.1.3 arrester discharge voltage: The voltage that appears across the terminals of an arrester during the passage of discharge current.

3.1.4 arrester disconnector: A means for disconnecting an arrester in anticipation of, or after, a failure in order to prevent a permanent fault on the circuit and to give indication of a failed arrester.

3.1.5 arrester duty-cycle rating: The designated maximum permissible root-mean-square (rms) value of power-frequency voltage between its line and ground terminals at which it is designed to perform its duty cycle.

3.1.6 basic lightning impulse insulation level (BIL): The electrical strength of insulation expressed in terms of the crest value of a standard lightning impulse under standard atmospheric conditions. BIL may be expressed as either statistical or conventional.

3.1.7 basic switching impulse insulation level (BSL): The electrical strength of insulation expressed in terms of the crest value of a standard switching impulse. The BSL may be expressed as either statistical or conventional.

3.1.8 coefficient of grounding (COG): The ratio, $E_{\mathrm{LG}}/E_{\mathrm{LL}}$ (expressed as a percentage), of the highest root-mean-square (rms), line-to-ground, power-frequency voltage E_{LG} on a sound phase, at a selected location, during a fault to ground affecting one or more phases to the line-to-line power-frequency voltage E_{LL} that would be obtained at the selected location with the fault removed.

~~[5]NEMA publications are available from the National Electrical Manufacturers Association, 1300 N. 17th St., Ste. 1847, Rosslyn, VA 22209, USA.~~

3.1.9 conventional BIL (basic lightning impulse insulation level): The crest value of a standard lightning impulse for which the insulation shall not exhibit disruptive discharge when subjected to a specific number of applications of this impulse under specified conditions, applicable specifically to non- self-restoring insulations.

3.1.10 conventional BSL (basic switching impulse insulation level): The crest value of a standard switching impulse for which the insulation does not exhibit disruptive discharge when subjected to a specific number of impulses under specified conditions, applicable to non-self-restoring insulations.

3.1.11 conventional withstand voltage: The voltage that an insulation is capable of withstanding with a 0% probability of failure.

3.1.12 coordination of insulation: The selection of insulation strength consistent with expected overvoltages to obtain an acceptable risk of failure.

[6] The numbers in brackets correspond to those of the bibliography in Annex H.

3.1.13 crest value: (of an impulse): The maximum value that an impulse attains. *Syn*: **peak value**.

3.1.14 critical flashover voltage (CFO): The amplitude of voltage of a given wave shape that, under specified conditions, causes flashover through the surrounding medium on 50% of the voltage applications.

3.1.15 deadfront type arrester: An arrester assembled in a shielded housing providing system insulation and conductive ground shield~~,~~ intended to be installed in an enclosure for the protection of underground and padmounted distribution equipment and circuits.

3.1.16 disconnector, surge arrester: *See*: **arrester disconnector**.

3.1.17 disruptive discharge: The sudden and large increase in current through an insulating medium due to the complete failure of the medium under electrical stress.

3.1.18 distribution arrester:

a) **heavy duty class:** An arrester most often used to protect overhead distribution systems exposed to severe lightning currents.

b) **light duty class:** An arrester generally installed on and used to protect underground distribution systems where the major portion of the lightning stroke current is discharged by an arrester located at the overhead line/cable junction.

c) **normal duty class:** An arrester generally used to protect overhead distribution systems exposed to normal lightning currents.

3.1.19 ferroresonance: Sustained oscillations involving a capacitance in series with a nonlinear inductance, characterized by highly distorted waveforms. ~~Can also occur between the capacitance to ground of an ungrounded circuit and voltage transformers with primary windings that are grounded. This phenomenon is also possible in gas- insulated systems~~

3.1.20 flashover: A disruptive discharge around or over the surface of a solid or liquid insulator.

3.1.21 ground flash density (GFD): The number of lightning strokes to ground per square kilometer per year.

3.1.22 impulse: A surge of unidirectional polarity.

3.1.23 insulation level: A combination of voltage values (both power frequency and impulse) that characterize the insulation of an equipment with regard to its capability of withstanding dielectric stresses.

3.1.24 lightning overvoltage: The crest voltage appearing across an arrester or insulation caused by a lightning surge.

3.1.25 lightning surge: A transient electric disturbance in an electric circuit caused by lightning.

3.1.26 liquid-immersed type arrester: An arrester designed for use immersed in an insulating liquid.

3.1.27 maximum continuous operating voltage rating (MCOV): The maximum designated root-mean- square (rms) value of power frequency voltage that may be applied continuously between the terminals of the arrester.

3.1.28 metal-oxide surge arrester (MOSA): A surge arrester utilizing valve elements fabricated from non–linear resistance metal-oxide materials.

3.1.29 nominal rate of rise (of an impulse) For a wave front, the slope of the line that determines the virtual zero. It is usually expressed in volts or amperes per microsecond.

3.1.30 nominal system voltage: A nominal value assigned to designate a system of a given voltage class.

3.1.31 non-self-restoring insulation: An insulation that loses its insulating properties or does not recover them completely after a disruptive discharge caused by the application of a test voltage; insulation of this kind is generally, but not necessarily, internal insulation.

3.1.32 overvoltage: Abnormal voltage between two points of a system that is greater than the highest value appearing between the same two points under normal service conditions. Overvoltages may be low frequency, temporary, and transient (surge).

3.1.33 peak value: *See*: **crest value.**

3.1.34 riser pole type arrester: An arrester for pole mounting most often used to protect underground distribution cable and equipment.

3.1.35 self-restoring insulation: Insulation that completely recovers its insulating properties after a disruptive discharge caused by the application of an overvoltage; insulation of this kind is generally, but not necessarily, external insulation.

3.1.36 series gap: An intentional gap(s) between spaced electrodes in series with the valve elements across which all or part of the impressed arrester terminal voltage appears.

3.1.37 standard lightning impulse: The wave shape of the standard impulse used is 1.2/50 µs voltage wave (when not in conflict with products standards).

3.1.38 standard switching impulses: The wave shapes of standard impulse tests depend on equipment being tested:

a) For air insulation and switchgear: 250/2500 µs

b) For transformer products: 100/1000 µs

c) For arrester sparkover tests (the tail duration is not critical):

  1) 30 µs to 60 µs /90 µs to 180 µs

  2) 150 µs to 300 µs /450 µs to 900 µs

  3) 1000 µs to 2000 µs /3000 µs to 6000 µs

3.1.39 statistical basic lightning impulse insulation level (BIL): The crest values of a standard lightning impulse for which the insulation exhibits a 90% probability of withstand (or a 10% probability of failure) under specified conditions, applicable specifically to self-restoring insulations.

3.1.40 statistical basic switching impulse insulation level (BSL): The crest value of a standard switching impulse for which the insulation exhibits a 90% probability of withstand (or a 10% probability of failure), under specified conditions, applicable to self-restoring insulations.

3.1.41 statistical withstand voltage: The voltage that an insulation is capable of withstanding with a given probability of failure, corresponding to a specified probability of failure (e.g., 10% or 0.1%).

3.1.42 surge: A transient wave of current, potential, or power in an electric circuit.

3.1.43 surge arrester: A protective device for limiting surge voltages on equipment by discharging or bypassing surge current; it limits the flow of power follow current to ground and is capable of repeating these functions as specified.

3.1.44 switching overvoltage: Any combination of switching surge(s) and temporary overvoltage(s) associated with a single switching episode.

3.1.45 switching surge: A heavily damped transient electrical disturbance associated with switching. ~~System insulation flashover may precede or follow the switching in some cases but not all.~~

3.1.46 system voltage: The root-mean-square (rms) phase-to-phase power frequency voltage on a three-phase alternating-current electric system.

3.1.47 temporary overvoltage (TOV): An oscillatory overvoltage associated with switching or faults (for example, load rejection, single-phase faults) and/or nonlinearities (ferroresonance effects, harmonics) of relatively long duration, which is undamped or slightly damped.

3.1.48 transmission-line arrester: A surge arrester installed on a transmission line, usually for the purpose of protecting transmission-line insulation.

3.1.49 traveling wave: The resulting wave when an electrical variation in a circuit such as a transmission line takes the form of translation of energy along a conductor, such energy being always equally divided between current and potential forms.

3.1.50 unit operation: Discharge of a surge through an arrester while the arrester is energized.

3.1.51 valve arrester: An arrester that includes one or more valve elements.

3.1.52 valve element: A resistor that, because of its nonlinear current-voltage characteristic, limits the voltage across the arrester terminals during the flow of discharge current and contributes to the limitation of follow current at normal power-frequency voltage.

3.1.53 virtual duration of wave front: (of an impulse) The virtual value for the duration of the wave front is as follows:

a) For voltage waves with wave front durations less than 30 μs, either full or chopped on the front, crest, or tail, 1.67 times the time for the voltage to increase from 30% to 90% of its crest value.

b) For voltage waves with wave front durations of 30 μs or more, the time taken by the voltage to increase from actual zero to maximum crest value.

c) For current waves, 1.25 times the time for the current to increase from 10% to 90% of crest value.

3.1.54 virtual zero point: (of an impulse) The intersection with the time axis of a straight line drawn through points on the front of the current wave at 10% and 90% crest value or through points on the front of the voltage wave at 30% and 90% crest value.

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a) The wave shape of an impulse (other than rectangular) of a current or voltage is designated by a combination of two numbers. The first, an index of the wave front, is the virtual duration of the wave front in microseconds. The second, an index of the wave tail, is the time in microseconds from virtual zero to the instant at which one half of the crest value is reached on the wave tail. Examples are 1.2/50 and 8/20 waves.

b) The wave shape of a rectangular impulse of current or voltage is designated by two numbers. The first designates the minimum value of current or voltage that is sustained for the time in microseconds designated by the second number. An example is the 75 A · 2000 μs wave.

3.1.58 wave tail: (of an impulse) That part between the crest value and the end of the impulse.

3.1.59 withstand voltage: The voltage that an insulation is capable of withstanding with a given probability of failure. In terms of insulation, this is expressed as either conventional withstand voltage or statistical withstand voltage.

3.2 Acronyms and abbreviations

BIL	basic lightning impulse insulation level
BSL	basic switching impulse insulation level
CFO	critical flashover voltage
COG	coefficient of grounding
CVT	capacitor voltage transformer
CWW	chopped wave withstand
dc	direct current
EHV	extra high voltage
FACTS	flexible alternating current transmission systems
FOR	flashover rate of lines (flashovers per 100 km per year)
FOW	front of wave (protective level)
FW	full wave (lightning test)
FWW	front of wave withstand
GFD	ground flash density (flashes to ground per square kilometer per year)
GIS	gas-insulated substation
GTO	gate turnoff transistor
HVDC	high-voltage direct current
IGBT	insulated gate bipolar transistor
IV	induced voltage
LPL	lightning protective level
MCOV	maximum continuous operating voltage
MOSA	metal-oxide surge arrester
MTBF	mean time between failure
PM	protective margin
PR	protective ratio
SPL	switching protective level
SVC	static VAR compensator
TCSC	thyristor controlled series capacitors
TLA	transmission-line arrester
TOV	temporary overvoltage
TRV	transient recovery voltage
UPFC	universal power flow controller
VAR	volt-ampere reactive

4. General considerations

4.1 Overvoltages

Overvoltages in power systems may be generated by external events, such as lightning; by internal ~~events~~conditions including faults, switching, ferroresonance, load rejection, loss of ground, and ~~by internal conditions including faults,~~ so on, or by any combination of the above. The magnitude of these overvoltages can be above maximum permissible levels and therefore need to be reduced and protected against if damage to equipment and possible undesirable system performance are to be avoided.

4.1.1 Lightning currents and overvoltages

Lightning surge voltages that arrive at the line entrance of a station ~~are~~ may be caused ~~either~~ by the following factors:

a) A lightning flash terminating on the overhead shield wire or structure with a subsequent flashover to the phase conductor (denoted as a ~~or by~~ backflash)

b) A lightning flash terminating on the phase conductor (denoted as a shielding failure)~~.~~

c) A nearby lightning strike that induces a surge into the conductors

The lightning surge voltage magnitudes and wave shapes that enter a station are functions of the magnitude, polarity, and shape of the lightning stroke current, the tower and line surge impedance, the tower footing impedance, and the lightning impulse critical flashover voltage (CFO) of the line insulation.

The crest magnitude of the surge voltage arriving at tehe station caused by a backflash is generally considered to be 1 to 1.2 times the positive polarity CFO of the line insulation. This represents a reasonable worst-case condition. The steepness of the incoming surge (rate of rise) is dependent on the distance between the station and the backflash location. The steepness decreases approximately as an inverse function of this distance *d*, and it ranges from about 700/*d* kV/µs for a single-phase conductor to about 1700/*d* kV/µs for a three- to four-conductor bundle where *d* is in kilometers. Steepnesses in the range of 500 kV/µs to 2000 kV/µs are typically encountered. The tail of the incoming surge described is generally in the range of 10 µs to 20 µs decay to half value.

Lightning surge crest voltages caused by shielding failures generally do not exceed the negative polarity CFO of the line insulation. The wave fronts and tails at the location of the shielding failure are equal to those of the lightning stroke current. Therefore, the steepness of the incoming surge at the station is less than those from a backflash, whereas the tail is longer, with an average time to half value of about 92 µs.

For lines that are effectively shielded, for the same reliability criterion, the surge voltages caused by a backflash are usually more severe. That is, they have greater steepness and greater crest voltage and, therefore, are the only ones generally considered for analysis of station protection.

4.1.2 Switching overvoltages

Switching overvoltages occur on all systems (AIEE Committee Report [B1]; IEEE Committee Report [B87]; and IEEE Committee Report [B88]) and usually result from a circuit- breaker operation or the occurrence of a fault. These overvoltages are an important consideration in systems above 115 kV and in all systems where the effective surge impedance as observed from the arrester location is low (e.g., cable and capacitor bank circuits).

The switching surge duty on metal-oxide arresters applied on overhead transmission lines increases for increased system voltage and increased length of switched line. Typically, transients occurring from high- speed reclosing impose greater duty than energizing.

On extra high-voltage (EHV) systems, it is important that transients on the high-voltage network do not transfer excessive energy to arresters on the low-side windings of step-down transformers. This situation arises when a line is switched at one end and the other end of the line is transformer terminated. The per-unit protective levels of the low-side arrester should be higher than that of the high-voltage winding arresters so they do not respond to high-side surges.

Because of the likelihood of unusually high discharge currents, the application of arresters to shunt capacitor banks or cables may require a special review, such as a detailed analytical system study. Arresters

of higher energy capability or parallel arresters may be required (see 5.5).

4.1.3 Temporary overvoltages

Temporary overvoltages consist of lightly damped power frequency voltage oscillations, often with harmonics, usually lasting a period of hundreds of milliseconds or longer. Situations that may give rise to these overvoltages include single line-to-ground faults, ferroresonance, load rejection, loss of ground, long unloaded transmission lines (Ferranti rise), coupled-line resonance, and transformer-line inrush. The system configuration and operating practices should be reviewed to identify the most probable forms of temporary overvoltages that may occur at the arrester location. In addition, proper application of metal-oxide arresters requires that the duration of these overvoltages be known (see 4.2.4).

When detailed system studies or detailed calculations are unavailable, as a minimum, the overvoltages due to line-to-ground faults should be addressed. Single line-to-ground faults are ~~the most~~ a common type of ~~system disturbance,~~temporary overvoltage. The magnitudes of these overvoltages are related to system grounding and can be estimated by the "coefficient of grounding" (COG) as outlined in 5.2.1.2.1. Arresters on a well-grounded system are normally exposed to low-magnitude temporary overvoltages during single line-to-ground faults, whereas they are exposed to higher voltages when the system is either ungrounded or grounded through an impedance. This is also true of arresters installed on the neutral of reactance- or resistance-grounded transformers and for systems using resonant grounding and Peterson coils (Clarke [B31]).

4.2 Metal-oxide arresters

4.2.1 Design

Metal-oxide arresters fall into three broad design categories as follows: gapless arresters, shunt-gapped arresters, and series-gapped arresters. The general principles of these three design types are described in 4.2.1.1 through 4.2.1.3.

~~[6] The numbers in brackets correspond to those of the bibliography in annex D.~~

4.2.1.1 Gapless arresters

Gapless arresters utilize a single stacked column or two or more parallel columns of metal-oxide valve elements, as schematically shown in Figure 1(a). A typical volt-ampere characteristic for such an arrester is illustrated in Figure 1(b). Above the knee of the volt-ampere curve, the metal-oxide elements exhibit a very nonlinear behavior that may be approximated by the relationship $I = kV^{\alpha}$. Alpha (α) values will normally vary from 10 to 50, depending on the metal-oxide formulation and current range being studied. Typically, higher current values and wider ranges will yield lower values of α. For example, α may be 50 over a current range of 1 A to 600 A and may average 26 over the wider range of 1 A to 10 000 A. The arrester discharge voltage for a given surge-current magnitude is directly proportional to the height of the valve element stack and is thus more or less proportional to the arrester-rated voltage. Additionally, the arrester discharge voltage is a function of the rate of rise of the current surge, with higher voltages occurring for ~~faster~~greater rates of rise and lower voltages for lower rates of rise. Typically, for the same current magnitude, the voltage occurring for a current cresting in 1 µs is 8% to 12% higher than that occurring for a standard 8/20 ~~µs~~ lightning current wave. The voltage occurring for a current cresting in 45 µs to 60 µs is 2% to 4% lower than that for the 8/20 ~~µs~~ wave.

The maximum continuous operating voltage (MCOV) of the arrester is typically in the range of 75% to 85% of the duty-cycle voltage rating. At MCOV, the arrester current is usually not more than a few milliamperes, typically less than 10 mA. On the arrival of a surge, the increasing surge current is accompanied by a rise in arrester voltage to a maximum level determined by the volt-ampere characteristic.

As the surge current decreases, the discharge voltage will decrease back toward the presurge level.

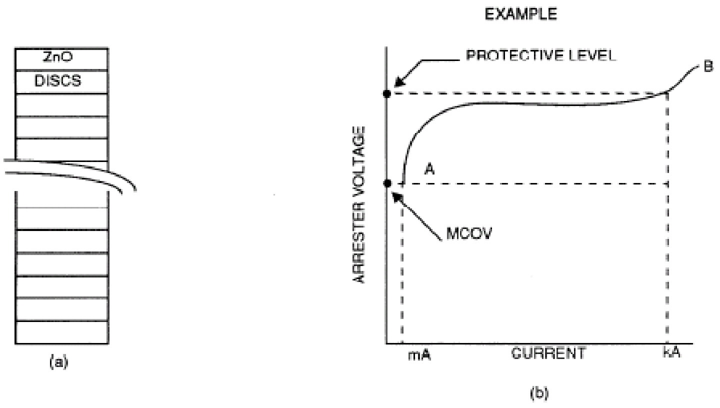


Figure 1—Gapless metal-oxide surge arrester

4.2.1.2 Shunt-gapped arresters

For surge currents above a certain magnitude, the discharge voltage of a column or columns of metal-oxide valve elements can be reduced by shunting a portion of the stack. This is the basic principle of a shunt- gapped arrester, which is schematically shown in Figure 2(a). A typical volt-ampere characteristic of such an arrester is illustrated in Figure 2(b). On arrival of a surge, the arrester voltage initially increases with increasing surge-current magnitude according to the volt-ampere characteristics A-B. When the surge current magnitude reaches 250 A to 500 A (range B to C on volt-ampere characteristic), the sparkover of a gap electrically connected in parallel with a few metal-oxide valve elements results in a shunting of the surge current around these valve elements, thereby proportionally lowering the discharge voltage (in the range D to E). For further increases in surge current, the voltage increases according to the characteristic E- F. As the surge current decreases, the arrester voltage decreases accordingly, following the characteristic F- G until the shunt gaps extinguish at a low level of current. ~~Following~~After the extinction of the arrester leakage current, the arrester operating point returns to A.

From an energy standpoint, the energy absorption capability is less after gap sparkover than before.

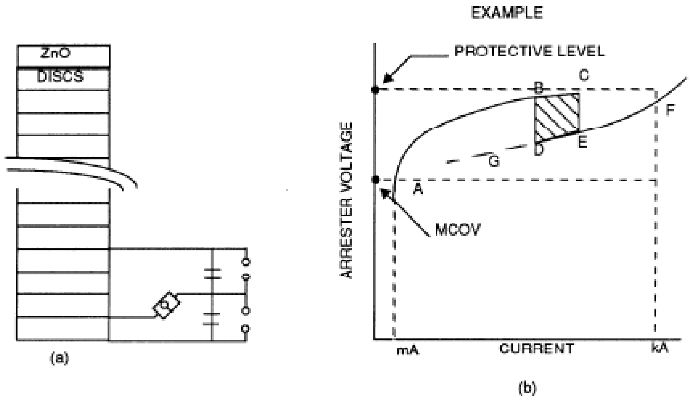


Figure 2—Shunt-gapped metal-oxide surge arrester

4.2.1.3 Series-gapped arresters

Another approach to obtain ~~reduced~~lower discharge voltage (greater protective ~~levels~~margin) is to use fewer valve elements in conjunction with series-connected spark gaps, as depicted in Figure 3(a). The series gaps are shunted by a ~~linear component~~ impedance network of such characteristics that the applied voltage is divided between the impedance network and the metal-oxide elements. A typical volt-ampere characteristic is illustrated in Figure 3(b). On the arrival of a surge, the arrester voltage begins to rise (A-B), the total voltage being the vector sum of the voltages across the metal-oxide elements and the series gap impedance network. At a level of current in the vicinity of 1 A (depending on rate of rise in the range B to C), the gap's sparkover and the arrester voltage is reduced to the discharge voltage of the metal-oxide elements only. For further increase in surge current, the voltage increases according to the characteristic D-E-F. As the surge current decreases, the arrester voltage decreases accordingly, following the characteristic F-G until the series gaps extinguish at a low level of current.

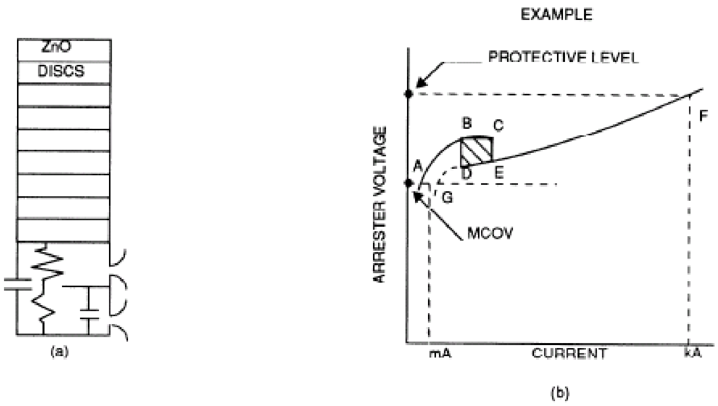


Figure 3—Series-gapped metal-oxide surge arrester

4.2.2 Test procedures

IEEE Std C62.11™-2005 contains test procedures that consider all three types of arrester design. The standard includes tests for both series- and shunt-gapped arresters to obtain the protective level that is the higher of either the gap sparkover or the discharge voltage. Protective levels for metal-oxide arresters can be treated in the same manner, irrespective of whether the levels are limited by sparkover or by discharge voltage (see 4.3).

4.2.2.1 Usual operating conditions

Arresters are designed to operate properly in continuous air temperatures in the general vicinity of the arrester between –40 ºC and 40 ºC, in temporary maximum air temperatures due to external heat sources near the arrester that do not exceed 60 ºC, and at altitudes that do not exceed 1800 m (6000 ft).

NOTE—Usual operating temperatures for special-application arresters, such as oil- or liquid-immersed, gas-insulated, and dead-front arresters, will typically differ from the above~~, but such operating temperatures had not been standardized at the time this guide was prepared.~~ (see IEEE Std C62.11-2005 for further information).[7]

[7] Notes in text, tables, and figures of a standard are given for information only and do not contain requirements needed to implement this standard.

4.2.2.2 Unusual conditions

In addition to operation beyond the limits of 4.2.2.1, exposure to damaging fumes, vapors, steam, salt spray, or excessive amounts of contamination may require special consideration. Arresters should not be installed where they may be subjected to excessive mechanical stresses or to abnormal vibrations or shocks.

4.2.3 Standard voltage ratings

The present metal-oxide design standard, IEEE Std C62.11-2005, specifies a dual voltage rating for each arrester. ~~The conventional~~ Each duty-cycle voltage rating~~ now~~ has a corresponding MCOV rating. Throughout this document, wherever an arrester is designated by a voltage, the voltage refers to the duty-cycle rating unless qualified as MCOV.

In applying the metal-oxide arrester, it is critically important that the arrester MCOV rating be equal to or greater than the maximum continuous voltage to which the arrester is exposed at any time.

4.2.4 Temporary overvoltage capability

The MCOV rating defines the maximum continuous voltage at which an arrester is designed to operate. However, metal-oxide arresters are capable of operating for limited periods of time at voltages in excess of the MCOV rating. ~~All~~ Manufacturers publish information on overvoltage capability. A typical 60 Hz temporary overvoltage capability curve is shown in Figure 4, and the test to confirm this capability is specified in IEEE Std C62.11-2005.

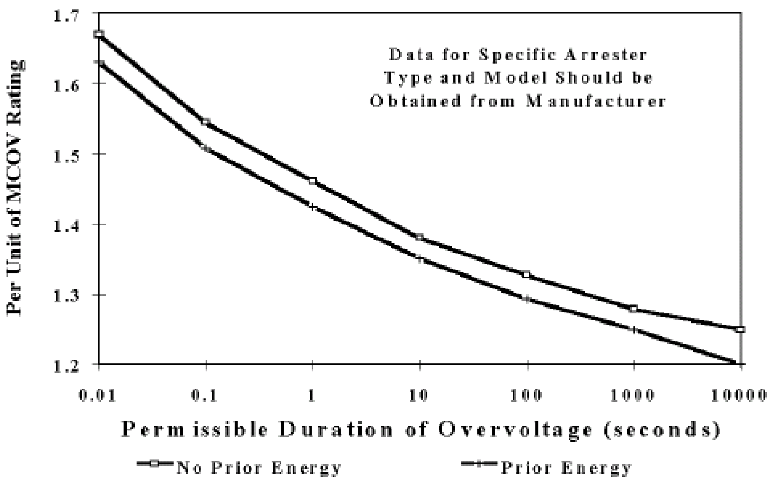


Figure 4—Example of typical arrester temporary overvoltage (TOV) data (do not use for application)

4.2.5 Energy handling capability

Metal-oxide arresters protect the equipment from high-voltage surges by absorbing the energy from the surge arrester. The energy handling capability (or also called “energy absorption capability” or “energy withstand capability”) is an important consideration in the design and application of metal-oxide arresters. Most manufacturers publish energy capability values of arresters; however, there are no specified tests either in current versions of IEEE or IEC standards, so there may be confusion in using these important application parameters. Both the IEEE and the IEC are contemplating writing standardized tests for the arrester energy handling capability.

When metal-oxide arresters are energized, valve elements of the arrester will absorb energy, which results in a temperature increase of the valve elements. Under normal operating conditions (i.e., absence of overvoltage), there is a balance between the heat generated by the valve elements and the heat dissipated by the arrester through conduction, convection, and radiation, such that a stable operating condition is maintained. Overvoltage events disturb this stable condition by causing the valve elements to absorb increased levels of energy for some limited amount of time~~ the overvoltage exceeds the normal operating voltage~~. The subsequent response of the arrester depends greatly on the magnitude and rate of energy input and on the specific design of the arrester.

For simple applications where overvoltages are well defined, the resulting energy absorbed by the arrester can be determined by calculation (use arrester minimum voltage characteristics ~~should be used).~~for energy calculation). For complex situations, computer simulation studies using programs such as the Electromagnetic Transients Program (EMTP) may be required. These studies require knowledge of the arrester minimum and maximum voltage-current characteristics, which are usually available from the arrester manufacturer, for modeling in EMTP.~~ Both the minimum as well as the maximum characteristics shall be used in order to calculate the actual energy and protective levels respectively.~~

4.2.5.1 Arrester failure modes

If the temperature rise of the valve elements due to energy absorption is too high, the arrester can be driven into a state of thermal runaway~~, a~~; in this condition, heat generated exceeds heat dissipated, resulting in further increase in valve element temperature. ~~If~~ It is possible for the temperature ~~of a valve element~~to reach a high enough level to cause damage to the valve ~~elements can occur~~ element material, leading to an electrical breakdown and failure of the arrester.

If the energy density is sufficiently high or if the distribution of energy density within the valve element is nonuniform to cause locally high temperature gradients, then thermomechanical damage in the form of valve element cracking or puncture may occur. This is possible even if the overall temperature rise of the valve elements would not have been high enough to drive the arrester into thermal runaway.

The energy~~ that an arrester can absorb during an overvoltage event without impairing the arrester’s ability to serve the intended function following the event is usually called ~~“~~energy ~~-handling ~~capability~~”~~ or ~~“~~energy withstand ~~capability of metal-oxide arresters is often expressed in terms of kilojoules per ~~kV~~kilovolt of arrester MCOV or per ~~kV ~~kilovolt of arrester duty-cycle rating.~~ Because it is dependent on the specific form (magnitude, waveshape and duration) of the overvoltage, the energy handling capability cannot be expressed by a single value of kJ/kV. Manufacturers typically publish some information on energy handling capability, but it should be recognized that, at present, there are no standardized tests for determination of arrester’s energy handling capability. Users are advised to consult with manufacturers on appropriate use of information provided.~~

First, the users must be aware to compare the right parameters, because the kilojoules per kilovolt MCOV rating can be 25% higher than the kilojoules per kilovolt of duty-cycle rating. Some manufacturers also publish the kilojoules per kilovolt values that are applicable for single shot energy discharge and another (higher) value for multishot (usually two or three) discharges within a 1 min period. The spacing between the shots gives time for the heat to distribute throughout the disk.

The energy-handling capability is dependent on the specific form (magnitude, wave shape, and duration) of the current discharged through the arrester; hence, it cannot be uniquely expressed by a single value of kilojoules per kilovolt. The arrester energy ratings are typically specified by the manufacturers based on transmission-line discharge (switching surge) tests. Manufacturers should be consulted for the specific types of discharges for which the published kilojoules per kilovolt values apply.

The energy capability of a metal-oxide surge arrester (MOSA) is also dependent on the operating voltage present subsequent to the discharge current. The arrester can potentially absorb more energy than its rating, without going into thermal instability if the postevent voltage is less than MCOV. Published arrester energy withstand data typically do not provide the necessary information to assess the influence of postevent voltage on arrester energy capability. For special applications where the arrester is applied substantially below its MCOV rating, the manufacturer should be consulted.

4.2.5.2 Discharge event characteristics and arrester energy duty

Some power system transients can be characterized as an approximately constant-current source of discharge current. For these events, the energy duty is approximately proportional to the arrester's residual discharge voltage. Other events can be characterized as a relatively stiff voltage source. The energy duty of arresters subjected to these events can significantly increase with decreasing residual voltage.

The discharge source characteristics of common classes of power system transients are summarized as follows:

Lightning: Lightning stroke currents are virtual constant-current sources. Because there are typically other paths for current than the arrester, there is some dependence of energy duty on arrester characteristics. Arresters having a lower discharge voltage will tend to discharge a larger portion of the lightning stroke current than arresters with higher discharge voltages. For critical applications, transient simulation should be performed using typical lightning stroke parameters and the given power system topology and parameters.

Switching transients: For worst-case line and capacitor bank restrike events, the prospective (without arrester) overvoltage will be on the order of two to three times crest operating voltage for a typical grounded transmission system. The discharge current magnitude and wave shape for a capacitor or line- switching transient, however, is highly dependent on the nature of the event and the system characteristics. The characteristics of the system on the source side of the switching location can be as important as the characteristics of the line or device that is switched. Line and capacitor switching transient arrester energy duties are only somewhat sensitive to arrester discharge voltage characteristics, with lower discharge voltages yielding increasing arrester current and energy.

Reactor switching transients. Due to current chopping, reactor switching transients create short-duration arrester discharge currents. This phenomenon can be characterized as a current source at the chopped current value. Generally, current chopping during reactor switching does not create critical arrester duty.

Temporary overvoltages: The temporary overvoltage classification covers a wide range of phenomena, which differ in their impact on arrester energy. Fundamental frequency overvoltages due to a neutral shift during unbalanced faults in poorly grounded systems can be characterized as a relatively stiff voltage source for which arrester discharge voltage characteristics will have a large influence on energy duty. Arrester discharge current will typically be relatively small, but each discharge may be on the order of 1 ms in duration and repeated twice per 60 Hz cycle. The arrester energy capabilities can be quickly exceeded if a fundamental frequency (power frequency) TOV causes arrester discharge. In general, manufacturers' published TOV withstand curves are recommended for TOV duty evaluation, instead of calculating arrester energy.

Harmonic resonance overvoltages, such as might occur during transformer energization in a weak system, present a weaker source than fundamental frequency overvoltages, and discharge current durations are not as long. The evaluation of energy duty by simulation provides more accuracy than the use of TOV capabilities based on fundamental frequency overvoltages.

Ferroresonance, despite the high overvoltage possible without an arrester, can result in very low discharge current magnitudes because the effective overvoltage source has high impedance. In many situations, the energy dissipated by an arrester is at a slow enough rate that significant heat may be conducted to the ambient environment. Tests have shown that metal-oxide arresters can limit ferroresonant overvoltages for an indefinite duration in certain circumstances. In such a case, the arrester energy capability is not as relevant as steady-state thermal resistance (power capability).

Approximate techniques for estimating arrester energy duty for various common events are described and illustrated in Annex G. Additional information on metal-oxide valve element energy handling capability is given in IEEE Working Group Report [B98] and Ringler et al. [B157].

4.3 Protective levels

The protective level of an arrester is the maximum crest voltage that appears across the arrester terminals under specified conditions of operation. For metal-oxide arresters without gaps, the protective level is the arrester discharge voltage for a specified discharge current. For arresters with gaps (shunt or series), the protective level is the higher of the gap sparkover voltage or the discharge voltage.

4.3.1 Classification current

IEEE Std C62.11-2005 specifies the magnitudes of lightning impulse "classification current" for each class of arrester. For station-class arresters, the classification current magnitude also depends on the voltage of the system to which the arresters are applied. For station- and intermediate-class arresters, IEEE Std C62.11-2005 also specifies the magnitudes of switching impulse classification current. These classification currents are, in effect, reference discharge currents and represent appropriate levels of discharge current for general considerations of insulation coordination (see 5.2.2.1). IEEE

Std C62.11-2005 requires that certain tests, including discharge voltage measurements, be made at the specified classification current magnitude.

4.3.2 Lightning impulse protective level (LPL)

LPL is the higher of the discharge voltages established by tests using 8/20 ~~μs~~ discharge current impulses or gap sparkover voltages for specified surge voltage waves. The discharge voltage is a function of current magnitude. IEEE Std C62.11-2005 specifies that tests should be made with 8/20 ~~μs~~ currents of 1500 A, 3000 A, 5000 A, 10 000 A, and 20 000 A. If the arrester lightning impulse classification current shown in IEEE Std C62.11-2005 is not one of these, then an additional test must be made at the classification current given for the particular arrester class.

4.3.3 Front-of-wave protective level (FOW)

FOW protective level for metal-oxide arresters is the higher of:

a) The crest discharge voltage resulting from a current wave through the arrester of lightning impulse classifying current magnitude with a rate-of-rise high enough to produce arrester crest voltage in 0.5 μs~~; or~~

b) Gap sparkover for specified rates-of-rise of wave shapes in IEEE Std C62.11-2005

4.3.4 Switching impulse protective level (SPL)

SPL is the higher of either:

a) The crest discharge voltage measured with a current wave through the arrester of switching impulse classifying current magnitude and a time to actual current crest of 45 μs to 60 μs~~; or~~

b) Gap sparkover voltage on similar wave shapes~~.~~

The switching impulse classifying currents given in IEEE Std C62.11-2005 are for a two-line substation and were calculated by dividing the line charge voltage (E), minus the switching surge-protective level of the minimum arrester rating used at that voltage, by one half of the surge impedance (Z_L). These currents are considered conservative for most arrester applications, but they may be exceeded in applications involving capacitor banks or cables or in other low-impedance circuits. The manufacturers should be consulted for information on protective levels for currents that exceed the switching impulse classifying current.

4.4 Insulation withstand

Insulation strength is expressed in terms of conventional or statistical basic lightning impulse insulation levels (BILs) and basic switching impulse insulation levels (BSLs). The withstand voltages of interest in arrester applications are taken from the list of preferred BIL and BSL values in IEEE Std 1313.1™-1996.

The following withstand levels for equipment and bus insulation are of interest in arrester application:

a) ~~*Chopped Wave Withstand* (~~CWW~~)~~: Tests are made with a 1.2/50 ~~μs~~ impulse chopped by the action of a gap in a minimum time as specified in the appropriate product standard.

b) ~~*Basic Lightning Impulse Insulation Level* (~~BIL~~)~~: Tests are made with full-wave 1.2/50 impulses as specified in the appropriate equipment standard.

c) ~~*Basic Switching Impulse Insulation Level* (~~BSL~~)~~: The test impulse depends on the type of equipment.

Transmission- and distribution-line insulation strength is usually statistically described by a ~~critical flashover voltage (~~CFO~~)~~ at which the insulation exhibits a 50% probability of flashover and by a standard deviation σ, which is approximately 5% of the CFO.

The insulation strength of apparatus within a station is expressed in terms of a BIL, a chopped-wave voltage, and for higher system voltages, a BSL. As noted from the definitions, the BIL and BSL may be either conventional or statistical. The statistical BIL (or BSL) is equal to CFO –1.28 σ.

4.5 Separation effects

The voltage at the protected insulation will usually be higher than at the arrester terminals due to oscillations on connecting leads (Witzke and Bliss [B188]). This rise in voltage is called a separation effect.

Separation effects increase with the increasing rate of rise of the incoming surge and with increasing distances between the arrester and protected equipment. For evaluation of separation effects due to lightning surges, refer to Annex C. Due to the relatively slow rates of rise of switching surges, separation effects need not be considered in applying the fundamental protective ratio formula to switching surge withstand (BSL).

Other considerations in locating arresters are discussed in 5.2.3.

4.6 Insulation coordination

Insulation coordination is defined in IEEE Std 1313.1-1996 and in this guide as "the selection of insulation strength consistent with expected overvoltages to obtain an acceptable risk of failure."

The degree of coordination is measured by the protective ratio (*PR*). The fundamental definition of *PR* is as follows:

$$PR = \frac{\text{Insulation withstand level}}{\text{Voltage at protected equipment}} \qquad (1)$$

"Voltage at protected equipment" includes a separation effect, if significant. If not, it is equal to arrester protective level.

Three protective ratios are in common use, comparing protective levels with corresponding insulation withstands.

$$PR_{L1} = {}^{\text{CWW}}\!/_{\text{FOW}} \qquad (2)$$

(A ratio of 1.2 is generally considered acceptable for non-self-restoring insulation.)

$$PR_{L2} = {}^{\text{BIL}}\!/_{\text{LPL}} \tag{3}$$

(A ratio of 1.2 is generally considered acceptable for non-self-restoring insulation.)

$$PR_{s} = {}^{\text{BSL}}\!/_{\text{SPL}} \tag{4}$$

(A ratio of 1.15 is generally considered acceptable for non-self-restoring insulation.)

The protective margin (*PM*) in percent is defined as follows: $PM = (PR - 1)100$. *PR* and *PM* applications are covered in Clause 5 and Clause 6. For transformers, see 5.2.5.3

A graphical approach to insulation coordination is also discussed in 5.2.5

5. Protection of transmission ~~systems~~equipment and substations

5.1 Introduction

The general procedures given here are applicable where transformers and other equipment and station components have a chopped-wave voltage withstand level at least 1.10 times the BIL. For this withstand level, the procedures for the selection and location of arresters in relation to the insulation system to be protected can generally be reduced to a series of steps. These are summarized in 5.2~~ and elaborated upon in 5.3 through 5.8~~.

Arrester applications for transformer or other series windings, unloaded windings, and ungrounded neutrals are discussed in 5.3.

Where a lower chopped-wave insulation level is specified in equipment such as dry-type transformers, the protection procedures are covered in 5.4.

Special surge protection application considerations for other substation and transmission equipment is covered in the remainder of this Clause 5. Surge protection of shunt capacitor banks, transmission cables, gas-insulated substations, high-power static devices, series capacitor banks, and circuit breakers is discussed in 5.5 through 5.10.

Basic to the application theory presented by this guide are the presumptions that:

a) Surge arrester ground terminals are connected to the grounded parts of the protected equipment.

b) Both line and ground surge arrester connections are as short as practical.

c) The station is shielded against direct strokes.

5.2 Transformer protection, step-by-step procedures

A summary of the steps required to select arresters is provided in Figure 5.

1. Select surge arrester
   - 1.1 MCOV ≥ Maximum phase-to-neutral Voltage (see 5.2.1.1)
   - 1.2 TOV capability ≥ system TOV (see 5.2.1.2)
   - 1.3 Switching impulse energy capability ≥ that produced by the system (see 5.2.1.3)
   - 1.4 Arrester class:

     a) Available ratings
     b) Pressure relief
     c) Durability

     (see Table 1)

2. Determine protective levels (see 5.2.2.1)
   - 2.1 Lightning impulse protective level (LPL)
   - 2.2 Front-of-wave protective level (FOW)
   - 2.3 Switching impulse protective level, (SPL)

3. Locate surge arrester (see 5.2.3)

   As close as possible to equipment to be protected

4. Determine voltage at equipment terminals (see 5.2.3)

   Arrester lead length and transformer-to-arrester separation distance effects can be determined per Annex C

5. Select insulation strength (see 5.2.4)

   See equipment standards for BILs, BSLs, and CWWs

6. Evaluate coordination (see 5.2.5)
   - 6.1 If effects of separation distance can be disregarded, the protective ratios for lightning, PR_{L1} and PR_{L2}, and switching impulses, PR_S, are:

     PR_{L1} = CWW/FOW
     PR_{L2} = BIL/LPL
     PR_S = BSL/SPL

   For acceptable coordination, PR_{L1} and PR_{L2} should be equal to or greater than 1.2, and PR_S should be equal to or greater than 1.15.

   - 6.2 If the voltage at the equipment terminals, V_T, is calculated per Annex C, the protective ratios are as follows:

     If the time-to-crest of the arrester voltage is equal to or less than 2 µs:

     PR_{L1} = CWW/V_T
     $PM_{L1} = (PR_{L1} - 1)$ 100%

     If CWW does not exist or the time-to-crest of the arrester voltage is greater than 2 µs:

     PR_{L2} = BIL/V_T
     $PM_{L2} = (PR_{L2} - 1)$ 100%

     Also
     PR_S = BSL/SPL
     $PM_S = (PR_S - 1)$ 100%

     For acceptable coordination, PR_{L1} or PR_{L2} and PR_S have to be equal to or greater than 1.15 (PM_{L1} or PM_{L2} and $PM_S \geq 15\%$).

7. Evaluate alternates (see 5.2.6)

   If acceptable coordination cannot be achieved, evaluate the following measures:

   a) Increase BIL and BSL
   b) Decrease arrester separation distance
   c) Add additional arresters
   d) Use arrester with lower protective characteristics

Figure 5—Summary of procedures for arresters selection and insulation coordination for transformer protection

The following sequence is used:

a) Select an arrester and determine its protective characteristics

b) Select (or determine) the insulation withstand

c) Evaluate the insulation coordination

Other sequences may be equally acceptable. The key step is insulation coordination evaluation. Withstand voltages may be selected to match the characteristics of certain arresters, or arresters may be matched to available insulation. The typical characteristics of station class and intermediate class arresters are given in Table 1. The distribution class arresters are sometimes used in stations, and typical characteristics of such arresters may be found in Table 9. Protective levels are given in per-unit values and typical per-unit ~~values may be converted to kilovolts and used~~ranges. The per-unit base is the fundamental-frequency voltage crest of the arrester rms MCOV rated voltage. The protective levels and ranges in Table 1 are only illustrative, are from IEEE Std C62.22-1991, and are not up to date. For arrester selection, refer to protective levels in manufacturers' current publications. Values in the columns under "Durability Characteristics" are specified requirements for the range of ratings as prescribed in IEEE Std C62.11-2005.

5.2.1 Arrester selection (Figure 5, item 1)

For a given application, the selection of an appropriate arrester (Figure 5, item 1) involves considerations of maximum continuous operating voltage, protective characteristics (lightning and switching impulse), durability (temporary overvoltage and switching surge), service conditions, and pressure-relief requirements. Durability and protective level considerations will primarily determine the class of arrester selected: station class, intermediate class, or occasionally, distribution class.

Station class arresters are designed for heavy-duty applications. They have the widest range of ratings (see Table 1), the lowest protective characteristics, and the most durability. Intermediate class arresters are designed for moderate-duty and for maximum system voltages of 169 kV and below (with the exception of transmission-line surge arresters, see 7.2). Distribution class arresters (see Table 8 and Table 9 of Clause 6) are used to protect lower voltage transformers, as well as transmission and distribution lines where the system-imposed duty is minimal and there is a need for an economical design.

5.2.1.1 ~~Maximum continuous operating voltage (~~MCOV~~)~~

For each arrester location, arrester MCOV must equal or exceed the expected MCOV of the system. Proper application requires that the system configuration (single-phase, delta, or wye) and the arrester connection (phase to ground, phase to phase, or phase to neutral) be evaluated. For example, in EHV systems, the arrester is typically connected phase to ground, and therefore, it is exposed to system phase-to-ground voltages on a steady-state basis. However, an arrester connected to a tertiary winding with one corner grounded, or to a delta-connected system with a fault on one phase, is exposed to phase-to-phase voltage.

Table 1—Typical station and intermediate class arrester characteristics from IEEE Std C62.22-1991

Refer to the manufacturer's current data

Station Class									
Steady-state operation system voltage and arrester ratings effectively grounded systems (NOTE 1)				**Protective levels range of industry maxima per unit (crest of 60 Hz) of MCOV**			**Durability characteristics IEEE Std C62.11-2005**		
Max system rms L-L voltage kV*	**Max system rms L-G voltage kV***	**Min rms MCOV rating kV**	**Duty-cycle rms voltage rating kV**	**0.5 µs FOW protective level (NOTE 2)**	**8/20 µs protective level (NOTE 3)**	**Switching surge protective level (NOTE 4)**	**High crest current withstand A**	**Trans. line discharge mi**	**Pressure relief rms symmetrical current kA (NOTE 5)**
4.37	2.52	2.55	3	2.32–2.48	2.10–2.20	1.70–1.85	65 000	150	40–80
8.73	5.04	5.1	6–9	2.33–2.48	1.97–2.23	1.70–1.85	65 000	150	40–80
13.1	7.56	7.65	9–12	2.33–2.48	1.97–2.23	1.70–1.85	65 000	150	40–80
13.9	8.00	8.4	10–15	2.33–2.48	1.97–2.23	1.70–1.85	65 000	150	40–80
14.5	8.37	8.4	10–15	2.33–2.48	1.97–2.23	1.70–1.85	65 000	150	40–80
26.2	15.1	15.3	18–27	2.33–2.48	1.97–2.23	1.70–1.85	65 000	150	40–80
36.2	20.9	22	27–36	2.43–2.48	1.97–2.23	1.70–1.85	65 000	150	40–80
48.3	27.8	29	36–48	2.43–2.48	1.97–2.23	1.70–1.85	65 000	150	40–80
72	41.8	42	54–72	2.19–2.40	1.97–2.18	1.64–1.84	65 000	150	40–80
121	69.8	70	90–120	2.19–2.40	1.97–2.18	1.64–1.84	65 000	150	40–80
145	83.7	84	108–144	2.19–2.39	1.97–2.17	1.64–1.84	65 000	150	40–80
169	97.5	98	120–172	2.19–2.39	1.97–2.17	1.64–1.84	65 000	175	40–80
242	139	140	172–240	2.19–2.36	1.97–2.15	1.64–1.84	65 000	175	40–80
362	209	209	258–312	2.19–2.36	1.97–2.15	1.71–1.85	65 000	200	40–80
550	317	318	396–564	2.01–2.47	2.01–2.25	1.71–1.85	65 000	200	40–80
800	461	462	576–612	2.01–2.47	2.01–2.25	1.71–1.85	65 000	200	40–80
Intermediate class									
4.37–145	2.52–83.7	2.8–84	3–144	2.38–2.85	2.28–2.55	1.71–1.85	65 000	100	16.1

* Voltage Range A, ANSI C84.1-2006

NOTE 1—See Table 8 and 6.4 for typical arrester ratings for systems with noneffectively grounded neutral. NOTE 2—Equivalent FOW producing a voltage wave cresting in 0.5 µs.

NOTE 3—The protective level is the maximum discharge voltage for a 10 kA impulse current wave on arrester duty-cycle rating through 312 kV, 15 kA for duty-cycle ratings 396 kV to 564 kV, and 20 kA for duty-cycle ratings 576 kV to 612 kV, per IEEE Std C62.11-2005.

NOTE 4—Switching surge characteristics based on maximum switching surge classifying current (based on an impulse current wave with a time to actual crest of 45 µs to 60 µs) of 500 A on arrester duty-cycle ratings 3 kV to 108 kV, 1000 A on duty-cycle ratings 120 kV to 240 kV, and 2000 A on duty-cycle ratings above 240 kV, per IEEE Std C62.11-2005.

NOTE 5—Test values for arresters with porcelain tops have not been standardized. Pressure relief classification is in 5 kA. steps.

5.2.1.2 ~~Temporary overvoltage~~ TOV capability

In addition to considerations affecting the selection of arrester MCOV, the user must also select the arrester to withstand the temporary overvoltages in the system at the arrester location. The basic requirement is that the power frequency voltage versus time characteristic of the arrester should be higher than the TOV amplitude versus duration characteristic of the system for all times of concern.

Figure 4 is a typical generic TOV curve for station and intermediate class arresters. The upper curve shows the time the arrester withstands given overvoltages and subsequently thermally recovers when MCOV is applied. The lower curve is similar to the upper but applies to a condition where the arrester has absorbed prior energy from two transmission-line discharges. For station and intermediate class arresters, the test procedure is described in IEEE Std C62.11-2005, and each manufacturer may publish different test results. Figure 4 is shown for illustrative purposes only. For applications, TOV data should be obtained from the manufacturers.

The selected arrester must have both MCOV and temporary overvoltage capability appropriate for the operating system. Sometimes the MCOV is decisive, and sometimes TOV considerations are decisive.

A change in relay setting or use of faster breakers may sometimes allow use of arresters based on MCOV when TOV would otherwise have been decisive.

5.2.1.2.1 Fault conditions

~~5.3.2.1.1 Overvoltage amplitude considerations~~

The most common source of TOV is voltage rise on unfaulted phases during a line-to-ground fault. The curves of Annex B may be used to determine quickly the temporary overvoltages during fault conditions for applications involving short lines operating at voltages through 242 kV.

The numbers adjacent to each of the curves of Annex B are the coefficients of grounding in percent. From known values of R_0/X_1 and X_0/X_1 at the fault location, the corresponding coefficient of grounding can be determined by interpolating between curves as necessary. Multiply the coefficient of grounding by the maximum system phase-to-phase operating voltage to determine the temporary overvoltage to ground at the point of fault. Alternatively, the voltage can be calculated from the equations in Figure 6 using equivalent system impedances as seen from the fault location. The effect of shunt reactors, shunt and series capacitors, and distributed line capacitances have to be included in the calculations where significant. This applies particularly to applications involving long lines and EHV lines (AIEE Committee Report [B1]). Where the shunt capacitance of lines is large, there may be significant additional voltage rise due to line-charging currents, harmonics due to transformer saturation, and (less frequently) resonance effects.

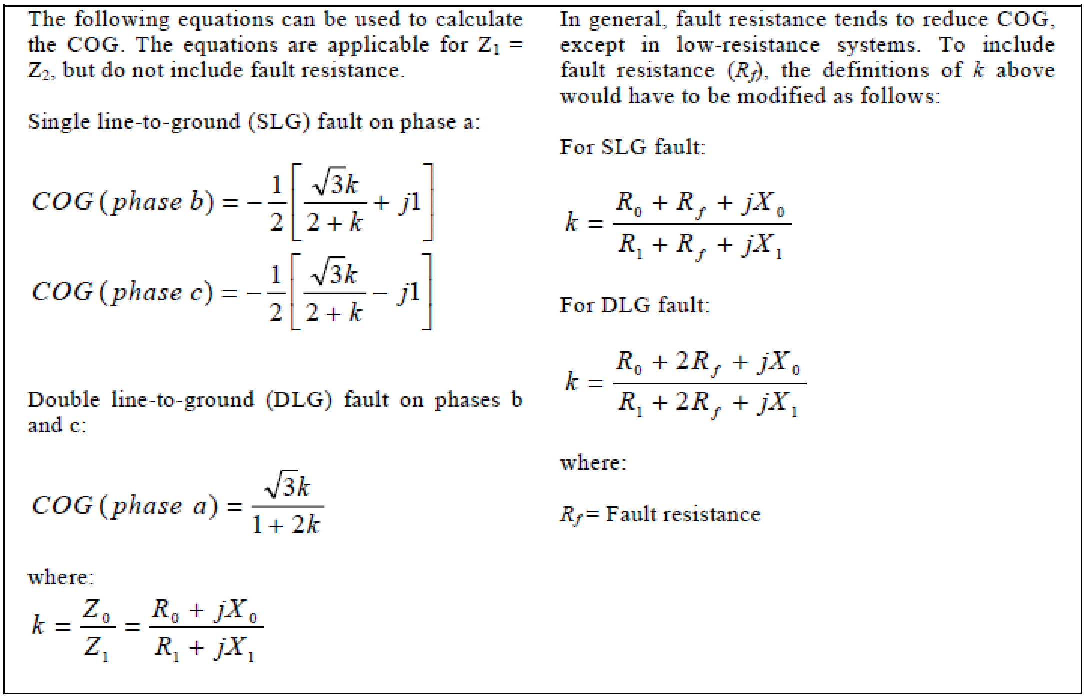
NOTE—Annex A of IEEE Std C62.92.1™-2000 contains additional information for determining the coefficients of ground~~–~~ing, more thoroughly addressing this subject.

~~5.3.2.1.2 Overvoltage duration considerations~~

The duration of overvoltages from line-to-ground faults depends on the adopted short-circuit relaying protection. In the absence of other information, the following typical values may be used:

Grounded neutral systems: TOV duration:
Line protection: 0.2 s
Back-up protection: 1 s (overcurrent relays may be slower)

Resonant grounded or isolated neutral systems:
Without ground fault clearing: 3 h
With ground fault clearing: 4 s



The following equations can be used to calculate the COG. The equations are applicable for $Z_1 = Z_2$, but do not include fault resistance.

Single line-to-ground (SLG) fault on phase a:

$$COG\,(phase\ b) = -\frac{1}{2}\left[\frac{\sqrt{3}k}{2+k} + j1\right]$$

$$COG\,(phase\ c) = -\frac{1}{2}\left[\frac{\sqrt{3}k}{2+k} - j1\right]$$

Double line-to-ground (DLG) fault on phases b and c:

$$COG\,(phase\ a) = \frac{\sqrt{3}k}{1+2k}$$

where:

$$k = \frac{Z_0}{Z_1} = \frac{R_0 + jX_0}{R_1 + jX_1}$$

In general, fault resistance tends to reduce COG, except in low-resistance systems. To include fault resistance (R_f), the definitions of k above would have to be modified as follows:

For SLG fault:

$$k = \frac{R_0 + R_f + jX_0}{R_1 + R_f + jX_1}$$

For DLG fault:

$$k = \frac{R_0 + 2R_f + jX_0}{R_1 + 2R_f + jX_1}$$

where:

R_f = Fault resistance

Figure 6—COG calculations

5.2.1.2.2 Load rejection

After disconnection of loads, the voltage rises at the source side of the operating circuit breaker. The amplitude of the overvoltage depends on the disconnected load and on the short-circuit power of the feeding substation. The temporary overvoltages can have particularly high amplitudes after full load rejection at generator transformers due to magnetizing and overspeed conditions. The amplitudes of load rejection overvoltages are usually not constant during their durations. When the time dependence of the amplitudes is known, a suitable representation of the overvoltage is the maximum amplitude with a duration equal to the time that the amplitude exceeds 90% of this value. Accurate calculations of temporary overvoltage have to consider many parameters and typically require detailed electromagnetic transient simulations.

As a guidance, the following typical values of such overvoltages may be used:

— In ~~moderately extended~~ systems with lines of moderate length, a full load rejection can give rise to phase-to-ground overvoltages with amplitude usually below 1.2 pu. The overvoltage duration depends on the operation of voltage-control equipment and may be up to several minutes.

— In ~~extended~~ systems with long lines, after a full load rejection, the phase-to-ground overvoltages may reach 1.5 pu or even more when Ferranti or resonance effects occur. Their durations may be in the order of some seconds.

— Where load is rejected from the load side of a generator step-up transformer, the temporary overvoltages may reach amplitudes up to 1.4 pu for turbo generators and up to 1.5 pu for hydro generators. The duration is approximately 3 s.

— When the time dependence of the amplitudes is known, a suitable representation of the overvoltage is the maximum amplitude with a duration equal to the time that the amplitudes exceed 90% of this value.

Other causes of temporary overvoltages need consideration in some ~~cases~~ situations, such as the following:

a) Resonance effects (e.g., when charging long unloaded lines or when resonances exist between systems). Temporary overvoltages due to ferroresonance should be considered and are addressed in 6.4.4. Temporary overvoltages due to ferroresonance should not form the basis for the surge arrester selection ~~and should be eliminated.~~

b) Voltage rise along long lines (Ferranti effect)

c) Harmonic overvoltages (e.g., when switching transformers)

d) Accidental contact with conductors of higher system voltage

e) Backfeed through interconnected transformer windings (e.g., dual transformer station with common secondary bus during fault clearing or single-phase switched three-phase transformer with an unbalanced secondary load)

f) Loss of system grounding

Sequences of causes of temporary overvoltages (e.g., load rejection caused by a ground fault) need consideration when the overvoltages due to the load rejection are comparable ~~severity. In such cases,~~

~~however, the amount of rejected load dependent on the fault location and the arrester location has to be carefully examined~~with the overvoltages due to the ground fault.

Combinations of causes such as ground faults caused by load rejection may result in higher temporary overvoltage values than the single events. When such combinations with overlapping durations are considered sufficiently probable, the load rejection overvoltage factor may need ~~for each cause have~~ to be multiplied~~, taking into account the actual system~~ by the ground fault overvoltage factor, with consideration of the system configuration.

5.2.1.3 Switching surge durability

Surge arresters dissipate switching surges by absorbing thermal energy. The amount of energy is related to the prospective switching surge magnitude, its wave shape, the system impedance, circuit topology, the arrester voltage-current characteristics, and the number of operations (single/multiple events). The selected arrester should have an energy capability greater than the energy associated with the expected switching surges on the system.

The actual amount of energy discharged by a metal-oxide arrester during a switching surge can be determined through detailed system studies performed with a transient network analyzer (TNA) and/or a digital circuit analysis program such as the ~~Electromagnetic Transients Program (~~EMTP~~)~~. When such study results are not available, the approximate arrester duty due to energizing and reclosing operations on transmission lines can be estimated from Equation (5) and curves.

The energy discharged by an arrester J in kilojoules~~,~~ may be conservatively estimated by the equation:

$$J = 2D_L E_A I_A / v \qquad (5)$$

where

E_A is the arrester switching impulse discharge voltage (in kilovolts) for I_A
I_A is the switching impulse current (in kiloamperes)
D_L is the line length (in ~~miles or~~ kilometers)
v is the speed of light, 300 km/ms~~) or 186 000 mi/s.~~

The equation assumes that the entire line is charged to a prospective switching surge voltage (which exists at the arrester location) and is discharged through the arrester during twice the travel time of the line. The discharge voltage and current are related by the equation:

$$I_A = (E_s - E_A)/Z \qquad (6)$$

where

E_S is the prospective switching surge voltage (in kilovolts)
Z is the single-phase surge impedance of line (in ohms)

To determine the prospective discharge energy, manufacturer data should be consulted to first determine consistent values of E_A and I_A per Equation (5) and Equation (6). The calculated energy can then be plotted in curve form for varying quantities of line length, switching impulse voltage, and surge impedance. A typical curve is shown in Figure 7 for a 209 kV MCOV rated arrester (258 kV duty-cycle rating) on a 345 kV, 160 km (100 miles) transmission line that dissipates approximately 0.33 MJ of energy during a 2.~~5~~6 pu switching surge. Because arresters are constructed with series repeated sections, the energy can be presented in per-unit of MCOV or duty-cycle rating. In this case, 0.33 MJ translates to 1.58 kJ/kV of MCOV or 1.28 kJ/kV of duty-cycle rating. The energy capability of station class arresters is within the range of 4.0 kJ/kV to 20.0 kJ/kV of MCOV and is a function of the volume, formulation, and processing of the metal-oxide disk. The number of discharges allowed in a short period of time (approximately 1 minute or less) is the arrester energy capability divided by the energy per discharge. A curve is also shown for a ~~276~~ 220 kV ~~duty cycle~~ MCOV rated arrester. Additional information is contained in the application guides of the manufacturer.

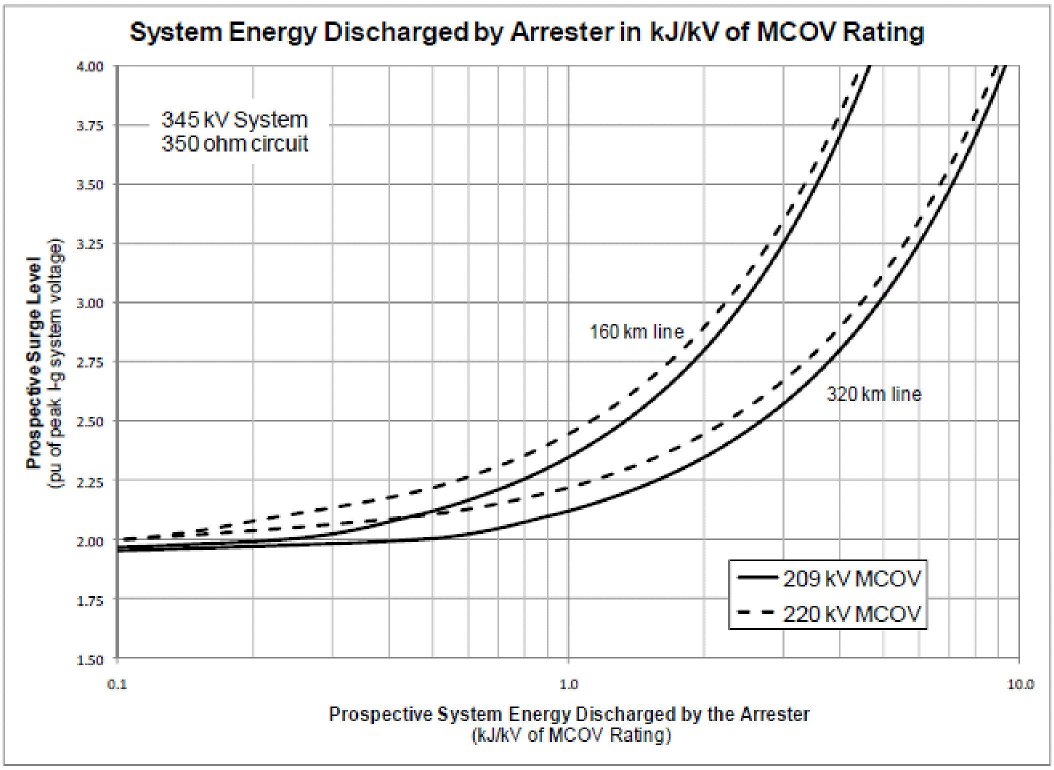


Figure 7—Typical curve for a prospective switching surge voltage versus arrester discharge energy for a 345 kV line

5.2.1.4 Tentative selection of arrester voltage rating

The arrester voltage rating should be tentatively selected on the basis of MCOV (5.2.1.1), TOV (5.2.1.2), and switching surge durability (5.2.1.3).

Special conditions that should be considered in choosing the arrester voltage rating are as follows:

a) *Abnormal system operating voltages*. The selection of arrester voltage ratings based on maximum system voltages assumes that, in service, the maximum system voltage is exceeded only under abnormal operating conditions, and only for durations within the arrester TOV capability. However, if maximum system voltages used in determining temporary overvoltages, as in 5.2.1.2 are likely to be exceeded frequently, increasing the probability of arrester operations during such conditions, it may be necessary to use an arrester with a higher voltage rating. Other causes of TOV as listed in 5.2.1.2 require consideration on an individual basis; no general rules are applicable. If any grounding source could be disconnected by sectionalizing, the effect on the COG and the arrester rating should be checked.

b) *Abnormal system frequency.* Normal system frequency of less than 48 Hz or more than 62 Hz may require special consideration in the design or application of surge arresters and should be a subject of discussion between the user and the manufacturer.

5.2.1.5 Selection of arrester class

The arrester class should be selected on the basis of required level of protection (protective levels summarized in Table 1) and the following:

a) Available voltage ratings

b) Pressure relief current limits, which should not be exceeded by the system's available short- circuit current and duration at the arrester location

c) Durability characteristics (see Table 1) that are adequate for systems requirements

The class of arrester selected may be influenced by the importance of the station or equipment to be protected. For example, station-class arresters should be used in large substations. Intermediate-class arresters may be used in smaller substations and on subtransmission lines and cable terminal poles at 161 kV and below. Distribution-class arresters might be used in small distribution substations to protect distribution voltage buses.

5.2.2 Protective levels of arrester (Figure 5, item 2)

5.2.2.1 Determination of protective levels

Protective levels are determined by either sparkover voltages or discharge voltages of the arrester under consideration, based on the measurement procedure outlined in 8.3 and 8.4 of IEEE Std C62.11-2005. The following protective levels should be considered:

a) *FOW*: The higher value of FOW sparkover or arrester discharge voltage cresting in 0.5 μs at the classifying current.

b) *LPL*: The higher value of lightning impulse sparkover for a 1.2/50 lightning impulse or arrester discharge voltage that results from an 8/20 current wave. The appropriate current magnitude is determined by the system voltage per Table 2.

c) *SPL*: The higher value of switching impulse sparkover or arrester discharge voltage that results from a current wave with a time to actual crest of 45 µs to 60 µs. The appropriate current magnitude is based on the system voltage as contained in 5.2.2.3.

Table 2—Recommended currents for determining discharge voltage in shielded stations with shielded incoming lines

Maximum system voltage (kV)	Coordinating current (kA)
48.3	5
72~~.5~~	5
121	10
145	10
169	10
242	10
362	10
550	15
800	20

5.2.2.2 Arrester coordinating currents for lightning surges

5.2.2.2.1 Factors that affect the selection of discharge currents for determining discharge voltage

To determine the protective levels of the arrester for lightning surges, proper coordinating currents need to be determined. Factors that affect this selection include the following:

a) The importance and degree of protection desired. Basing protective levels on higher current magnitudes and rates of rise increases the reliability of protection.

b) The line insulation. The potential for higher lightning currents increases with higher line insulations (e.g., fully insulated wood poles), unless the stroke occurs so close to the arrester that the impedance and insulation of the line cannot influence the surge.

c) The probability of occurrence of the higher stroke currents. The magnitude of lightning currents varies over a wide range of values (Orville et al. [B146]). The lines in areas of high keraunic levels have an increased chance of being struck by lightning with high-current magnitudes (see Annex A).

d) ~~-~~Line performance and lightning environment. Coordinating currents and rates of rise are functions of the backflash and shielding failure rates of the lines (or flashover rates of unshielded lines) that are within some limiting distance from the station. Higher (lower) failure rates increase (decrease) the coordinating current magnitude and rate of rise.

~~5.4.2.2 Recommended arrester coordinating currents for lightning surges~~

Thus, the appropriate coordinating current for lightning surges depends strongly on the effectiveness of line shielding.

5.2.2.2.2 Recommended currents for shielded stations with completely shielded lines

The lightning performance of shielded lines is based on the shielding failure and back-flashover rates of the lines. If the position of the ground wire(s) relative to the phase conductors is such that the line is considered “effectively shielded” (i.e., protected from direct lightning strokes), then the number of line insulation flashovers due to shielding failures will be negligible, and back flashovers will be the predominant mechanism of line insulation flashover. In either event, the magnitude of the arrester discharge current can be estimated from:

$$I = I_C = 3.84\left(E_{\mathrm{CFO}} - E_C\right)/Z_0 \tag{7}$$

where

I is the arrester discharge current (in kiloamperes)
I_C is the arrester coordinating current (in kiloamperes)
E_{CFO} is the positive CFO of line insulation (in kilovolts)
E_C is the arrester discharge voltage (in kilovolts) for the estimated value of the coordinating current (see Table 2)
Z_0 is the single-phase surge impedance of line (in ohms)
3.84 is the correction factor based on system studies (Hileman [B65]). The increase in current is due to transformer capacitance, reflections from open end-of-line, and assumed 20% safety margin

This relationship assumes the line flashover occurs at a considerable distance from the station or that the phase conductor is struck without ensuing flashover. Otherwise, the portion of the total stroke current discharged through the arrester can vary considerably depending ~~up~~on the parameters involved.

Using typical system parameters and the above equation, Table 2 contains coordinating currents that have been found to be satisfactory in most situations.

5.2.2.2.3 Discharge currents where lines are shielded for a short distance adjacent to the station

Where shielding does not include the entire line, increased arrester discharge currents become more probable. In assessing the probability of an arrester discharge current, it is necessary to consider the following:

a) The ground flash density

b) The probability of strokes to the line exceeding a selected value

c) The percentage of total stroke current that discharges through the arrester

Item a) and item b) can be evaluated using the methods of Brown and Thunander [B21] or from the ground flash density maps published by EPRI (Orville et al. [B146]). Conservative guidelines for item c) are contained in Table 3 (from Schei and Huse [B160]).

Table 3—Guidelines for total stroke discharge current

Distance line shielding extends from station	Percent of stroke current discharged through arrester
2.4 km (1.5 miles)	25%
1.6 km (1.0 miles)	35%
0.8 km (0.5 miles)	50%

5.2.2.2.4 Discharge currents in stations where lines are not shielded

Completely unshielded lines usually are limited to either:

a) Lower voltage lines, (i.e., 34.5 kV and below)

b) Lines located in areas of low lightning ground flash density

The probability may be high that arresters in the lower voltage stations are subjected to large currents and rates of rise in areas of high lightning ground flash density. In these cases, the coordinating current should not be less than 20 000 A. In severe thunderstorm areas, higher levels should be considered.

For lines located in areas of low lightning ground flash density, coordinating currents may be similar to those for completely shielded lines in areas of high lightning ground flash density. In this case, no specific guidelines can be given, and special studies are required.

5.2.2.3 Arrester coordination currents for switching surges

The current an arrester conducts during a switching surge is a complex function of both the arrester and the details of the system. The effective impedance seen by the arrester during a switching surge can vary from several hundred ohms for an overhead transmission line to tens of ohms for arresters connected near cables and large capacitor banks. In these two cases, the arrester current and the resulting arrester energy vary significantly for a switching surge of a given magnitude and duration.

In the case of arresters connected to overhead transmission lines, the recommended switching surge coordinating currents (per IEEE Std C62.11-2005) are listed in Table 4.

Table 4—Recommended switching surge coordinating currents

Maximum system voltage	Station class (A crest)	Intermediate class (A crest)
3–150	500	500
151–325	1000	—
326–900	2000	—

5.2.2.3.1 Surge transfer through transformers

When a transformer and connected transmission line are switched together, the low-side arrester may operate, causing it to discharge the energy transferred through the transformer from the higher voltage line. There is a possibility of overstressing an arrester on the low side of a transformer due to this surge transfer. Measures must be taken to ~~ensure~~verify that the high-side arrester operates to absorb the majority of the surge energy. This can be accomplished by coordinating the switching surge discharge voltages of the high- and low-side arresters.

The probability of failure of the low-side arrester can be reduced by selecting a low-side arrester with a higher relative ~~switching surge protective level (~~SPL~~)~~ than the arrester on the high side, taking the transformer turns ratio into consideration. For example:

$$\mathrm{SPL}_{\mathrm{LV}} > \frac{N_{\mathrm{LV}}}{N_{\mathrm{HV}}}\mathrm{SPL}_{\mathrm{HV}} \tag{8}$$

where

$\mathrm{SPL}_{\mathrm{LV}}$ is the switching surge protective level of the low-side arrester~~,~~
$\mathrm{SPL}_{\mathrm{HV}}$ is the switching surge protective level of the high-side arrester~~, and~~
~~N is transformer turns ratio.~~

$\frac{N_{LV}}{N_{HV}}$ is the ratio of low-voltage side phase-to-phase voltage to high-voltage side phase-to-phase voltage for wye-grounded two-winding transformers (Hileman [B67])

5.2.3 Locating arresters and determining voltage at protected equipment (Figure 5, items 3 and 4)

A major factor in locating arresters within a station is the line and station shielding. It is usually feasible to provide shielding for the substation even if the associated lines are unshielded. Station shielding reduces the probability of high voltages and steep fronts within the station resulting from high-current lightning strokes.

However, it should be recognized that the majority of strokes will be to the lines, creating surges that travel along the line and into the station. If the lines are shielded, then the surges entering the station are less severe than those from unshielded lines (Bewley [B16]). Consequently, the magnitude of the prospective arrester currents are lower, resulting in lower arrester protective levels.

As a general rule, the voltage at the protected equipment is higher than the arrester discharge voltage (see 4.5 and Annex C). Therefore, it is always good practice to reduce separation between the arrester and major equipment to a minimum. However, it is sometimes possible to protect more than one piece of equipment with a single arrester installation provided that rates of rise can be restricted, as in the case where both the station and the overhead feeder lines are shielded.

5.2.3.1 Locating arresters in unshielded installations

Such installations are subjected to the highest lightning currents and voltage rates of rise. The minimum possible separation is recommended for installations where complete shielding is not used.

With a single unshielded incoming overhead line, the arrester should be located as near as possible to the terminals of the equipment (usually a transformer) to be protected.

When several unshielded incoming overhead lines meet in the station, the incoming overvoltage waves are reduced by refraction. However, consideration should be given to the case when one or more of the lines are out of service.

When one or more circuit breakers or disconnecting switches are open in such a station, the corresponding line entrances or certain parts of the station may be left without protection from the arresters at the transformers. Lightning flashover of insulation on a deenergized line is unlikely to cause damage, but other insulation in equipment such as circuit breakers, potential transformers, and current transformers connected on the line side might be damaged. If protection is required in such cases, then arresters can be installed at the respective line entrances.

5.2.3.2 Locating arresters in shielded installations

Incoming voltages from shielded lines are lower in amplitude and steepness than voltages from unshielded lines. In many cases, this will permit some separation between the arresters and the insulation to be protected.

With a single shielded incoming overhead line, one set of arresters may be located at a point that provides protection to all equipment but gives preference to the transformer. The method in Annex C can be used to determine the maximum separation distance between the arrester and the transformer.

At stations with multiple shielded incoming overhead lines (associated with large installations with transformers, switchgear, and measuring equipment), arresters are not always placed at the terminals of every transformer. The methods described in 5.2.5.4 and Annex C can be used to determine the maximum separation distances for arresters used to protect more than one transformer. More important installations may justify a detailed transient study. Such studies and interpretation of their results are outside the scope of this guide.

Consideration has to be given in the calculations to the possibility that the station may become sectionalized or that lines may be disconnected during service. Under all circumstances, the proper protective ratios for both lightning and switching surges should be maintained.

5.2.3.3 Arrester clearance requirements

For proper insulation coordination, arresters should be installed to maintain, as a minimum, the clearances listed in Table 5. Regulations or other considerations may dictate larger clearances in exposed locations.

Table 5—Recommended minimum clearances

Arrester's 20 kA, 8/20 peak discharge voltage (kV) [b]	Recommended minimum clearances [a]			
	To ground		Between phases	
	mm	inches	mm	inches
27	26	1	51	2
43	51	2	77	3
53	77	3	102	4
65	102	4	127	5
77	127	5	153	6
88	153	6	178	7
100	178	7	229	9
112	204	8	254	10
124	229	9	280	11
134	254	10	305	12
150	305	12	331	13
200	407	16	458	18
250	534	21	610	24
350	788	31	864	34
550	1270	50	1423	56
650	1499	59	1677	66
750	1728	68	1956	77
825	1931	76	2159	85
900	2109	83	2388	94
1050	2464	97	2820	111
1175	2769	109	3175	125

[a] The clearances are measured from metal parts of arrester line terminal and dictated by minimum flashover to maintain BIL in accordance with IEEE Std C62.11-2005 and to allow for the bias effect of 60 Hz voltage between adjacent phases. Air insulation between arrester and wall(s) or between arresters is assumed. The minimum clearances required between bottom stud on arrester and enclosure floor need be only that required to install ground connection and to provide sufficient space for free operation of the arrester disconnector, if used.

[b] The discharge voltage-current characteristics peak voltage can be obtained using a current 20 000 A crest with an 8/20 wave shape from 8.3.2.1 in IEEE Std C62.11-2005. Refer to the manufacturer's specifications.

5.2.3.4 Cable-connected equipment

Cable-connected equipment involves a station, substation, or individual apparatus connected to cable, which in turn is connected to an overhead line. The overhead line may or may not be shielded at the line- cable junction. In the case of unshielded overhead lines, it may be advantageous to mount additional protective devices a few spans before this junction.

5.2.3.4.1 Arresters at protected cable-connected equipment

If arresters can be installed at the equipment, then a procedure analogous to that outlined in Figure 5 should be followed. However, the methods of 5.2.5.4 and Annex C are not applicable (Owen [B147]; Owen and Clinkenbeard [B148]; and Witzke and Bliss [B189]).

The grounded end of any arrester installed at the protected equipment should be connected to the equipment ground and the station ground with the shortest possible lead.

5.2.3.4.2 Arresters at the overhead line-cable junction

It is preferable to install arresters at the overhead line-cable junction for protection of junction equipment. If it is impossible or undesirable to install arresters at the protected equipment terminals, then it is necessary to determine whether adequate protection can be obtained with an arrester at the junction. The following procedure may be used:

a) Determine the length of the cable connection.

b) Determine the maximum impulse voltage at the protected equipment, using procedures and recommendations from either Powell [B152] or Witzke and Bliss [B189].

Arresters installed at the line-cable junction should be grounded to the station ground through a low-impedance path, which may be the cable shield, if suitable. If the cable shield is not suitable, or for cables without a metallic shield, then the grounded end of the arrester should be connected to the station ground with a conductor in proximity to the cable. Special consideration may be necessary for cables with shields that cannot be grounded at both ends because of shield currents.

5.2.3.5 Phase-to-phase transformer protection

Arresters are typically installed phase to ground and as such may not provide adequate phase-to-phase pro-tection for delta connected transformer windings. Solutions are to increase phase-to-phase insulation strength (BIL) or apply phase-to-phase arresters.

5.2.3.5.1 Sources of phase-to-phase overvoltages

Phase-to-phase overvoltages exceeding transformer insulation withstand can result from switching surges, lightning surges, or from a backflashover caused by a strike to a tower, which is explained as follows:

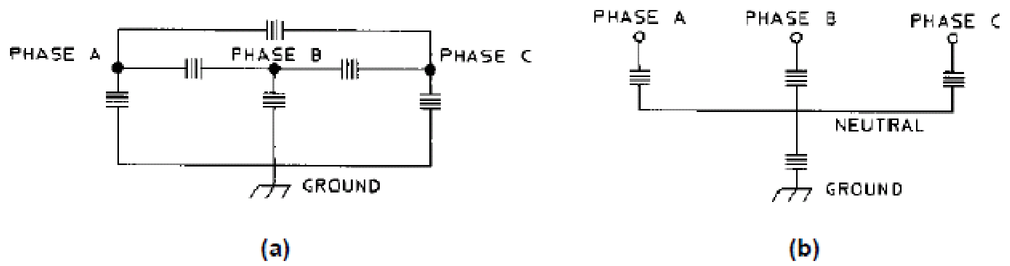
a) *Switching surges:* High phase-to-phase switching overvoltages may occur due to capacitor bank switching or misoperation of capacitor bank switching devices (Jones and Fortson [B107]; Lishchyna and Brierley [B120]; and O'Leary and Harner [B143]).

b) *Lightning surges:* High phase-to-phase lightning overvoltages may result from lightning striking a phase conductor of a transmission line. Lightning initiates current and voltage waves, which propagate along the struck phase conductor and induce voltage on the other phase conductors. At the struck location, the induced voltages have the same polarity as the struck phase voltage. Thus, this phase-to-phase voltage is the difference of the struck and the induced phase voltages. However, due to the propagation phenomenon, it is possible for the voltage wave forms to become of opposite polarity, and the maximum phase-to-phase overvoltage could be as high as the sum of the absolute values of the peak (line mode) voltages on the struck and the induced phases. For these cases, the phase-to-phase overvoltage can exceed a delta-connected transformer insulation withstand level (Keri et al. [B109]).

c) *Surge transfer through transformer windings:* Lightning surges entering a transformer terminal can excite the natural frequencies of delta-connected windings resulting in phase-to-phase overvoltages in excess of the transformer insulation withstand (Keri et al. [B109]).

5.2.3.5.2 Surge protection

Because surge arresters are typically installed phase to ground at each terminal of the delta-connected transformer windings, each winding is protected by two arresters connected in series through their ground connection. The protective level of the two series-connected arresters may not provide the minimum recommended protective ratios for the transformer insulation. Delta-connected transformer windings can be protected by directly installing phase-to-phase and phase-to-ground surge arresters. This can be accomplished by either of the arrangements shown in Figure 8 (Keri et al. [B109]).



(a)

(b)

Figure 8—Phase-to-phase protection

Figure 8(a) represents a six-surge arrester arrangement, consisting of three phase-to-phase and three phase- to-ground arresters for three-phase bank. Figure 8(b) represents a four-legged surge arrester arrangement, consisting of three surge arresters connected from three phases to common neutral, and one arrester con~~-~~nected from the common neutral to ground.

5.2.3.5.3 Guidelines for phase-to-phase ~~surge~~ arrester protection at delta connected transformers

Application of phase-to-phase surge arresters using either the six-surge arrester or the four-legged surge arrester arrangement should be considered under the following conditions:

a) Protective level of two arresters connected in series through their ground connection does not provide the minimum recommended protective ratio for the transformer CWW, BIL, and BSL (Figure 5, item 6).

b) The transformer is subjected to phase-to-phase overvoltages due to switching of a remote capacitor bank, without means for switching surge control (such as preinsertion inductor, resistor, or controlled closing~~), or~~).

c) ~~The number of~~Three or fewer transmission lines are connected to the transformer bus ~~is less than~~and the length of each line is 10 km or greater~~equal to three transmission lines and the length of each line is equal to or more than 6 mi~~.

~~5.5.4.4 Selection of surge arrester ratings~~

The following describes the process recommended for selecting the surge arrester duty-cycle rating, MCOV ratings, and TOV capability depending on whether a four- or six-arrester arrangement is selected (Keri et al. [B109]):

a) Six-surge arrester arrangement:

   1) The traditional selection process should be used to select the phase-to-ground surge arresters (Figure 5).

   2) The phase-to-phase surge arrester MCOV rating should be equal to or slightly greater than the maximum phase-to-phase system voltage.

b) Four-legged surge arrester arrangement:

   1) Phase-to-neutral arrester MCOV should be equal to or slightly greater than the maximum phase-to-phase system voltage divided by square root of three. The arrester MCOV rating determined is often the same as that used on the solidly grounded transformer. In addition, the phase-to-neutral arresters must be matched to avoid overstressing the neutral-to-ground surge arrester. Proper insulation coordination must be established between the series combination of two phase-to-neutral arresters and the transformer phase-to-phase insulation.

   2) Neutral-to-ground arrester MCOV rating: The design of the neutral-to-ground arrester should be the same as that used for the phase-to-neutral arrester.

      i) Determine minimum required phase-to-ground MCOV based on the traditional phase-to- ground requirements (Figure 5).

      ii) Subtract phase-to-neutral arrester MCOV obtained in item b)1) from minimum required phase-to-ground MCOV obtained in item b)2)i). Select a surge-arrester MCOV rating equal to or slightly greater than this value.

      iii) If the phase-to-neutral arrester MCOV rating was increased to utilize ANSI/IEEE ~~Standard~~ MCOV ratings, then the neutral-to-ground arrester MCOV may be reduced, provided the conditions of item b)2)ii) are met. This iteration will permit the lowest ANSI/IEEE MCOV ratings to be used. Proper insulation coordination should be established between the series combination of the phase-to-neutral and neutral-to-ground arrester and the transformer phase-to- ground insulation.

5.2.4 Determining insulation strength (Figure 5, item 5)

BIL, BSL, and CWW voltages may be obtained from equipment standards. However, BSLs and CWWs do not exist for all equipment voltage ratings. Refer to IEEE Std C57.12.00™-2000, IEEE Std C57.13™-1993, IEEE Std C57.21™-1990, and IEEE Std C37.04™-1999.

The BSL for various types of equipment is presented in Table 6. The optional front-of-wave test for some transformers and reactors is also listed but is not used in this guide for purposes of insulation coordination.

The negative polarity lightning impulse CFO voltage of air insulation is approximately 600 kV/m (180 kV/ft), and for positive polarity CFO, the values are 560 kV/m (170 kV/ft). Bus and line support insulators have volt-time characteristics that increase substantially at short times to flashover. At 3 µs, the breakdown voltage is approximately 1.3 to 1.4 times the CFO.

Table 6—Factors for estimating the withstand voltages of mineral-oil-immersed equipment

Type of equipment	Impulse duration	Withstand voltage
Transformers and reactors	Front of wave (0.5 µs)	1.30 to 1.50 · BIL
Breakers 15.5 kV and above[a]	Chopped wave (2 µs)[b]	1.29 · BIL
Transformers and reactors	Chopped wave (3 µs)[b]	1.10 to 1.15 · BIL
Breakers 15.5 kV and above[a]	Chopped wave (3 µs)[b]	1.15 · BIL
Transformer and reactor windings	Full wave (1.2/50 µs)	1.00 · BIL
Transformer and reactor windings	Switching surge—250/2500 µs wave	0.83 · BIL
Bushings	Switching surge—250/2500 µs wave	0.63 to 0.69 · BIL
Breakers 362 kV to 800 kV[a]	Switching surge—250/2500 µs wave BSL	0.63 to 0.69 · BIL

[a] Includes air blast and SF$_6$ circuit breakers; the BIL given in the table is for the circuit breaker in the closed position. The BIL across the open contacts of the circuit breakers in the opened position is 9% to 10% greater.

[b] Time to chop.

5.2.5 Evaluating insulation coordination (Figure 5, Item 6)

Insulation coordination is evaluated on the basis of the margin between the insulation strength and the surge voltage at the equipment terminals, which may be estimated by use of Annex C. If separation distances are less than those shown in Table 7, then the use of Annex C is not necessary.

In general, there are two methods of portraying the insulation coordination, as follows:

a) Tabulation of the protective ratios or margins

b) Graphical presentation of coordination~~.~~

Regardless of the method, the same minimum ~~protective~~ ratios and margins apply. ~~The graphical presentation is shown in Figure 9. It should be recognized that data from the~~ To illustrate the concept, assume that there is no separation distance between the arrester and the equipment. The graphical presentation for this case is shown in Figure 9. The insulation strength of the transformer is usually provided by one to possibly four ~~(at most) generally available insu- lation tests~~ or five test points that can be used to develop an approximate insulation volt-time curve. A curve plotted in accordance with Figure 9 is a graphical interpretation of the test results, which is presented as an aid to insulation coordination. It is not a true volt-time curve for the transformer, and the curve should not be used to interpolate the values between the test points. Consult the transformer manufacturer for transformer insulation strength at points other than the test points. Similarly, the arrester curve is simply a represen~~-~~tation of the three protective levels. An evaluation of insulation coordination by the curve method is made in accordance with Figure 9.

~~NOTE The transformer surge arrester insulation coordination process is currently under revision for large power~~

5.2.5.1 Description of the transformer insulation strength volt-time curve

The insulation strength for liquid-immersed transformers ~~(123 kV and above). A new characteristic for transformer insulation coordination~~ may be described by a continuous curve (Figure 9), which has been ~~tenta- tively recommended by~~ published by members of the Dielectric Tests Subcommittee of the IEEE Transformer Committee [B11]. The curve is constructed through the following test points [B11]: ~~will replace the one shown in Figure 9 and will be used to calculate surge arrester protective margins. Surge arresters satisfying these protective margins will be considered acceptable.~~

~~Results of the revision will be published in a future supplement~~

a) *The front-of-wave (FWW) test*: A lightning impulse having a crest voltage at 1.3 to 1.5 times the BIL chopped at 0.5 µs. This is a standard test, and it may be used upon agreement between the user and the manufacturer. The test is represented on the curve as an FWW level.

b) *The 3 µs CWW test*: A standard lightning impulse having a crest of 1.1 times the BIL, chopped at 3 µs. The test is represented on the curve as a CWW level.

c) *The full-wave (FW) test*: A standard lightning impulse having a crest voltage equal to the BIL, plotted at 8 µs.

d) *The switching impulse (SI) test*: The BSL equal to 0.83 times the BIL plotted at 300 µs. This is a standard test for system voltages rated 115 kV and above.

e) *The induced-voltage (IV) test*: An induced voltage having a low-frequency (less than 1 kHz) rms voltage equal to approximately 1.5 times the maximum system phase-to-ground voltage applied for 1 h. The time duration above 90% of crest voltage is 1034 s.

Thus, the induced voltage test is not a function of the BIL but is plotted as a per unit value of the BIL. For example, for a 115 kV transformer with 450 kV BIL, with maximum system voltage of 121 kV, the induced voltage is 105 kV rms (crest value 148 kV). The plotted crest value is 33% of the BIL.

Line segments on semi-log paper are drawn through these five points.

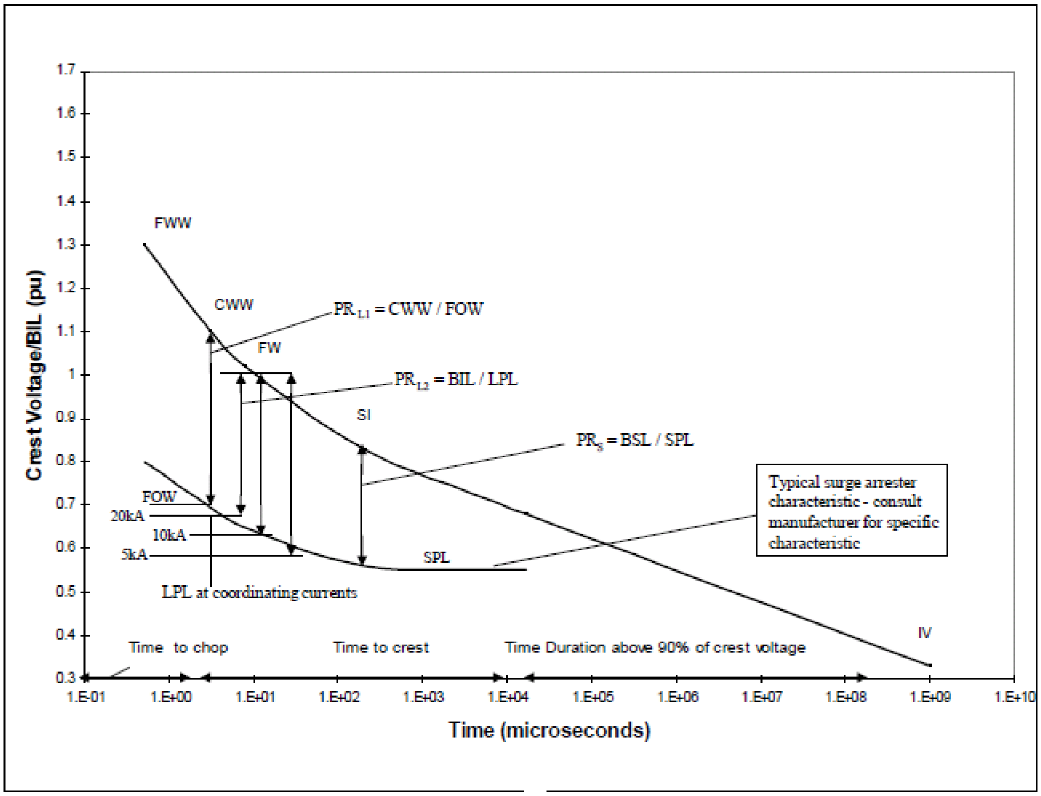


Figure 9—Typical transformer and arrester volt-time curves for coordination of arrester protective levels with insulation withstand strength for liquid-filled transformers

In the lightning region, the curve is the crest voltage versus time to chop or time to crest. In the switching impulse and longer time region, the curve portrays the crest voltage versus the time duration above 90% of the crest voltage. The front-of-wave and chopped-wave tests stress the turn-to-turn insulation, whereas the full-wave test stresses both the turn-to-turn and ground-to-wall or major insulation. The switching impulse test and the 1 h induced-voltage test describe the insulation strength for the long duration voltages that primarily stress the major insulation.

5.2.5.2 Description of the surge arrester characteristic

The surge arrester characteristic curve (see Figure 9) is constructed through the following points:

FOW: Front-of-wave protective level
This is the higher of either the arrester sparkover for a front-of-wave lightning impulse voltage or the 0.5 µs discharge voltage at the classifying current as called for in Table 6 of IEEE Std C62.11-2005. See 8.4.2.1 of IEEE Std C62.11-2005.

LPL: Lightning protective level
This is the higher of either the arrester sparkover voltage for a standard 1.2/50 lightning impulse or the standard discharge voltage with an 8/20 discharge current as called for in Table 6 of IEEE Std C62.11-2005. See 8.4.2.2 of IEEE Std C62.11-2005.

SPL: Switching protective level

This is the higher of either the arrester slow front sparkover voltage or the switching surge discharge voltage at its classifying current as called for in Table 7 of IEEE Std C62.11-2005. See 8.4.2.3 of IEEE Std C62.11-2005.

5.2.5.3 Interpretation of the transformer insulation strength volt-time curve (application criteria)

Insulation strength for non-self-restoring or internal insulation as typified by the transformer must be estimated by a subjective method. The subjective assessment compares the test voltages and their wave shapes with the oscillatory surges that may appear at the transformer terminals with equal volt-times as shown by the curve. In IEC 60071-2-1997, the insulation strength independent of the wave shape is assumed equal to the BIL (a chopped-wave test is not required). IEEE Std 1313.2™-1999 recommends the following:

- If the time to crest of the voltage surge that appears at the transformer terminals is equal to or less than 3 µs, then the transformer insulation strength is equal to the chopped-wave test (i.e., 1.10 times the BIL).
- If the time to crest of the voltage surge that appears at the transformer terminals is more than 3 µs, then the transformer insulation strength is equal to the BIL.
- These simple criteria do not cover all possible events. A careful consideration has to be given to long-tail voltages. In IEEE Std 1313.2-1999, some examples are given to explain the nature of the problem and to illustrate the insulation coordination process for long-tail surges. The suggested criteria are as follows (IEEE Std 1313.2-1999):

a) For short-tail incoming surges, i.e., t_c less than or equal to 60 µs (see NOTE below).

1) if $t_T \leq 3.0$ µs and $E_t/E_d \leq 1.10$, then:

$$\text{Minimum BIL} = (PR_{L2})\, E_d \qquad (9)$$

2) if $t_T \leq 3.0$ µs and $E_t/E_d > 1.10$, then:

$$\text{Minimum BIL} = (PR_{L2})\, E_t/1.10 \qquad (10)$$

3) if $t_T > 3.0$ µs, then:

$$\text{Minimum BIL} = (PR_{L2})\, E_t \qquad (11)$$

b) For long-tail incoming surges (i.e., t_c more than 60 µs; see NOTE below; for example, incoming surge caused by a shielding failure without a flashover):

$$\text{Minimum BSL} = (PR_S)\, E_d \qquad (12)$$

$$\text{Minimum BIL} = E_d\,(PR_S)/0.83 \qquad (13)$$

NOTE—t_c = the time during which the arrester voltage significantly decreases may be estimated by Equation (14) (Hileman [B65]).

$$t_c = -t \cdot ln\left(\frac{0.77 \cdot E_{10} + V_{PF}}{2E}\right) \qquad (14)$$

where

E	crest voltage of the incoming surge
E_{10}	arrester discharge voltage at 10 kA using 8/20 current wave
t	tail time constant of the incoming surge [see Equation (36) in IEEE Std 1313.2-1999]
V_{PF}	power frequency voltage (crest value)
t_T	the time to crest of the transformer voltage
E_t	voltage to ground at the transformer
E_d	arrester discharge voltage (i.e., voltage to ground)
PR	protective ratio (a value of PR = 1.2 is suggested for general use)

Protective margins (ratios) commonly used for the transformer range from 15% to 30% (PR = 1.15 to 1.3). The larger margins generally apply to assessment methods that do not consider the actual surge voltage that impinges on the transformer. When the actual voltage at the transformer is considered, the margins used or suggested are reduced to about 15% to 20%. A margin of 15% is recommended for self-restoring insulation. A margin of 20% for non-self-restoring insulation is recommended for general use.

The curve in the lightning impulse region is unchanged from previous representations (IEEE Std C62.22-1997), except that now the curve is continuous. In the switching impulse and power frequency region, the continuous curve versus the logarithm of time is new and may be used when considering the effect of long-tail surges.

5.2.5.4 Alternative method (Figure 5, item 6.1)

If the sum of the arrester lead length and the transformer-to-arrester separation distance is less than the values presented in Table 7, then the voltages at the equipment need not be determined. The assumptions made in developing the values in Table 7 are similar to those used in C.6 using station-class surge arresters. However, to simplify the calculations, the rate of rise of the incoming surge on the transmission line was assumed to be 11 kV/µs per kilovolt of MCOV rating to a maximum of 2000 kV/µs as specified in IEEE Std C62.11-2005.

For the situation discussed above, the following protective ratios for lightning overvoltages (PR_{L1} and PR_{L2}) and for switching overvoltages (PR_S) apply:

$$PR_{L1} = \mathrm{CWW}/\mathrm{FOW} \tag{15}$$

$$PR_{L2} = \mathrm{BIL}/\mathrm{LPL} \tag{16}$$

$$PR_{S} = \mathrm{BSL}/\mathrm{SPL} \tag{17}$$

$$PM_{L1} = (PR_{L1} - 1)100\% \tag{18}$$

$$PM_{L2}(PR_{L2} - 1)100\% \tag{19}$$

$$PM_{S} = (PR_{S} - 1)100\% \tag{20}$$

	MCOV ratings (kV)^{b}																										
BIL (kV)	**42**	**48**	**57**	**70**	**76**	**84**	**98**	**106**	**115**	**131**	**140**	**144**	**152**	**181**	**190**	**209**	**212**	**220**	**230**	**235**	**245**	**318**	**336**	**353**	**372**	**462**	**470**	**485**
250	15	8	3																									
350	55	32	17	7	4																							
450				20	14	9	4	2																				
550				44	31	21	12	8	5																			
650						41	22	16	12	6	4																	
750							39	29	21	12	9	8	6															
825											14	12	10	4	2													
900											20	18	14	7	5	3												
1050																8	7	6	5	4	3							
1175																14	12	11	9	8	7							
1300																						2	1					
1475																						6	4	2				
1550																						11	8	6	4			
1675																						16	13	11	8			
1800																						22	19	16	13	2		
1925																										6	5	3
2050																										10	9	4

NOTE 1—Use Annex C for all cases not covered by this table.
NOTE 2—Conversion factor to feet: meters multiplied by 3.28.
NOTE 3—The allowable separation distances in this table were rounded off.

[a] This table is based on the following:

↓ Use of station-class surge arresters
↓ Use of maximum value for the 0.5 µs FOW protective level from Table 1
↓ Use of 7.6 m for the surge arrester lead length

[b] The MCOV ratings in this table are commonly used. Use Annex C for other ratings.

For acceptable coordination, the protective PR_{L1} and PR_{L2} should be equal to or greater than 1.2, which means that the protective margins PM_{L1} and PM_{L2} should be equal to or greater than 20%. Similarly, PR_S should be equal to or greater than 1.15, which means that the protective margin PM_S should be equal to, or greater than, 15%.

5.2.5.5 Voltage at equipment calculated (Figure 5, item 6.2)

If the alternative method is not applicable and the voltage at the equipment, V_T, is calculated by the methods presented in Annex C, the protective ratios and margins are as follows:

If the time-to-crest of the arrester voltage is less than or equal to 2 µs:

$$PR_{L1} = \text{CWW}/V_T \tag{21}$$

$$PM_{L1} = (PR_{L1} - 1)100\% \tag{22}$$

If CWW does not exist or the time to crest of the arrester voltage is greater than 2 µs:

$$PR_{L2} = \text{BIL}/V_T \tag{23}$$

$$PM_{L2} = (PR_{L2} - 1)100\% \tag{24}$$

Also:

$$PR_s = \text{BSL}/\text{SPL} \tag{25}$$

$$PM_S = (PR_s - 1)100\% \tag{26}$$

For acceptable coordination PR_{L1} or PR_{L2} and PR_S have to be equal to or greater than 1.15 (PM_{L1} or PM_{L2} and $PM_S \geq 15\%$).

5.2.6 Evaluation of alternatives (Figure 5, item 7)

If acceptable coordination cannot be achieved, the following measures may be evaluated:

a) Decrease arrester-transformer separation distance
b) Use arresters with lower protective characteristics
c) Add additional arresters
d) Increase the BIL and BSL

Because the method presented in Annex C is conservative, an additional suggestion is to determine the surge voltage at the equipment more accurately by modeling the ~~use of computers~~system and computing the surges and transients.

5.3 Special considerations for protection of transformers

5.3.1 Series windings

Sometimes it is desirable to provide surge protection across series windings of equipment. When arresters are connected in parallel with the series winding, it is necessary to insulate both arrester terminals from ground. In such case, install the arrester at or close to the terminals of the equipment

5.3.2 Unloaded transformer windings

In some cases, multiwinding transformers have connections brought out to external bushings that do not have lines connected. Arresters should always be connected at or close to the terminals of such bushings.

5.3.3 Transformer ungrounded neutral

This clause applies to wye-connected (Y-connected) transformers or transformer banks, with neutrals isolated or grounded through an impedance.

Neutral terminals are subjected to surge voltages as a result of overvoltages at the line terminals propagating through the windings, and thus, they may require arrester protection. Neutral terminals are also subjected to temporary overvoltages caused by line-to-ground faults. Isolated neutral terminals may experience overvoltages due to the reflection of impulse voltages from the line terminals.

In selecting an arrester voltage rating for protection of a neutral terminal, the general consideration of 5.2.1.1 is particularly applicable. The equations of Figure 6 cannot be used. The overvoltage at the neutral is equal to system zero-sequence voltage during faults involving ground. Calculations using the method of symmetrical components are straightforward (Clarke [B31]).

If the transformer power source is switched with single-phase devices or protected by fuses, then the voltage at the ungrounded neutral may become equal to system phase-to-neutral voltage for an extended period. This condition occurs when one fuse or switch remains closed, whereas the other two remain open. Because the neutral voltage for this condition will generally be higher and of longer duration than the TOV due to ground faults, it should be taken into account when selecting the MCOV rating for the neutral arrester.

Care has to be taken to use the BIL of the neutral (which is not usually as great as the transformer BIL) in determining required arrester protective level. A protective level PR_{L2} = BIL (neutral)/LPL of 1.2 is required, where LPL is the discharge voltage (usually at 3 kA for determining this PR) or the gap sparkover voltage.

5.4 Protection of dry-type insulation

The dry-type insulation equipment covered by this subclause includes such apparatus as dry-type transformers, which may have full-wave impulse withstand insulation strengths lower than liquid-immersed equipment of the same voltage rating. Generally, the impulse-withstand strengths with waves of short dura~~–~~tion are considered to be the same, or nearly the same, as the full-wave impulse withstand strength, as given for dry-type transformers in Table 4 and Table 5 of IEEE Std C57.12.01™-2005. Check with the manufacturer of the equipment for specific values.

5.4.1 Dry-type transformers

The following procedure is recommended:

a) Apply the information in 5.2.1 for selection of the arrester rating and class.

b) Determine the minimum permissible full-wave impulse insulation strength (BIL) of the transformer by multiplying the FOW protective level of the arresters by 1.2.

5. 5 ~~Protection of~~ Special considerations for shunt capacitor ~~banks~~ applications

~~Shunt capacitor banks (IEEE Committee Report [B63], NEMA [B101], and CAN3-C155-M84 [B23]) are used on power transmission systems at voltage levels up to 500 kV, with~~ **bank** ~~sizes ranging from a few MVAR to over 300 MVAR. The banks are usually installed at substations, wye-connected, with or without grounded neutrals, and connected to the station busbars through circuit breakers (IEEE Working Group Report [B72] and Reid [B113]). The primary technical benefits of shunt capacitors include the following:~~

~~Supply VARs to local loads~~
~~Power factor correction~~
~~Voltage control~~
~~Increase system capacity~~
~~Reduce system losses~~

Overvoltage protection should be considered wherever shunt capacitor banks are installed, regardless of voltage level, size, connection, or switching arrangement. The possibility of overvoltages due to lightning, switching surges, and temporary overvoltages requires a detailed evaluation to determine the duty on any surge arresters close to the capacitor bank (Working Group Reports [B96], [B101]).

Shunt capacitor banks in shielded stations are exposed to incoming lightning surges resulting from line shielding failures or back flashovers on any connected transmission lines. The increase in capacitor bank voltage due to an incoming lightning surge does not depend on the rate of rise but on how much charge is absorbed. If the charge results in excessive overvoltages, surge arresters should be installed to discharge energy and limit the overvoltage level. Due to the low surge impedance of shunt capacitor banks, adding additional surge arresters beyond those that already exist at a station may not be necessary. This may apply to some installations where the surge arresters, for the protection of other equipment, are rated for lightning surge discharge duty (Uman [B178]).

Consequently, a detailed study should be carried out to determine whether the bank is adequately protected against lightning. Such a study should include many factors, including origin of the incoming surge, magnitude and wave shape, and the capacitor bank size, configuration, and location.

The switching of any shunt capacitor bank produces transient overvoltages (Greenwood [B57]). Certain switching operations can present some potentially hazardous overvoltage conditions, not only to the capacitor bank but also to other nearby equipment such as circuit breakers and transformers. Literature discussing switching surges associated with ~~the installation of~~ shunt capacitor banks include the following (Bayless et al. [B14]; Boehne and Low [B19]; Dunsmore et al. [B44]; Erven and Narang [B48]; Lishchyna and Brierley [B121]; McCauley et al. [B128]; McGranahan et al. [B131], [B132]; Mikhail and McGranaghan [B137]; Schultz et al. [B161]; and van der Sluis and Janssen [B181]):

- Bank energization
- Bank deenergization with restrike
- Energization or deenergization combined with a single line-ground fault
- Voltage magnification

Transient overvoltages will always occur on “switching in” a capacitor bank~~,~~ but will only occur on “switching out” if restrikes occur in the switching device. Arresters installed in a substation to protect transformers and other equipment from overvoltages can be subjected to severe energy absorption duty during capacitor switching because of the large energy (1/2 CV^2) stored in the capacitor bank. The capability of all nearby surge arresters to withstand the energies dissipated during capacitor switching is, therefore, an important consideration. In particular, if some existing surge arresters are gapped silicon-carbide units, these units may have to be replaced for one of the following reasons: 1) the higher duty imposed by the addition of the shunt capacitor bank~~;~~ and 2) the sparkover level will cause them to operate on capacitor switching (Janssen and van der Sluis [B105]).

Due to the frequent switching of shunt capacitor banks, there will be a significant increase in the number and magnitude of transient overvoltages on the power system. Shunt capacitor banks are normally switched in during peak loading conditions and switched out during light loading conditions or high voltage.

Overvoltage protection should be considered at the following locations (Alexander [B2]; Brunke and Schockelt [B23]; IEEE Std 575™-1988 [B81]; Jones and Fortson [B107]; O’Leary and Harner [B143]; Pflanz and Lester [B150]; Sabot et al. [B158]; and Stenstrom [B169]):

a) On the capacitor primary and backup switchgear to limit transient recovery voltages (TRV) when shunt capacitors are being switched out

b) At the end of transformer terminated lines to limit phase-to-phase overvoltages resulting from capacitor switching or line switching in the presence of shunt capacitor banks

c) On transformers when energized in the presence of shunt capacitor banks

d) On shunt capacitor banks in series or parallel with transformers

e) On lower voltage systems that are inductively coupled through transformers to higher voltage systems with shunt capacitor banks

f) On the neutrals of ungrounded shunt capacitor banks

An approximate technique for estimating arrester duty from capacitor switching overvoltages is described in Annex G.

5.6 Protection of underground transmission cables ~~(Witzke and Bliss [B134])~~

Many concerns identified in 5.5 should be considered also for high-voltage cable installations (IEEE Std 422™-1986 [B77] and IEEE Std 525™-1992 [B79]). In addition, overvoltage protection of the junction between overhead lines and cables should be evaluated, as discussed in 5.2.3.4.2. Lightning may also be an important consideration at cable terminals. Cables may require further consideration because of traveling wave phenomena and the effects of distributed and smaller capacitance values.

5.6.1 Cable insulation

Any equipment that is connected to overhead transmission lines needs consideration for overvoltage protection. Any dielectric failure in an underground power cable will undoubtedly involve non-self-restoring insulation. This implies that any breakdown of cable insulation would require extensive outage time for repairs at a high cost. The conventional method for protecting cable circuits within overhead line sections from high transient overvoltages has been to apply rod gaps or surge arresters at both terminals. Cable circuits connected between substations and overhead lines should also be protected from overvoltages.

Cable circuits, due to their relatively high capacitance, have low surge impedance. A typical value is about 50 Ω, which means that surges incoming from overhead lines will be reduced significantly at the line–cable junction. However, surges originating at a substation will enter a cable only to undergo an increase in voltage at the cable–line connection due to the much higher surge impedance of the line. Because there is little attenuation of surges in cables and the ratio of surge impedances is so large, it is common for the reflected wave plus the oncoming wave to cause a voltage doubling at the cable–line connection. This effect should be considered when evaluating the margin of protection.

Metal-oxide surge arresters can provide excellent cable protection, but the arrester should be capable of absorbing the high energy that can be stored in a cable when subjected to an overvoltage that causes the arrester to discharge.

For multiple cable and overhead line connections, optimum protection against overvoltages can best be achieved by carrying out a comprehensive transients study of the interconnected system (Greenfield [B56]; Greenwood [B57]; Marti [B125]; and van der Merwe and van der Merwe [B180]). The selection of arrester placement, voltage rating, and energy absorption capability can be based on model studies.

5.6.2 Sheath and joint insulation

High-voltage power cables are provided with metallic sheaths to give a uniform field distribution to the solid dielectric, to protect it from external damage, and to provide a return path for fault current.

~~To ensure~~ Special bonding and grounding of the metallic sheath circuits are required to provide safety and to avoid the losses associated with circulating currents. The special sheath bonding systems in common use in North America are single-point bonding and cross bonding. The length of the cable sheath circuit involved in each case is usually determined by the allowable 60 Hz voltage under steady-state and fault conditions. A disadvantage of both methods, however, is that a change in surge impedance occurs at the ungrounded terminals of the cable sheath and at the sheath sectionalizing insulators. As a result, all traveling wave surges entering the cable system due to lightning, switching operations, or faults will be subjected to partial reflection and refraction at these locations. As a consequence, hazardous transient overvoltages can be developed across the sheath joint insulators and sheath jacket insulation (Ball et al. [B10]; Erven and Ringler [B27]; Halperin et al. [B63]; Kuwahara and Doench [B116]; Watson and Erven [B187]; and CIGRE Report [B59]).

Metal-oxide surge arresters can offer excellent protection for cable sheath and joint bonding providing the following conditions are met (Reid et al. [B156]):

a) Should be suitable for continuous operation under operating voltages during normal and emergency loads on the cable circuit

b) Should withstand 60 Hz overvoltages resulting from faults in or external to the cable circuit

c) Should limit surge voltages below the surge withstand strength of the jacket and sheath joint insulators

d) Should absorb, without damage, impulse currents and energy during discharge conditions associated with switching, fault initiation, and lightning

5.7 Protection of gas-insulated substations (GIS)

SF_6-GIS at voltages up to 500 kV have been installed in increasing numbers over the past 25 years (*Proceedings* [B154]). From the design standpoint, a GIS is more sensitive to overvoltages than an air- insulated station ~~(AIS)~~. This is a result of the high electrical stress placed on relatively small geometries. With GIS, the dielectric performance is independent of the atmospheric conditions; therefore, the insulation coordination is based solely on the rated insulation level of the GIS and the margin considered to satisfy the risk of flashover. In this case, the risk should be kept very low since any flashover involves non-self- restoring insulation. Any flashover in a GIS involves an outage to inspect the damage, coupled with a long restoration time.

Another important feature about GIS is that the volt-time characteristics of pressurized SF_6 are much flatter than for atmospheric pressure air or for solid dielectrics, especially for fast fronts. This means that any incoming surge having a sufficiently high peak value and rate of rise is likely to cause breakdown in the GIS before flashing over any coordinating air gaps. Insulation co~~-~~ordination can be achieved with a device that has volt/time characteristics similar to those of the SF_6 system. In practice, this can be obtained through the use of metal-oxide surge arresters. Their highly nonlinear characteristics and construction make them ideally suited for this duty. Due to the differences mentioned, some consideration should be given to increasing the protective margin for fast front surges as compared with an air-insulated substation.

In general, GIS with connections to overhead lines will need arresters on each line entrance. One of the most common questions is related to the location and type of the surge arrester within the GIS system. Currently ~~there are~~, two types of metal-oxide arrester structures are available: an insulated housing type and a metal tank type. If the arrester is air insulated and located as close as feasible to the GIS, the arrester rating should be selected based on the insulation level chosen for the GIS and the margin required (Alvinsson et al. [B3]; Boeck et al. [B18]; and Hileman and Weck [B70]). The MCOV and TOV requirements for the surge arrester should be satisfied, and a minimum 20% protective margin is recommended. Such coordination based on the insulation level chosen for the GIS and the catalog data (V-I characteristic for the surge arrester) is needed with the GIS systems. Difficulty arises when the same protective margin is required with respect to fast front surges (1–3 μs fronts), such as lightning striking overhead lines or towers close to the GIS. In addition to surge arresters, capacitance such as capacitor voltage transformers (CVTs) may be used at the overhead junction to slow the fast fronts of the incoming surges and to extend the protective zone of the arrester at that location. If the arrester is a tank type, then its rating can also be selected on the same basis. However, if it is connected as part of the GIS system, which is often desirable to save space, then the arrester will have to be disconnected from the rest of the GIS when high potential tests are being conducted. This occurs during commissioning and following repairs to adjacent parts of the system.

Although there has been much discussion about the use of metal-oxide surge arresters within a GIS, there does not seem to be a strong body of evidence to indicate the need for surge arresters within a well- designed GIS~~,~~ and particularly for GIS rated 230 kV and below. However, GIS switchgear, notably disconnect switches, have been known to generate very fast transients. Although metal-oxide surge arresters have demonstrated capabilities to respond to fast front surges, it seems doubtful that the dimensions involved will allow for control of the extremely fast fronts (nanoseconds) that are associated with GIS switching. The effect of fast transients on the equipment, such as transformers connected to the high-voltage side, however, should be taken into account.

5.8 Protection of ~~rotating machines~~high-power static devices and systems

Solid-state devices of concern to power system performance and reliability are employed in high-power apparatus such as flexible alternating current transmission systems (FACTS), high-voltage direct current (HVDC), and medium-voltage custom power equipment. The main solid-state elements of concern are diodes, thyristors, gate turnoff transistors (GTOs), and insulated gate bipolar transistors (IGBTs). These solid-state elements are always part of a complex system designed for specific power control capability. Examples are HVDC converter stations, static VAR compensators (SVCs), Statcoms, thyristor-controlled series capacitors (TCSCs), static voltage regulators, and universal power flow controllers (UPFCs).

~~At present a guide for the protection of rotating machines is in preparation.[7] In the interim refer to NEMA and IEC Standards in the Reference Section, and refer to the Annex D (Dick et al., [B29], Dick et al., [B30], Gupta et al., [B47], Gupta et al., [B48], IEEE Working Group Report [B72], Jackson [B74], and McLaren and Abdel-Rahman [B97]~~

Solid-state elements are sensitive to the rates of change of both voltage and current (dv/dt and *di/dt*) as well as voltage amplitudes when not in the conducting state. In contrast to insulation systems such as air, oil- paper, and solid dielectrics, the withstand characteristics of solid-state elements have little turn-up in their fast front (impulse or short time) voltage withstand characteristics. These devices are generally protected from excessive dv/dt by capacitors or series resistor-capacitor (snubber) circuits. They are protected from excessive *di/dt* by series reactors. Surge arresters protect the devices from overvoltages.

The users of FACTS devices are generally not responsible for the design and insulation coordination associated with surge protection of the solid-state devices. Protection of these devices is specific to the design of the FACTS equipment and is generally the responsibility of the equipment manufacturer. The user must only be sure that the manufacturer has good equipment design so that it is properly protected from overvoltages generated both within the FACTS power electronic equipment and externally by lightning, switching, or other power system events.

~~5.15 Protection of power line insulation~~

~~Transmission and distribution line insulators may be protected from lightning flashover by overhead shield wires. However, the effectiveness of the shield wire depends on many factors. Prime among these are shield angle and structure ground footing resistance.~~

~~Strokes to the shield wire will cause surge voltages to be induced in the phase conductors. The magnitude of the induced voltage is a function of the current magnitude, resistance, and geometry (Anderson [B4]). Stroke currents exceeding a critical current value will develop sufficient voltage between the structure and the phase conductor to cause an insulator flashover. The phase with the poorest coupling to the shield wire will be the most highly stressed and therefore most likely to flash over.~~

~~The possibility of a flashover of the line insulation and subsequent service interruption may be significantly reduced through the application of line arresters (Brewer [B17]). Line arresters may also be applied on one circuit of a double circuit line in order to reduce double circuit interruptions due to lightning. Line arresters may be installed phase-to-ground, either in parallel with the line insulators (Koch et al., [B83]), or built into the insulators (Yamada et al., [B135]). While the failure rate of these arresters is low, the user should consider the failure mode of the arrester. After failure, the arresters should be disconnected from the line to allow for successful line reclosing.~~

~~The protective level of the line arresters should be greater than the protective levels of the adjacent substation arresters. This will reduce the energy absorbed by the line arresters due to switching surges and therefore reduce the possibility of a line arrester failure (Anderson [B4]).~~

~~The appropriate location of the surge arresters depends on many factors including lightning ground stroke density, exposure, span length, conductor geometry, footing resistance, insulation level, and desired line performance goals. In general, the more frequently arresters are installed, the better the performance. There are several computer models available to assist in selecting the location of surge arresters, or the arrester manufacturer may be contacted for a recommendation.~~

[7] ~~IEEE PC62.21~~

~~In some cases, arresters are being used successfully in place of a shield wire(s). The user should consider energy, mechanical strength, and weight requirements in developing the system design. The arrester manufacturer should be contacted for recommendations.~~

5.9 Protection of series capacitor banks

The development of metal-oxide materials has now matured to a point where the material is commonly used to protect the capacitor units within a series capacitor bank. When used in this form, it is commonly called a varistor. A varistor protects the capacitor units by controlling the voltage across the capacitor units to the design protective level by commutating a portion of the capacitor current. When the capacitor voltage falls significantly below the varistor protective level, the capacitors are automatically electrically reinserted. Depending on the series capacitor location and available fault current, the varistor may be protected by a bypass device such as a breaker, gap, or a thyristor. Field experience indicates that capacitor life will be extended by eliminating or minimizing bypass operations. This should be considered when varistor energy handling capability makes it economically feasible. For additional relevant information, see IEEE Std 824™-2004.

The following performance characteristics should be considered for properly applying a varistor:

a) Protective level—This is the maximum voltage appearing across the capacitor at the specified current (usually worst-case fault). This level is generally determined by performing system studies. The protective level is usually set above steady-state and dynamic overcurrents such as the 30 min overload rating of the bank and system swings.

b) Energy handling capability—This is the thermal withstand capability of the varistor. The manufacturers' design is based on the identified duty cycle, and the dissipated energy for the various system events associated with the duty cycle. The dissipated energies (varistor duty) are determined by system study simulations and based on the time until the bypass device operates, or when circuit breakers clear a fault condition, and the number of circuit breaker line reclosures to which the series capacitor bank is exposed. The above capabilities are described below:

    1) Thermal capability—The maximum temperature at which the varistors can continue to be operated without the need for bypassing to allow the varistor to cool. This is typically determined by the bank's duty cycle consisting of a combination of internal and external faults, system swings and/or operation at the bank's 30 min rating, and the number of circuit breaker line reclosures to which the series capacitor bank is exposed.

    2) Withstand capability—The maximum short time energy that may be withstood, above which disks are exposed to a statistical probability of failure due to an unequal current distribution or excessive temperature rise.

c) Current sharing—The manufacturer should balance the varistor disk columns to avoid exposing individual columns to a disproportionately large current. To accomplish this, the discharge voltage of the disk columns should be matched and tested to show that each column, including spare units (which should be energized), are exposed to approximately the same current and, hence, energy.

d) Pressure relief—Because the varistor is paralleled with the capacitor bank and only a small amount of inductance is present in the loop during a varistor failure, extremely large currents at high frequency will be present. These currents will produce a large overpressure within the porcelain or enclosure. To avoid catastrophic failure and the associated safety hazard, a pressure-relief system ~~may~~should be provided to vent this overpressure safely.

Under fault conditions, the varistor should be capable of withstanding the currents and energies present until the fault is removed or a bypass takes place. To control varistor duty, a protection system is usually provided that typically monitors varistor and, in some cases, capacitor currents. The following protective functions for the varistor are usually provided:

a) Fast bypass—Monitor the varistor current and calculated energy to detect internal faults that can be bypassed as soon as detected. To speed detection, the capacitor current can also be monitored.

b) Thermal bypass—Takes place when varistor temperature exceeds a preset level. This would normally indicate that either normal operation or operation at some specified additional duty (e.g., external fault and 30 min rating) could produce a thermal bypass. A bypass can also take place following a significant energy injection to allow equalization of disk temperature.

c) Imbalance—Detects a current difference between groups of parallel varistor units and bypasses and locks the bank out if the imbalance exceeds preset limits. Such an imbalance is normally due to the failure of either a partial or complete varistor unit. For every reclosure of the line with the series capacitor bank, the bank ~~protection~~ is exposed to additional energy with the possibility of a sustained fault, and the actions of the above functions should be repeated.

5.10 Protection of circuit breakers

5.10.1 Transient recovery voltage ~~TRV~~ control

Metal-oxide surge arresters can be used to limit the magnitude of TRV across circuit breakers to acceptable values. This may provide a more economical solution than increasing the number of interrupting chambers to withstand the higher TRV.

Surge arresters electrically connected across the circuit breaker terminals are the most direct means of controlling TRV, as the amplitude of the TRV cannot exceed the protective level of the surge arresters. If the surge arresters are mounted across the interrupters of multichambered circuit breakers, then caution should be exercised when interrupting fault currents. A reignition of a single series chamber can result in fault currents flowing through the surge arrester across the nonreignited chamber. Surge arresters across the open circuit breakers during reclosing should be able to withstand the difference of the power frequency out-of-phase overvoltages on each side of the open circuit breakers for the time required for the reclosing.

Surge arresters can be used across an interrupter to limit reactor switching TRV (IEEE Std C37.015™-1993). Surge arresters can be used instead of opening resistors on circuit breakers to reduce trapped charge on shunt capacitors or transmission lines. Surge arresters have been considered to limit the TRV across circuit breakers used to switch series-compensated lines. The voltage appearing on the series capacitor during a fault augments the higher-frequency fault component of the TRV. The location of the series capacitor bank (i.e., on the load side of the circuit breaker or on the source side) can have a significant effect on the magnitude of the TRV. Series-capacitor banks protected against overvoltage with metal-oxide varistors as opposed to spark-gap protection deserve special consideration. Following clearing of the fault, a dc voltage equal to the protective level of the varistor can remain on the bank throughout the duration of the TRV.

Surge arresters can also be installed phase to ground at either or both sides of the circuit breakers. However, depending on the required rating and protective levels of the surge arresters for TRV control, this usually requires appropriate studies with proper simulation of the surge arresters. Studies should include coordination with any other surge arresters installed in the substation or on shunt reactors.

5.10.2 Lightning surge protection of breakers

Lightning surges can originate in a station by either a direct stroke to the station or a stroke to a transmission line feeding the station (Johnson [B106] and Hileman [B65]). In a well-designed station, the former is extremely rare so only line strokes are usually considered in lightning insulation studies.

When the surge arrives at a station, it is modified by the terminating impedance of the station. Taking the extreme condition of the stroke terminating at an open breaker, the surge would double in amplitude. The required impulse insulation levels for substation equipment depend on the protective characteristics of the voltage-limiting devices applied, as well as on the number and location of the devices (Andrel et al. [B7]; Clayton and Powell [B32]; Hileman [B65]; Hileman et al. [B69]; and Wagner et al. [B183]. In the station itself, surge arresters are the normal protective devices used, whereas arresters or rod gaps are used on the line entrance terminals. However, see 5.10.2.2.2 for a precaution regarding the usage of rod gaps on line entrance terminals.

5.10.2.1 Closed breaker protection

For existing stations exposed to lightning, the objective is to determine the number and location of surge arresters to protect the existing breaker insulation level. Surge arresters are normally applied directly on the terminals of power transformers, so the arrester-protective characteristics are determined to protect the transformer BIL with a suitable margin. Therefore, circuit breakers for protection must rely on surge arresters located remotely from their terminals. Arresters protect equipment not only ahead of the arrester but also behind the arrester. Thus, if the arrester is located at or near the transformer, the arrester can protect backward to the circuit breaker. Considering the fact that the breaker BIL and other station equipment BILs are greater than that of the transformer, the arrester can often provide effective protection to the closed breaker.

Lightning strokes to transmission lines produce traveling waves, which develop higher voltages at the remote breaker locations. For example, the 192 kV duty-cycle rated arrester limits its voltage to 500 kV, but the voltage 200 ft away will be over 600 kV. Clayton and Powell [B32] and Hileman [B65] present methods for determining these voltages. Also, computer programs are available to calculate the peaks and shapes of the overvoltages for even the most complex stations. For new stations, the problem is to balance the cost of additional surge arresters against the savings in breaker cost due to the lower breaker BIL (Wagner et al. [B183]).

5.10.2.2 Lightning surge protection of opened circuit breakers

Lightning surges within the station may originate either by a direct stroke to the station or by a lightning flash to a transmission line feeding the station (Johnson [B106] and Wagner et al. [B183]). For an effectively shielded station, the former is extremely rare so that only surges that originate on the transmission line are considered. The high surge voltage often causes a traveling envelope of corona. The effect of corona is to reduce the amplitude and front steepness of surges arriving at the station. The surge impedance of the station further modifies the surges entering the station.

In air-insulated stations, arresters are located within the station to provide protection to all apparatus, including the circuit breaker in the closed position. However, with the breaker opened, no protection exists for the line side of the breaker, and a lightning surge may result in flashover of the breaker either across the contacts or across insulation to ground.

This opened breaker condition may occur when a breaker is standing opened on a line. Normal operating practice, however, dictates that when the breaker is opened for a prolonged period, the breaker disconnecting switches are also opened, so that surges will not impinge on the breaker and any flashover would occur to ground at the disconnecting switch. Departure from this practice is rare, but if an opened breaker with a closed disconnecting switch normally exists, then some form of protection should be used.

Another, more likely, condition that places a breaker in a vulnerable position is caused by a subsequent stroke of the lightning flash. The event may be described as follows:

a) The first stroke of a flash terminates on the shield wire or phase conductor of the line resulting in a flashover.

b) The resulting surge travels into the substation, but because the breaker is closed, arresters within the station provide protection to the breaker.

c) Next, the relay senses the fault and the breaker opens (in about 50 ms), and in about 300 ms, the breaker recloses.

d) However, a lightning flash is composed of one or more strokes, and a subsequent stroke may occur within the 50 ms to 300 ms time period and produce a surge voltage that exceeds the breaker's insulation strength.

The following three alternative solutions to this problem have been proposed:

↓ Apply arresters to the line side of all breakers

↓ Apply protective gaps to the line side of all breakers

↓ Do nothing (i.e., leave line side of the breakers unprotected)

5.10.2.2.1 Surge arrester option

The first method provides the greatest degree of protection but may be expensive. Recently, polymer arresters have been employed with the cost advantage that no extra steel supports or foundations are required. Where breakers without closing resistors are employed at EHV, line side arresters may be present to control switching overvoltages. These arresters will also provide lightning protection to the opened breaker.

5.10.2.2.2 Protective gap option

Line-side protective gaps have been known to cause the catastrophic failure of oil circuit breakers. For example, if the protective gap should flash over during the opening of the circuit breaker on line or load switching, and the current being interrupted changes suddenly from a low-level current to a high-level fault current, the breaker will most likely blow up. The reason for this sequence of events is that the interrupting process in an oil circuit breaker is dependent on the production and control of high-pressure hydrogen gas during the initial current arcing period. Any sudden increase in current during this period will result in a dramatic pressure rise, which may exceed the capabilities of the interruption chamber.

5.10.2.2.3 Unprotected option

This approach relies on the low probability or high mean time between failure (MTBF) of the breaker failure. The MTBF is a function of the flashover rate of the lines and the BIL of the breaker. The breaker MTBF is lower for lower voltage lines (higher probability of failure) than for higher voltage lines because the lower voltage lines have lower BIL and higher flashover rates than higher voltage lines. Thus, the “do nothing approach” is better applicable to higher voltage stations. Some methods are available to estimate the MTBF so as to better define the risk (Hileman [B65]).

5.10.2.3 Insulation strength of breakers

Breakers are tested not only for the BIL but are given a chopped-wave test with a magnitude equal to 1.29 (BIL) and chopped at 2 µs. Usually, this test voltage is used to evaluate the MTBF; however, the actual insulation strength is a function of the time of contact parting (breaker opening) and the immediately preceding current interruption duty. The dielectric strength is significantly reduced during parting and interruption.

In general, all three methods of open breaker protection have been used. Breaker failures have occurred, but the extent is not well known. In general, as in all applications, the method selected is based on the experience of the utility coupled with a study of the problem.

6. Protection of distribution systems

6.1 Introduction

This clause covers the application of metal-oxide surge arresters to safeguard electrical distribution equipment and lines against the hazards of abnormally high-voltage surges, particularly those caused by lightning. Although the basic principles of arrester selection and application as outlined in Clause 5 also apply to distribution arresters, there are specific differences that require special consideration.

Distribution lines are generally not shielded and therefore are particularly susceptible to direct lightning strokes (Brown and Thunander [B21]; Eriksson et al. [B47]; Goldenhuys et al. [B55]; Linck [B119]; MacCarthy et al. [B122]; and McEachron and McMorris [B130]). The transient overvoltages developed by lightning are of greater concern than those caused by switching. Insulation coordination based on lightning surge voltages is thus the major consideration for distribution systems.

The level and frequency of occurrence of discharge currents varies widely and depends to a great extent on the exposure of the distribution system and the ground flash density. Detailed reviews of material relating to this subject are available in references (Barker et al. [B12] and [B13]; Berger et al. [B15]; Darveniza and Uman [B37]; Gaibrois [B51]; Grumm [B58]; MacCarthy et al. [B122]; and McEachron and McMorris [B130]). Arresters applied on exposed systems (few trees and buildings) of a rural nature (less frequent equipment and grounds) located in areas of high ground flash density (GFD) will see large magnitude currents more often than arresters in shielded locations. The peak magnitudes and frequencies of discharge for exposed arrester applications are shown by the exposed line curves of Figure 10. Arresters applied on systems that are moderately to well shielded (many trees or surrounding buildings) and are of a suburban or urban nature with closer equipment spacing will see fewer large magnitude discharges (see environmentally shielded line curves in Figure 10).

The arrester discharge current incidence curves of Figure 10 are intended to provide the lightning protection engineer with an estimate for the magnitudes and rates of occurrence of discharges at typical distribution arrester locations under various conditions. For specific arrester applications, Figure 10 and Figure 11 can be used to assist in determining an adequate lightning-coordination current for protective margin calcula—tions. For example, the lightning-coordination current for protection calculations is 10 kA in normal situa—tions. However, for a highly exposed location with a GFD of 10 flashes per square kilometer per year, Figure 10 indicates that an arrester discharge current of 30 kA or greater would occur about once every 10 years. If the expected life of the protected equipment is 30 years, then this suggests that coordination should be made with a current level higher than 10 kA (perhaps as high as 40 kA). In other situations where GFD is very low and there is significant environmental shielding (limited exposure), the coordination current may be reduced to values less than 10 kA. The decision to utilize a coordination current different than the standard 10 kA level may impact the type of arrester selected and the arrangement of arresters utilized.

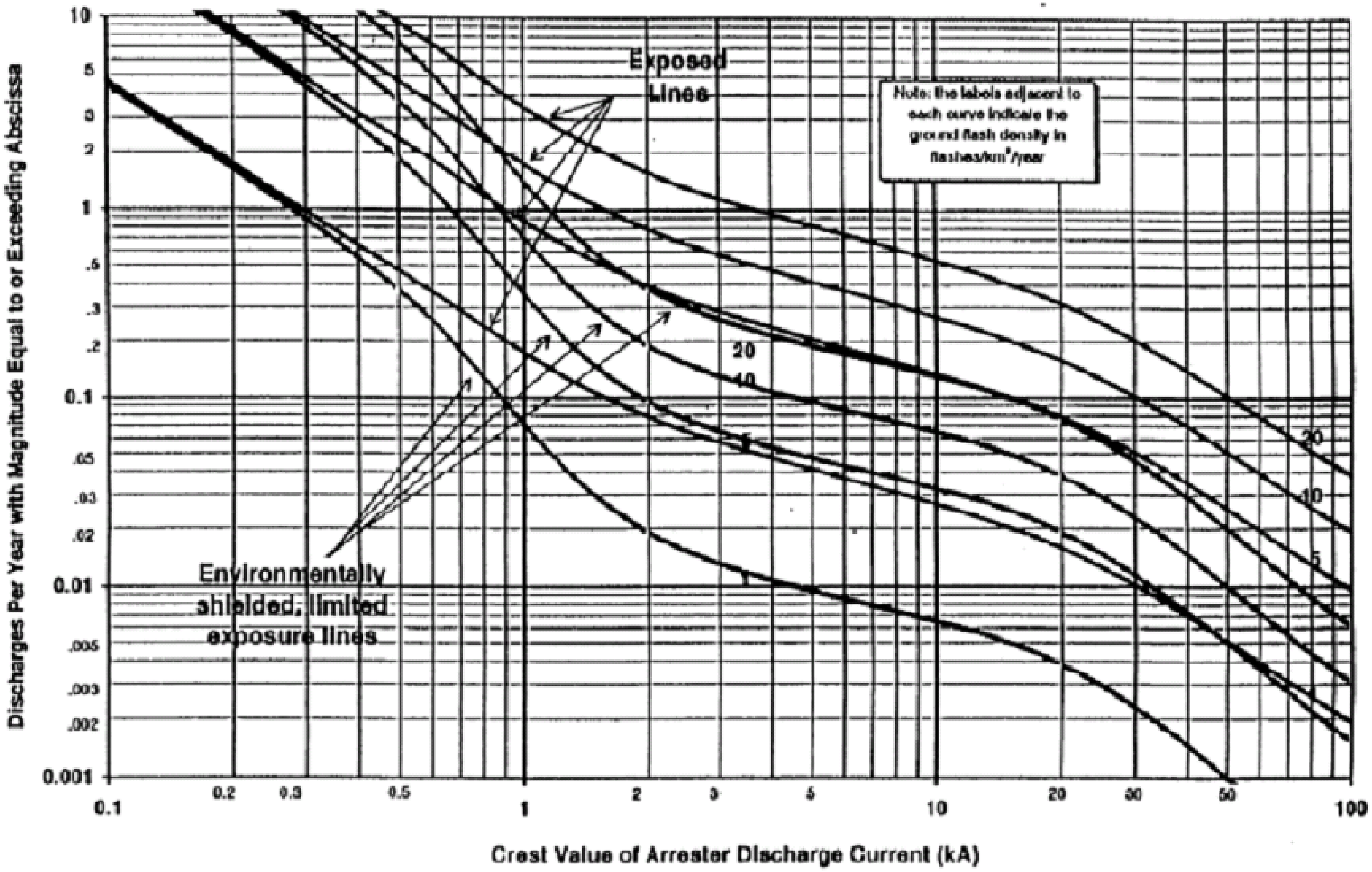
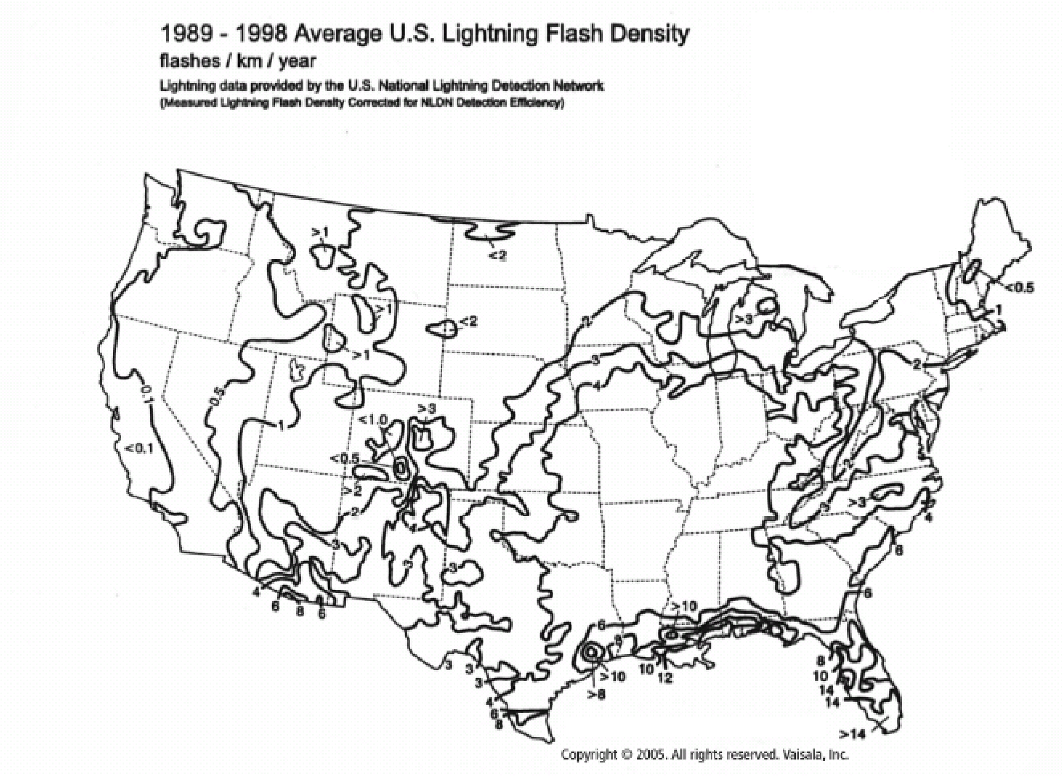


Figure 10—Distribution arrester discharge currents

Environmentally Shielded Lines = Situations with average to high levels of environmental shielding (nearby trees and buildings) - suburban lines usually fit this definition. Exposed lines = Exposed situations (few nearby trees and building or located along elevated ridges, etc.) - rural lines often fit this definition. (*Note: these curves are intended for arresters on lines without overhead ground wires, static wires or shield wires)*



Graphic reproduced with permission from Vaisala Group, Tucson, Ariz. Lightning data provided by the U. S. National Lightning Detection Network.

Figure 11—1989 to 1998 average U.S. lightning flash density; ground flashes per square kilometer per year (Byerley et al. [B25] and Cummins et al. [B36])

In cases where only thunderstorm days or thunderstorm hours are known, the GFD can be estimated as follows:

Converting thunderstorm days to GFD (Anderson et al. [B5])

$$N_g = 0.04T_D^{1.25} \tag{27}$$

where

T_D is the Keraunic level in thunderstorm days

N_g is the ground flash density (flashes/km^2/year)

Converting thunderstorm-hours to GFD

$$N_g = 0.054T_H^{1.1} \tag{28}$$

where

T_H is the thunderstorm-hours

N_g is the ground flash density (flashes/km^2/year)

Other potential causes of severe arrester duty occur when arresters are used to protect switched capacitor banks (see 6.7.1) or when arresters are subjected to ferroresonant overvoltages (see 6.4.4) or backfeed over-voltage (see 6.4.5).

Distribution equipment, including arresters, is low in unit cost compared with station equipment but is used in large quantities. It is usually not economically feasible to make independent studies for each specific arrester application. Consequently, distribution arresters are usually selected so that they can be used for similar application anywhere on a system rather than for a particular location.

6.2 General procedure

The general procedure for selecting a distribution arrester is to determine the proper arrester MCOV that can be used at all similar locations on the distribution system to be protected. Also, the TOV capability of the arrester should not be exceeded by the magnitude and duration (total accumulated cycles) of any TOV of the system at the arrester location. For arrester application on distribution systems, the TOV is usually based on the maximum phase-to-ground voltage that can occur on unfaulted phases during single line-to- ground faults. Surge arrester selection is discussed in 6.3.

Insulation coordination is discussed in 6.5. For system voltages up to 15 kV, insulation coordination for overhead connected equipment has not been rigorously studied because the ~~protective margin (~~ PM~~)~~ between standard equipment BIL and the protective characteristics of modern distribution arresters is substantially in excess of 20% in usual applications. Insulation coordination becomes a primary consideration for higher distribution voltage systems because PM is reduced (particularly when reduced BIL values are used). Insulation coordination may also be important for line protection (see 7.3) and for protection of underground distribution systems (see 6.7.4).

6.2.1 Installation practice~~s~~ that jeopardize insulation coordination

Installation practices that jeopardize insulation coordination include the following:

a) Long leads between line and arrester line terminal and between arrester ground terminal and tap to the equipment case (see 6.6.1)

b) Large separation distances between the arrester and the protected equipment (see 6.6.2)

c) Failure to interconnect the arrester and equipment ground terminals (see 6.6.4)

6.2.2 Applications requiring special considerations

Applications that require special considerations, either with regard to duty requirements imposed on the arrester or with regard to protection requirements, include the following:

a) Ungrounded systems (see 6.4.3)

b) Shunt capacitor banks (see 6.7.1)

c) Switches, reclosers, etc. (see 6.7.2)

d) Voltage regulators (see 6.7.3)

e) Underground circuits (see 6.7.4)

f) Contaminated atmospheres (see 6.7.5)

6.3 Selection of arrester ratings

Power systems to be protected by distribution arresters are either:

a) Three-wire wye or delta, high or low impedance grounded at the source~~; or~~

b) Four-wire multigrounded wye

Construction includes open wire, spacer cable, and underground cable systems.

Proper application of metal-oxide surge arresters on distribution systems requires knowledge of:

– The maximum normal operating voltage of the power system

– The magnitude and duration of TOVs during abnormal operating conditions

This information is compared with the arrester MCOV rating (see 6.3.1) and with the arrester TOV capability (see 6.3.2). The user should be careful not to replace silicon-carbide arresters with metal-oxide arresters that have the same duty-cycle voltage rating without first analyzing the expected magnitude and duration of TOVs (Gaibrois et al. [B53]).

Commonly applied voltage ratings of metal-oxide arresters on distribution systems are shown in Table ~~7.~~8. Protective characteristics of metal-oxide distribution arresters are given in Table 9. See the qualifying comment immediately following Table 9.

Table 8—Commonly applied voltage ratings of metal-oxide arresters on distribution systems

System RMS voltage (V)		Commonly applied arrester duty-cycle (MCOV) voltage rating (kV) on distribution systems		
Nominal voltage	Maximum voltage range B	Four-wire multigrounded neutral wye	Three-wire low impedance grounded	Three-wire high impedance grounded
2400	2540			3 (2.55)
4160Y/2400	4400Y/2540	3 (2.55)	6 (5.1)	6 (5.1)
4160	4400			6 (5.1)
4800	5080			6 (5.1)
6900	7260			9 (7.65)
8320Y/4800	8800Y/5080	6 (5.1)	9 (7.65)	
12 000Y/6930	12 700Y/7330	9 (7.65)	12 (10.2)	
12 470Y/7200	13 200Y/7620	9 (7.65) or 10 (8.4)	15 (12.7)	
13 200Y/7620	13 970Y/8070	10 (8.4)	15 (12.7)	
13 800Y/7970	14 520Y/8380	10 (8.4) and 12 (10.2)	15 (12.7)	
13 800	14 520			18 (15.3)
20 780Y/12 000	22 000Y/12 700	15 (12.7)	21 (17.0)	
22 860Y/13 200	24 200Y/13 970	18 (15.3)	24 (19.5)	
23 000	24 340			30 (24.4)
24 940Y/14 400	26 400Y/15 240	18 (15.3)	27 (22.0)	
27 600Y/15 935	29 255Y/16 890	21 (17.0)	30 (24.4)	
34 500Y/19 920	36 510Y/21 080	27 (22.0)	36 (29.0)	

6.3.1 MCOV rating

Valve elements in a gapless and shunt gapped metal-oxide surge arrester are continuously exposed to line- to-ground power-frequency voltage. The MCOV rating of a metal-oxide arrester is the maximum designated rms value of power-frequency voltage (at maximum temperature levels as indicated in IEEE Std C62.11-2005) that may be applied continuously between the terminals of the arrester. Consequently, the MCOV rating should be at least equal to the expected maximum continuous operating voltage at the location where the arrester is to be applied.

6.3.2 TOV

Metal-oxide surge arresters are capable of operating for limited periods of time at power-frequency voltages above their MCOV rating. The amount of overvoltage that a metal-oxide arrester can successfully tolerate depends on the length of time that the overvoltage exists. Manufacturers can describe the arrester overvoltage capability in the form of a curve that shows temporary power-frequency overvoltage versus allowable time. A typical curve is shown in Figure 12. (These curves are sensitive to ambient temperature and prior energy input.)

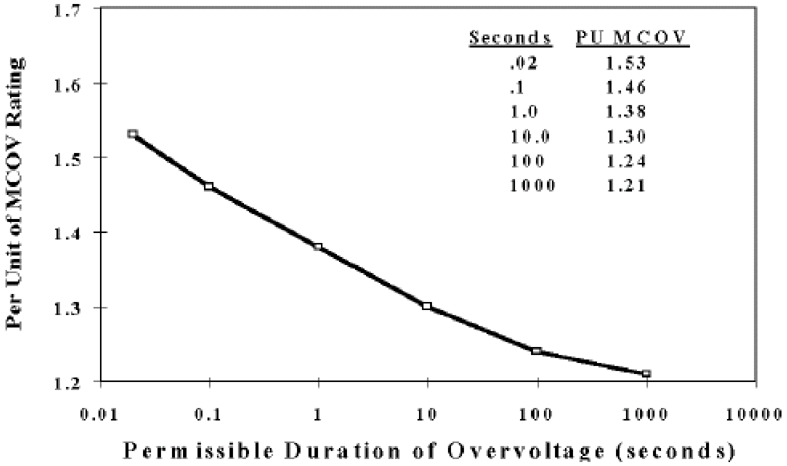


Figure 12—Minimum expected TOV capability of gapless distribution class MOSAs, no prior duty-arrester preheated to 60 °C (North American Manufacturers, May 1995)

To verify that the arrester TOV capability is not exceeded, the maximum TOV of the power system has to be determined along with the maximum time that the system is operated in the abnormal voltage state. This abnormal voltage state can result from several factors, some of which are overvoltage on an unfaulted phase during a phase-to-ground fault, switching transients, and ferroresonance. In the case of the overvoltage due to a phase-to-ground fault, this voltage can be calculated using the equations shown in the annex of IEEE Working Group Report [B101], the methods described in Lat [B118], or a computer program capable of modeling the distribution system. A conservative approach is to multiply the maximum phase-to-phase operating voltage by the coefficient of grounding (see Figure 6 and Annex B). During this type of fault, the surge arrester is subjected to a TOV whose duration is a function of the operating times of protective relays and fault interrupting devices. The MCOV of the arrester selected should be high enough so neither the magnitude nor the duration of the TOV exceeds the capability of the arrester.

6.3.2.1 Application of arresters on distribution systems

See 4.2.4 for use of the TOV curve. For distribution systems, the usual problem is not lack of data but a large number of locations, overvoltages, and durations. These differences have to be considered to determine the single arrester rating to be used on the entire feeder.

TOV should be a primary consideration for non-effectively grounded systems.

Ferroresonance is a particular concern on distribution systems. Applications prone to ferroresonance may require attention to arrester rating and capabilities (see 6.4.4).

When accurate data are available on feeder overvoltages and durations, these data can be compared with the single standard curve to select the appropriate arrester rating.

If the user has distribution arrester failures attributed to TOV, the selection of the next higher voltage rating may resolve the problem, or in extreme cases, a system study may be warranted to determine TOV amplitudes and durations at problem locations.

6.3.2.2 Application of arrester for distribution system generators

Overvoltages may occur when generation units are present on distribution systems. Overvoltages can be caused when a generator and part of the distribution network are separated from the utility. This is called “islanding” and could be caused by ungrounded transformer connections, self-excitation, or ferroresonance. Generator overvoltages have not been a major problem in the past. One reason is that a small number of generation units were in operation and most of these were quite small. Another reason is that gapped arresters, used almost exclusively until about the early 1980s, may not have sparked over from the overvoltages and therefore would not be harmed. Since some metal-oxide arresters do not have gaps, they may not be able to survive the sustained overvoltages caused by the presence of a generator. As generator use and size increases and surge arresters are used more at the distribution level, generation overvoltages could become a problem.

The results of studies suggest that surge arresters should survive most overvoltage situations if the protection scheme can relay the generator off the utility system in a few seconds. Fault protection schemes used at the generation site would be expected to sense the “islanding” condition and disconnect from the system in a matter of a few seconds. On systems with large generation relative to the possible load, utilities may con–sider using higher rated surge arresters.

6.3.3 Normal-duty versus heavy-duty surge arresters

The application of normal- or heavy-duty surge arresters is not well defined and is more a choice of the user than a decision based on actual firm requirements or performance data.

Table 10 compares design requirements for tests on normal and heavy-duty arresters (IEEE Std C62.11-2005).

Table 9—Distribution arrester protective characteristics

Voltage ratings (rms)		Peak protective level—Range of industry maxima (kV)					
Duty-cycle rating (kV)	MCOV (kV)	Front-of-wave protective level			Discharge voltage with 8/20 wave		
		5 kA normal duty	10 kA heavy duty	10 kA riser pole	5 kA normal duty	10 kA heavy duty	10 kA riser pole
3	2.55	11.2–17	13.5–17	10.4	10.2–16	9.1–16	8.2
6	5.1	22.3–25.5	25.0–27	17.4–18	20.3–24	18.2–25	16.2
9	7.65	33.5–36	26.5–35.3	22.5–36	30.0–33.5	21.7–31.5	20.0–24.9
10	8.4	36.0–37.2	29.4–39.2	26.0–36	31.5–33.8	24.5–35	22.5–26.6
12	10.2	44.7–50	35.3–50	34.8–37.5	40.6–44	32.1–44	30.0–32.4
15	12.7	54.0–58.5	42.0–59	39.0–54	50.7–52	35.9–52	33.0–40.2

18	15.3	63.0–67	51.0–68	47.0–63	58.0–60.9	43.4–61	40.0–48
21	17.0	73.0–80	57.0–81	52.0–63.1	64.0–75	47.8–75	44.0–56.1
24	19.5	89.0–92	68.0–93	63.0–72.5	81.1–83	57.6–83	53.0–64.7
27	22.0	94.0–100.5	77.0–102	71.0–81.9	87.0–91.1	65.1–91	60.0–72.1
30	24.4	107.0–108	85.0–109.5	78.0–85.1	94.5–99	71.8–99	66.0–79.5
36	29.0	125.0	99.0–136	91.0–102.8	116.0	83.7–125	77.0–96

The protective levels and ranges in Table 9 are only illustrative and are not up to date (IEEE Std C62.22-1991). For arrester selection, refer to protective levels in manufacturers’ current publications.

Table 10—Design requirements for tests on normal- and heavy-duty arresters

Test performed	Normal duty	Heavy duty
High current-short duration	65 kA (4/10 µs)	100 kA (4/10 µs)
Low current-long duration	75 A · 2000 µs	250 A · 2000 µs
Duty-cycle impulse current	5 kA (8/20 µs)	10 kA (8/20 µs)
Surges after duty-cycle test	5 kA (8/20 ⌠s)	40 kA 8/20 µs)

The heavy-duty arrester is therefore capable of discharging a higher energy than a normal-duty arrester and should be used when greater than normal withstand capability is desired or required. High energies due to lightning are more likely to occur in areas with a high yearly number of thunderstorm days where lightning flashes are more frequent and there can be a higher number of lightning surges above 65 kA.

The total lightning current is unlikely to be discharged by a single arrester and the amount of current discharged by an arrester depends on the distance between the strike and the arrester, the presence of other arresters, and the level of line insulation (Brown and Thunander [B21]).

Heavy-duty arresters could also be chosen to discharge higher energy surges, such as those generated while switching large capacitive loads. For these cases, other arrester classes may be considered.

Finally, heavy-duty arresters generally have a lower discharge voltage characteristic than normal duty arresters, but prior to selecting any arrester, all characteristics, as well as the economics of one arrester classification versus the other, should be closely scrutinized.

6.4 Distribution system overvoltages

6.4.1 Four-wire multigrounded-wye systems (including spacer-cable circuits)

The arrester MCOV rating should be equal to, or greater than, the maximum continuous operating voltage applied to the arrester.

Most distribution systems in use in North America are of the four-wire multigrounded type. In lieu of calculations to determine phase-to-ground voltage during ground faults, it can be assumed that the TOV on unfaulted phases exceeds the nominal line-to-ground voltage by a factor of 1.25. The 1.25 factor applies when line-to-ground resistance is low (i.e., less than 25 Ω) and neutral conductor size is at least 50% of the phase conductor (McMillen et al. [B134]). The factor can exceed 1.25

when small-size neutral conductors are used (Kershaw et al. [B113]).

Because the metal-oxide arrester may be more sensitive to overvoltages caused by poor grounding and poor regulation, many utilities use a factor of 1.35.

6.4.2 Three-wire, low-impedance, grounded systems (grounded at source only)

As mentioned in 6.4.1, the arrester MCOV rating should be greater than the MCOV applied to the arrester.

In lieu of calculations to determine phase-to-ground voltages during ground faults, the general practice has been to assume the TOV on the unfaulted phases rises to 1.4 pu (Report [B28]). The maximum duration of this TOV has to be determined, and the arrester overvoltage-versus-time curve has to be examined to be sure the arrester can withstand the TOV for the duration of the fault.

If the system is grounded through an impedance, the voltage rise on the unfaulted phases could easily be greater than 1.4 pu and therefore should be calculated. When a fault occurs at the arrester installation, the voltage on unfaulted phases can rise on the order of 80% (Report [B28]) due to the ground resistance at the point of fault. Values for both unfaulted phases should be calculated since grounding through a resistance can result in unequal voltages (IEEE Tutorial [B93]).

Where it is possible to backfeed a portion of the circuit that has been disconnected from the source through devices such as transformers or capacitors that are connected to that part of the circuit, the TOV should be assumed to be equal to the maximum phase-to-phase voltage. In this case, it should be assumed that the duration of this situation is within the capability of the arrester. If duration cannot be determined, then the arrester should be selected so that its MCOV rating equals or exceeds the maximum system phase-to-phase voltage.

6.4.3 Three-wire, high-impedance ground, or delta-connected systems

The arrester MCOV rating should equal, or exceed, the MCOV applied to the arrester.

During a single line-to-ground fault, the line-to-ground voltage on the other two unfaulted phases will rise to line-to-line values. Because fault current values are extremely low, relaying schemes could allow this type of fault to exist for considerable time. Consequently, the general practice is to choose an arrester with an MCOV rating greater than the maximum system phase-to-phase voltage.

A lower MCOV rating may be used if fault detection relaying limits the duration, but the arrester should have the capability to withstand line-to-line voltage for the maximum time required to clear the fault. This could result in a duty-cycle rating lower than that recommended for a silicon-carbide arrester (but caution is advised in making this choice).

6.4.4 Overvoltages caused by ferroresonance effects

Ferroresonant overvoltages result when a saturable inductance is placed in series with a capacitance in a lightly damped circuit. The series L-C circuit topology usually results when a three-phase transformer, or bank of transformers, is left with one or two phases disconnected from the source. The capacitance is typically provided by overhead lines, underground cables, the internal capacitance of the transformer windings, or shunt capacitor banks. One of the following combinations of transformer and capacitance connections should be present to create the ferroresonant circuit:

a) An ungrounded transformer primary connection (delta, open delta, ungrounded-wye, three- phase transformer or bank, or a phase-phase connected single-phase) and phase-ground capacitance(s) connected to the transformer phase(s) disconnected from the source.

b) A grounded wye-wye three-phase transformer or transformer bank with one or two phases disconnected from the source and an ungrounded capacitance connected between the opened transformer phases on either the primary or the secondary terminals of the bank. The ungrounded capacitance is typically in the form of a delta or ungrounded-wye capacitor bank, or a length of overhead three--phase primary line.

c) A grounded wye-wye three-phase transformer, constructed with a five-leg or four-leg core, having one or two phases disconnected from the source and having phase-ground capacitance(s) connected to these same phases on the primary or secondary transformer terminals.

Ferroresonant overvoltage magnitudes are dependent on the transformer primary winding connection and on the amount of capacitance present compared with the transformer characteristics. They tend to be more severe for higher system voltage classes, smaller transformer kVA ratings, and higher efficiency (lower core loss) transformers. References predating the 1980s, characterizing ferroresonant overvoltage magnitudes or the conditions necessary to have ferroresonance (Auer and Schultz [B8]; Crann and Flickinger [B35]; Hopkinson [B71], [B72], and [B73]; and Smith et al. [B166]), were based on transformers with core losses considerably greater than are now typically installed. More recent research (Walling et al. [B185]) suggests ferroresonance occurs more easily and overvoltage magnitudes are more severe for contemporary transformer designs. A conservative approach is to consider ferroresonance possible for any open-phase conditions with the transformer and capacitance configurations listed above.

For transformers with ungrounded primary connections, ferroresonant overvoltages can easily exceed 3–4 pu (Hopkinson [B71] and Young et al. [B192]). Internal transformer capacitance can often be sufficient to support severe ferroresonance in ungrounded-primary transformers and banks, without any connected line, cable, or capacitor banks. This “self-ferroresonance” phenomenon previously existed only with small banks at 24.9Y/14.4 kV and 34.5Y/19.9 kV (Hopkinson [B71]), but it has now been observed with more efficient 15 kV class banks.

Overvoltage magnitudes from ferroresonance involving grounded-wye padmount transformers on five leg cores can exceed 2.5 pu Underground cable lengths on the order of a few hundred feet are sufficient to create crest voltages of this severity. Self-ferroresonance previously was thought to not occur with these transformers, but more recent testing has shown moderate overvoltages in 24.9Y/14.4 kV and 34.5Y/19.9 kV units for switching at the transformer terminals (Walling et al. [B184]).

Provided sufficient capacitance, compared with the transformer characteristics, is present and the transformer is virtually unloaded (load less than a few percent), the ferroresonant overvoltage can persist for as long as the open-phase condition continues. In practice, the open-phase condition is usually the result of intentional switching by the utility or is due to the operation of a protective device such as a fuse. In the case of intentional phase-by-phase switching of cutouts or load-break elbows, the overvoltages are present until the switching of the last phase is completed. Single-phase protective device (e.g., fuse) operations can result in the open-phase condition being present for an extended period of time. For ferroresonance to be present, however, there should not be a permanent fault on the opened phase, and the transformer should be virtually unloaded on the associated phase(s).

Ferroresonant overvoltages can result in arrester failure. The ferroresonant circuit, however, is a high-impedance source, and gapless metal-oxide arresters limit the voltage while discharging relatively small currents (Walling et al. [B185]). Consequently, the accumulation of energy is usually relatively slow, and an arrester can often withstand exposure to ferroresonant overvoltages for a period of minutes or longer (Short et al. [B164] and Walling et al. [B185]). Arrester TOV curves are based on the application of a strong power-frequency voltage source and do not accurately reflect the ability of metal-oxide surge arresters to withstand ferroresonant overvoltage duty. If the valve elements of an arrester are raised to an excessive temperature by ferroresonant overvoltage exposure, arrester failure is not apparent until the open phase, to which the arrester is connected, is reclosed into the low-impedance system source.

In many cases, the arrester is not overheated by ferroresonance during the brief time required to complete a switching operation. Also, where an arrester has the ability to dissipate the heat to the ambient without an excessive metal-oxide temperature rise, the arrester may survive indefinite exposure to the ferroresonance. With due consideration of the ferroresonant circuit and arrester thermal characteristics, metal-oxide arresters can provide a means for short-term or extended duration limitation of ferroresonant overvoltages in situations where the ferroresonance cannot be easily avoided (Walling et al. [B185]).

6.4.5 Overvoltages caused by backfeed

6.4.5.1 Ungrounded wye-delta banks

Ungrounded wye-delta banks are particularly susceptible to ferroresonant overvoltages. However, ungrounded wye-delta banks have the advantage that, when both single- and three-phase loads need to be serviced, different impedance transformers can be used in the three-phase bank. Zero-sequence currents are eliminated in the primary, particularly during fault conditions.

Ungrounded wye-delta banks present an unusual condition for metal-oxide surge arresters installed on the open phase of the wye with an unbalanced load on the delta secondary. As shown in Annex D, voltages of 2.7 pu, high enough to force the normally applied arrester into thermal runaway, can exist on the open primary by feedback from the secondary. This condition can occur if a three-phase secondary load is removed during work on the system, leaving a single-phase load connected for lighting, refrigeration, and so on. Rather than installing higher rated metal-oxide arresters on these wye-delta banks and thereby jeopardizing equipment protection, the following practices are recommended:

~~a) Balance the load so that the load on each phase of the delta is no more than four times that on each of the other two phases. If nearly balanced three-phase loads are served from a transformer, it is not subject to this overvoltage.~~
~~b) Ground the wye. This would eliminate the problem, but may raise concerns for serving unbalanced three-phase loads and single-phase loads. It also provides a path for zero-sequence currents that may be a problem.~~

a) Close the disconnect last on the phase that has the largest single-phase load.
b) Apply a grounding resistor or reactor in the neutral of the ungrounded-wye windings.
C) Close a neutral grounding switch during the energization of the phases and open it after all three phases have been closed. The neutral switch has to be able to clear the unbalanced load current that may be flowing.

d) Place arresters on the source side, instead of the load side, of circuit interrupters to prevent arrester damage due to the backfeed overvoltage. This connection, however, does not provide protection of the bank from ferroresonant overvoltage (refer to 6.4.4) or the backfeed overvoltage described here. This connection may also reduce the lightning overvoltage protection due to longer lead lengths (refer to 6.6.1).

6.4.5.2 Dual-transformer station

Annex E shows a situation that can lead to overvoltage on surge arresters in dual-transformer substations. Although a single line-to-ground fault on the primary of one transformer is isolated from the HV supply system, the faulted circuit is still energized back through the transformer from the distribution system by the normally closed bus breaker. Surge arresters on the unfaulted phases at the fault location, therefore, see an overvoltage of 1.73 pu because the neutral voltage on the faulted primary is shifted until this breaker is opened.

6.4.6 Distribution system neutral conductors and grounding effect on overvoltage magnitude

A study on the effect of neutral wire size on distribution system overvoltages, which is provided in Annex A of Kershaw et al. [B113], shows that values as high as 1.68 pu can occur on unfaulted phases if the neutral conductor is inadequately grounded throughout the system and the wire size is too small. Although this would be unusual, it can occur when converting an older ungrounded system and emphasizes the importance of good grounding practices during construction and maintenance.

When ground resistivity or system conversion results in a system that is not effectively grounded, special attention has to be given to the TOV capability of the metal-oxide surge arrester. A higher duty-cycle and MCOV rating may be required. It may be better to rebuild part of the system to bring it up to state-of-the-art technology. If the arrester duty-cycle and MCOV rating are increased, then the insulation coordination of the system has to be rechecked to ensure that the required protective margins are still met.

6.4.7 Regulated voltage

Special attention has to be given to the actual voltage on distribution systems. Standards on voltage levels apply only at the metering point of the customer. Out on the distribution circuit, much larger voltage variations are permitted as long as the voltage at the metering point of the customer is within the standard. A study (Burke et al. [B24]) on a random sample of system voltages found some voltages 17% above nominal. Most voltage studies, until recently, did not take into consideration the mutual coupling effect between phases as a result of different load currents in the phases. Some three-phase switched capacitor banks sense only single-phase voltage. This can result in capacitor compensation being added to other phases at a time when they are not in need of voltage correction. Arrester MCOV and actual maximum phase-to-ground voltage have to be taken into account when selecting metal-oxide surge arresters for a specific application.

When regulators are used to control system voltage, special care is required to make sure the MCOV rating of metal-oxide surge arresters is not exceeded. For example, unstable voltage swings may result when three single-phase voltage regulators are installed at an unstable system neutral point. When three single-phase regulators are connected wye, the controls measure line-to-neutral voltage so that, if the neutral is permitted to float, there is no stable reference point from which to excite the regulator controls. Each regulator control will measure this shift and try to correct it. The operation of regulators under these conditions will be erratic.

6.4.8 Non-effectively grounded systems

A system is considered to be noneffectively grounded when the coefficient of grounding exceeds 80%. This value can be exceeded when the system X_0/X_1 ratio is negative or is positive and ≥3 or the system R_0/X_1 ratio is positive and ≥1. Because the temporary overvoltage magnitude for a noneffectively grounded system exceeds that of an effectively grounded system during ground faults, it is common to use a higher voltage rated arrester for the noneffectively grounded system.

Although effectively grounded systems can typically use an arrester with an MCOV rating of about 80% of the system phase-phase voltage, noneffectively grounded systems often require an arrester whose MCOV rating is about 100% of the system phase-phase voltage where ground faults are removed within a few seconds. Such systems might include three- or four-wire systems with the neutral grounded either directly or through a low inductance or resistance. Users should review their system grounding conditions to determine the actual system coefficient of grounding and maximum fault clearing time and compare this against the TOV capability of the intended arrester. There may also be seasonal effects. Systems that may be effectively grounded when there is a high soil water content may change to a noneffectively grounded condition as the water content is reduced. Worst-case temporary overvoltage conditions and maximum fault clearing times should be reviewed to determine the appropriate arrester MCOV (see Figure 12). Ungrounded delta systems and systems with high-resistance grounding and neutral grounding are typically not effectively grounded. If ground faults are not cleared rapidly, such systems may require arresters with a duty-cycle rating of about125% of the system phase-phase voltage to withstand the relatively high overvoltage resulting from neutral shift. High impedance arcing faults that occur on an ungrounded system can result in excessively high overvoltages, greater than phase-phase voltage, and may result in arrester failure.

6.5 Insulation coordination

Distribution system insulation coordination is normally based on the following protective margins:

$$PM_{L1} = \left(\left[\frac{\mathrm{CWW}}{\mathrm{FOW} + L\dfrac{di}{dt}}\right] - 1\right)100\% \tag{29}$$

$$PM_{L2} = \left(\left[\frac{\mathrm{BIL}}{\mathrm{LPL}}\right] - 1\right)100\% \tag{30}$$

where

PM_{L1}	is FOW protective margin (in percent)
PM_{L2}	is full wave protective margin (in percent)
CWW	is chopped wave withstand of protected equipment (in kilovolts)
FOW	is front-of-wave protective level of arrester (in kilovolts)
BIL	is basic impulse insulation level of protected equipment (in
LPL	is lightning protective level of arrester (in kilovolts)
Ldi/dt	is connecting lead wire voltage drop (in kilovolts)—see 6.6.1

For oil-filled, air, and solid (inorganic) insulation, CWW can be assumed to be $1.15 \cdot$ BIL; for dry-type (organic) insulation, the CWW is assumed to be the same as the BIL.

The general rule is that PM_{L1} and PM_{L2} both have to be at least 20%. However, experience with surge protection of distribution systems (15 kV and less) has been gained with protective margins well above 20%, usually exceeding 50%. Separation effects ~~(SE) —~~ are ~~minimized~~diminished by connecting distribution arresters directly across overhead equipment insulation.

The discharge voltage of an arrester is greater for the less frequent, high-current lightning surges~~,~~ and increases with higher rates of rise of the lightning current (Sabot et al. [B158]). It is the usual practice to select a reference value of discharge current that will be exceeded infrequently. The discharge voltage at this reference level is used to calculate PM_{L2}. Obviously, the selection of a higher reference level will result in a smaller PM_{L2} for a given BIL.

There is no universally accepted surge-current level on which to base insulation coordination. Currents in the 10 to 20 kA range are often used, 10 kA for low-flash-density areas and 20 kA (or more) for high-flash- density areas. The range of arrester discharge voltage values at 10 kA (8/20 wave) is shown in the last two columns of Table 9. Reference currents above 20 kA can be considered. This will account for lightning currents with faster rates of rise than the standard test waves used to make discharge voltage measurements (Auer and Schultz [B8]) or where severe lightning is common. (Arrester discharge voltage values can be obtained from the manufacturer for currents greater than 20 kA.) Strict application of the 20% margin rule will then favor the use of arresters with low discharge voltages. PM_{L2} includes an allowance for the voltage developed across arrester connecting lead wires (see 6.6.1). The arrester discharge voltage characteristic to be used for insulation coordination purposes is the total of the arrester discharge voltage plus the connecting lead wire voltage. Maintaining lead wire lengths to be as short as possible is particularly important when protecting underground systems (see 6.7.4 and IEEE Std 1299/C62.22.1™-1996).

6.6 Arrester connections

6.6.1 Effect of connecting leadwires

The discharge of lightning currents through the inductance of connecting lead wires produces a voltage that adds to the arrester discharge voltage. Lead length includes the ground lead length as well as the primary lead. The total length of these leads is measured from the point at which the arrester line connection is made to the point where interconnection is made between the arrester ground lead and the protected equipment ground lead, excluding the arrester length.

The inductance per unit length of the lead is a complex function of the lead geometry. The effect of lead conductor diameter is relatively minor. Tests indicate that an inductance of 1.3 μH/m (0.4 μH/ft) is representative of typical applications. The inductance per length of conductor for a coiled lead will be much greater than this value. For this reason, arrester leads should not be coiled.

Recorded lightning data indicates that the mean rate of current rise is 24.3 kA/μs for first strokes and 39.9 kA/μs for subsequent strokes in a lightning flash (AIEE Committee Report [B1]). The current discharged by a surge arrester may be the entire stroke current if it terminates on the line very close to the arrester location, or it may be a portion of the total stroke current. A lightning stroke terminating more than one span away from any arrester location is likely to result in line flashover. Flashover does not eliminate significant conduction in nearby arresters. This is because a portion of the stroke current will be carried away from the struck location on both the phase and the neutral conductors of a multigrounded distribution line. A significant portion of the stroke current can pass through arresters located within several spans of the line flashover.

The typical current rate-of-rise for distribution insulation coordination is one half of the mean subsequent lightning stroke current rate of rise, or 20 kA/μs. The product of the current rate-of-rise times the total lead inductance is the lead voltage. The lead voltage adds to the arrester discharge voltage only during the rise of the discharge current. The time duration that the protected device is exposed to the sum of the lead voltage and arrester discharge voltage is the rise time of the current. In strokes where the rate of rise is high, the front time will be a maximum of 1–2 μs. Therefore, it is appropriate to coordinate the sum of the lead voltage and arrester discharge voltage with the chopped-wave withstand of the protected device. The discharge voltage, without lead length effects, should also be coordinated with the full-wave withstand of the protected device.

Lead length effects can have a substantial role in distribution insulation coordination. This is illustrated in the following example of a typical 10 kV duty-cycle voltage rated arrester with a 1.83 m (6 ft) total lead length protecting a 95 kV BIL transformer:

Assumed arrester characteristics:

- 37 kV lightning protective level (8/20, 10 kA)
- 41 kV front of wave protective level

Insulation withstand:

- 95 kV full-wave withstand
- 110 kV chopped-wave withstand

The calculated protective margins are as follows:

$$PM_{L1} = \left(\left[\frac{\mathrm{CWW}}{\mathrm{FOW} + \left(1.3\,{}^{\mu\mathrm{H}}\!/_{\mathrm{m}} \times 1.83\,\mathrm{m}\right)\left(20\,{}^{\mathrm{kA}}\!/_{\mu\mathrm{s}}\right)}\right] - 1\right)100 \tag{31}$$

$$\mathrm{PM}_{L1} = \left(\left[\frac{110}{41 + (1.3 \times 1.83)(20)}\right] - 1\right)100 = 24\% \tag{32}$$

$$PM_{L2}\left(\left[\frac{\mathrm{BIL}}{\mathrm{LPL}}\right] - 1\right)100 \tag{33}$$

$$PM_{L2} = \left(\left[\frac{95}{37}\right] - 1\right)100 = 156\% \tag{34}$$

~~Protection of distribution lines~~

~~Distribution arresters are frequently used, instead of overhead shield wires, to protect the distribution lines from flashover resulting from lightning strikes.~~

~~The protection of overhead distribution circuits has been studied, and reports (Task Force Report [B122]; Task Force Report [B123]) have been made regarding the degree of protection afforded by gapped silicon-carbide surge arresters. These reports indicate the number of line flashovers to be expected as a function of arrester spacing along the line, line design, and keraunic level. Similar studies have not yet been made based on the operational characteristics of metal-oxide arresters, but the application of metal-oxide surge arresters should result in an equal or possibly lower, number of outages per circuit mile than that expected using silicon-carbide arresters (Owen [B106]). Arrester ratings employed for circuit protection are the same as those used for equipment protection at the given line voltage level.~~

6.6.2 Effect of separation distance

Distribution arresters are often used to protect a single piece of equipment and therefore should be connected as close as possible to that equipment. This reduces separation effects (see 4.5 and Annex C). Arresters used to protect equipment should not be installed at locations a pole-span away from the equipment to be protected. This is particularly important where only one arrester is used to protect equipment (a transformer) that is connected to a line that runs in two directions from the tap point. In effect, surges approaching from the unprotected side can exceed the protective level of the arrester, diminishing the effectiveness of the arrester, and equipment failure may result. Surges approaching from the arrester side are limited by arrester action, but the separation effect can be very high.

6.6.3 Location of arresters with respect to equipment fuses

Locating an arrester on the source side of a fused cutout often results in very long arrester lead lengths. As presented in 6.6.1, excess lead length can severely impair equipment protection, particularly at the higher distribution voltage classes. Location of the fuse ahead of the arrester, however, requires that the fuse carries arrester discharge current. Nuisance fuse blowing or fuse damage can result. Experience has shown that nuisance fuse blowing is generally limited to fuse links smaller than 15T or 20K (Gaibrois et. al., [B52]).

Some utilities coordinate fuses for transformer overload protection, whereas others consider only coordination with upstream protection. Fuses selected to provide overload protection are often small and are vulnerable to nuisance fuse blowing. Alternatives that allow both overload protection of small transformers and avoid excess arrester lead lengths are as follows:

- Dual-element fuses, which have both low-current sensitivity for overload protection and immunity from lightning discharge currents, applied in cutouts ahead of tank-mounted or internal arresters
- Internal fuses located between the transformer winding and a tank-mounted or internal arrester

Three-phase transformer banks with ungrounded primary connections are subject to overvoltages generated within the bank when one or two phases are disconnected from the source. These overvoltages can be the result of ferroresonance involving the internal capacitance of the transformers (refer to 6.4.4), or in the case of ungrounded wye-delta banks only, the overvoltage can be the result of feedback from the secondary (refer to 6.4.5). The location of the arrester on the source side of the fuse can leave the bank unprotected from these overvoltages if the bank is open phased by fuse operation or cutout operation. Transformer insulation failure has been observed due to ferroresonant overvoltages. The location on the transformer side of the circuit interrupter provides transformer protection, but there is a risk of arrester failure. This risk is primarily limited to ungrounded wye-delta banks with unbalanced secondary loads.

6.6.4 Interconnection of grounds

See Figure 13 and Figure 14.

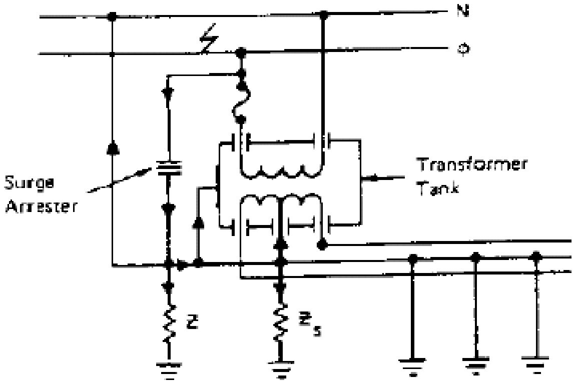


Figure 13—Arrester protection with solid interconnection

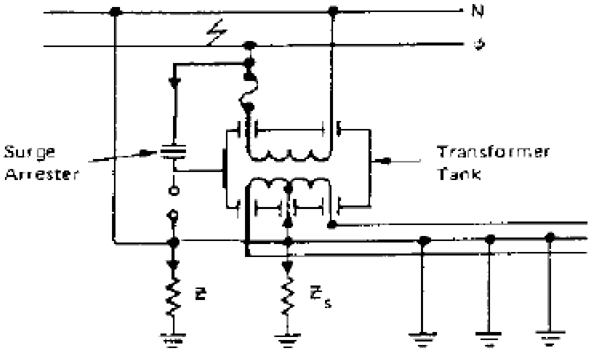


Figure 14—Arrester protection with interconnection through gaps

6.6.4.1 Primary and secondary ground

It is recommended that primary and secondary grounds of the distribution transformer be interconnected with the arrester ground terminal.

6.6.4.2 Tanks, hardware, and support structures

Where possible and where local regulations permit, ground connections should be made to the tanks of transformers, reclosers, capacitor support frames, and all hardware associated with the protected equipment (Figure 13).

6.6.4.3 Protective gaps

Where regulations do not allow grounding of equipment support structures, protective gaps should be connected between the arrester ground terminal and the structure. Transformer-mounted arresters are grounded to the transformer tank, and the tank can be isolated from ground by inserting the protective gap between the transformer tank and the ground (Figure 14).

~~6.7.4.4 Clearances of arresters to energized conductors and equipment and to grounds~~

~~For proper insulation coordination, distribution arresters should be installed to maintain, as a minimum, the clearances listed~~ in Table ~~10. Regulations or other considerations may dictate larger clearances in exposed locations. The listed clearances are suitable for arresters in metal enclosures~~.

~~Table 10 Recommended minimum clearances~~

~~Arrester duty cycle voltage rating (kV rms)~~	~~Surge arrester housing BIL (kV crest)~~[a]	~~Recommended minimum clearances [in. (mm)]~~[b]	
		~~To grounds~~	~~Between phases~~
~~3~~	~~45~~	~~1-3/4 (45)~~	~~2 (51)~~
~~6~~	~~60~~	~~2-3/4 (70)~~	~~3-1/4 (83)~~
~~9~~	~~75~~	~~4 (102)~~	~~4-3/4 (121)~~
~~10~~	~~75~~	~~4 (102)~~	~~4-3/4 (121)~~
~~12~~	~~85~~	~~4-3/4 (121)~~	~~5-1/2 (140)~~
~~15~~	~~95~~	~~5-1/2 (140)~~	~~6-1/2 (165)~~
~~18~~	~~125~~	~~8 (203)~~	~~9 (229)~~
~~21~~	~~125~~	~~8 (203)~~	~~9 (229)~~

~~24~~	~~150~~	~~9-1/2 (241)~~	~~11 (279)~~
~~27~~	~~150~~	~~9-1/2 (241)~~	~~11 (279)~~
~~30~~	~~150~~	~~9-1/2 (241)~~	~~11 (279)~~

~~[a]Clearances measured from metal parts of arrester line terminal and dictated by minimum flashover to maintain BIL in accordance with IEEE Std C62.11-1993, and to allow for the bias effect of 60 Hz voltage between adjacent phases. Air insulation between arrester wall(s) or between arresters is assumed. Minimum clearances required between bottom stud on arrester and enclosure floor need be only that required to install ground connection and to provide sufficient space for free operation of the arrester disconnector, if used. [b]1.2/50 full-wave BIL per Table 2 in IEEE Std C62.11-1993.~~

6.6.4.4Arrester clearance requirements

The recommended clearances of arresters to energized conductors and to grounds

6.7 Special applications

6.7.1 Protection of capacitor banks

Pole-mounted shunt capacitor banks may be protected by line-to-ground connection of arresters mounted on the same pole as the bank. Connections should be as outlined in 6.6 (refer also to 5.5). The ratings of arresters used are usually the same as used elsewhere on the system.

Capacitor banks connected grounded-wye can be charged to high voltages by lightning currents. When protected by metal-oxide surge arresters, these capacitor banks can only be charged to the protective level of the arrester. The stroke current will then be shared by the arrester and bank for the duration of the stroke current. At the completion of the stroke current, the arrester will cease to conduct, leaving some charge on the capacitors. As a result, energy dissipated by the arrester may be less than it would have been for a silicon-carbide arrester.

Arrester operation on ungrounded banks is usually caused by a high transient voltage transmitted from the line to the bank, developing between neutral and ground, such that relatively little of the transient energy is added to the stored energy in the capacitors. Therefore, no special high-energy capability is required for arresters protecting ungrounded capacitor banks against lightning surges.

If a capacitor bank is switched, then arresters having high-energy absorption capability may be required regardless of the circuit configuration. Surge arresters applied to switched capacitor banks can be exposed to high-energy surges if restriking of the switching device occurs when the bank is being deenergized. In the case of an ungrounded capacitor bank, a two-phase restrike can cause excessive current to flow in both arresters associated with the restruck phases. Arresters on either side of the switching device can experience high-energy switching transients. The arrester manufacturer should be consulted for aid in selecting arresters suitable for this duty.

6.7.2 Protection of switches, reclosers, sectionalizers, and so on

Switches operated in the open position should be protected by arresters at both sides of the switch. The special case of switches in an underground system is covered in 6.7.4.

Reclosers are best protected by installing arresters on both the source and the load side. However, some reclosers are designed with a built-in bypass protector across the series coils. A fair degree of protection may therefore be obtained, assuming normal operation of the reclosers in the closed position, by applying one arrester from line to ground on the source side. However, it should be recognized that there is some risk of lightning damage when the recloser is open for any reason.

The arresters usually have the same rating as those used in other parts of the system. Connections should follow the recommendations outlined in 6.6.

6.7.3 Protection of regulators and series apparatus

6.7.3.1 Line voltage regulators

Voltage regulators connected to exposed circuits should be protected on both line and load sides with the same arresters used on other distribution apparatus. For the most effective protection, the arrester should be mounted on the tank with the arrester ground connected to the tank. The series winding is usually protected with an arrester selected by the regulator manufacturer and connected between the source and load bushings, or on winding terminals inside the tank.

6.7.3.2 Bus voltage regulators

Bus voltage regulators at substations are often protected by station- or intermediate-class arresters on the substation bus or on the substation transformer low-voltage bushings, and by distribution arresters adjacent to the substation on the outgoing feeders. The series winding is protected by arresters selected by the manufacturer of the regulator. The series winding arrester can get inordinate operating duty because a disproportionate share of the incoming current is discharged by the station arrester as a result of its low discharge voltage characteristic. In order to prevent premature failure of the series winding, it is recommended that at least intermediate arresters with lower discharge voltage characteristics be substituted for the distribution arresters on the outgoing line terminals.

6.7.3.3 Series current-limiting reactors

Unless coil protection is built into a current-limiting reactor by the manufacturer, an arrester connected from terminal to terminal can be installed to prevent overvoltages due to incoming surges. In addition, an arrester connected between line and ground should be installed on the source side of the reactor. In all cases, the reactor manufacturer should be consulted.

6.7.3.4 Autotransformers

The remarks on series windings of regulators are generally applicable to autotransformers where the voltage across the series winding is small compared with the common winding ($<$-25%). For other applications, arresters at the high-voltage and low-voltage terminals with the arrester interconnection to the transformer tank will be adequate.

6.7.4 Protection of equipment on underground systems (including cables)

Underground sections of the distribution system usually take the form of relatively short cable runs to transformers or that of long loops that are open at the center. For longer cable lengths, equipment such as transformers or switchgear is installed along the entire cable length. In either case, the system can basically be described as a length of cable terminated by an open point.

Surge voltages enter the underground system from the overhead feeder at the riser pole. The magnitude of surge voltage entering the cable is limited by the arrester on the riser pole. However, surge voltage in excess of the protective level of the riser pole arresters can occur on the cable and at equipment locations remote from the riser pole because of amplification by reflection from the open point (Owen [B147]).

Most problems associated with protection of underground systems result from the practical difficulties involved in locating arresters as close as desired to terminating points or points where substantial changes in surge impedance occur in the underground system. Sometimes, consideration has to be given to the installation of arresters on underground transformers to provide adequate protective e margins (Miller and Westrom [B138]; Owen [B147]; and Owen and Clinkenbeard [B148]). Recent developments in elbow and liquid-immersed arresters make individual equipment protection practical. When it is possible to install arresters at equipment locations, application procedures are similar to those used for protection of overhead equipment. When it is not possible to install arresters at individual equipment locations in the underground system, protection is usually provided by arresters located at the junction of the overhead line conductors and the underground system cables. IEEE Std 1299/C62.22.1-1996 provides recommendations on the installation of surge arresters at the underground cable junction with overhead line.

For system voltages of 15 kV and below, and where the arrester leads between the overhead line and the cable sheath are short [< 1.6 m (5 ft)], the use of a distribution arrester at the riser pole generally will provide an adequate margin of protection for cable-connected equipment. For 25 kV system voltages, an arrester with lower discharge voltage than a distribution arrester may have to be used. Other possibilities are discussed in (IEEE Working Group Report [B100] and Kershaw [B110], [B111]). For 28 kV and 34.5 kV systems, arresters at the riser pole only will not provide adequate protection, and the use of one or more arresters installed on the cable circuit is necessary.

When arrester protection is provided at the riser pole only, the voltage held at the riser pole by a gapless metal-oxide surge arrester is the sum of the arrester discharge voltage and the inductive voltage drop in the arrester connecting leads (Kershaw and Clinkenbeard [B112]) (see 6.6.1). This voltage propagates into the cable circuit and can approach double its value on the cable and at connected transformers because of the reflections at points such as open switches and terminating transformers. The following rules (Owen [B147]) are directed toward determining the voltages at terminations to permit the calculation of protective margins:

a) Assume no attenuation. This assumption becomes conservative for cable lengths greater than 900 m (3000 ft ~~(900 m~~) (Valentine et al. [B179]).

b) Assume the incident voltages will double at open points and terminating transformers.

c) Assume that a significant number of lightning surge currents will have faster rise times than the 8 μs used for published discharge voltage characteristics. Discharge voltages can be significantly higher under these conditions.

d) Use a 10 kA crest surge when considering protection schemes for a shielded system and a 20 kA crest surge for an unshielded system.

e) Calculate inductive voltage drop in an arrester connecting lead from:

Total voltage = lead length (m or ft) × lead inductance (L) × rate of rise factor (*di/dt*)

Where L is 1.3 μH/m or 0.4 μH/ft, and the rate of rise factor (*di/dt*) is calculated by dividing the crest current by the time to crest (i.e., *di/dt* for a 10 kA impulse cresting in 8 μs is 1.25; *di/dt* for a 10 kA impulse cresting in 1 μs is 10).

The inductive voltage will vary as a function of current magnitude and current impulse rate of rise. At 10 kA with a rise time of 8 μs, the inductive voltage is about 1.625 kV/m (0.5 kV/ft). Also, at 10 kA, the inductive voltage can be as high as 13 kV/m (4 kV/ft) when the rise time is 1 μs. A 20 kA surge will double the above voltages. Leads should be kept as short as possible. Even with the best arrester at the riser pole, the system will not be protected if the leads are long.

For gapless arresters, compare the doubled sum of the FOW protective level and the connecting lead voltage with CWW (assumed to be 1.15 BIL) for liquid-filled transformers and with BIL for dry-type transformers and cables.

For gapped arresters, compare the greater of:

Doubled FOW protective level (if determined by sparkover)~~; or~~
Doubled sum of FOW protective level (if determined by discharge voltage) and connecting lead voltage with CWW for liquid-filled transformers and with BIL for dry-type transformers and cables

For both gapless and gapped arresters, compare the doubled sum of the discharge voltage, at the assumed discharge current, and the connecting lead voltage with transformer and cable BIL. Then, using a recommended protective margin of 20%:

Oil insulation: CWW ≥ 1.2 × 2 × FOW
Dry insulation: BIL ≥ 1.2 × 2 × FOW
Both insulations: BIL ≥ 1.2 × 2 × LPL

f) Example: A 10 kV duty-cycle-rated riser pole type arrester is chosen to protect a 15 kV class underground distribution system. The BIL of the system is equal to 95 kV. Assume that the arrester has 1.52 m of lead and that the current surge through the arrester at the riser pole is 10 kA with a 1 μs rise time.

$$\text{Maximum surge voltage} = 2 \times (\text{FOW} + 1.52\ \text{m}\ (L\ di/dt)) \qquad (35)$$

Using a common value for the FOW protective level, this becomes:

$$\text{Maximum surge voltage} = 2 \times (29\ \text{kV} + 1.52\ \text{m}\ (13\ \text{kV/m})) = 98\ \text{kV} \qquad (36)$$

This shows that even on a 15 kV system, the insulation may not be adequately protected with an arrester at the riser pole only.

Another protection method is to use an arrester at the riser pole and a second arrester at the remote end of the cable, which is a reflection point for the traveling wave. The voltage at the reflection point will be limited to the discharge voltage of the remote arrester at a current of less than one fourth of the current through the riser pole arrester (unless the cable is very short) (Miller and Westrom [B138]; Owen and Clinkenbeard [B148]). Because the remote arrester appears as an open circuit until it becomes conductive, it permits the reflection of a portion of the incoming wavefront, which is then superimposed on the approaching surge voltage wave. Therefore, the voltage at intermediate points in the cable circuit will usually be higher than at either end. The maximum voltage at intermediate points will be the protective level of the riser pole arrester (discharge voltage plus lead voltage drop), plus some fraction of the discharge voltage of the reflection point arrester. A conservative number to use for coordination is the discharge voltage of the riser pole arrester plus one half of the 1.5 kA discharge voltage of the reflection point arrester. (The 1.5 kA value is obtainable from the published literature of the manufacturer and, because of the nonlinear characteristics of metal-oxide valve elements, will yield a value very close to one-fourth of any assumed current through the riser pole arrester.) A computer simulation of this effect can be found in Smith et al. [B166].

The effectiveness of the previous method can be substantially improved by installing a single arrester at an equipment location about 100 m (300 ft) or more upstream from the open-point termination. This midcircuit arrester will suppress the reflected surge as it is being superimposed on the incoming surge voltage wave. A significant distance is necessary for recombination of surge voltages with longer rise times (Lat [B117]). The protective level between the riser pole and the midcircuit arrester will be the greater of the protective level of the riser pole arrester or the discharge voltage of the reflection-point arrester. The protective level in the cable between the reflection-point arrester and the midcircuit arrester is as in the previous example. Equipment connected between the reflection-point arrester and the midcircuit arrester may need individual arrester protection.

The most effective protection method is to install arresters at the riser pole, at the open point, and at each underground equipment location. The voltage on each piece of equipment will be held to the low-current discharge voltage of its arrester, and only the section of cable between the open point and the first upstream arrester will see a higher surge voltage.

The surge energy, or duty, discharged by an arrester installed on an underground system is controlled by the exposure of the arrester at the riser pole and is usually a small fraction of the energy discharged by the riser pole arrester. For arresters with identical discharge voltage characteristics, the arrester in the cable system will discharge only about 20% of the total surge current (Owen and Clinkenbeard [B148]). The use of arresters at the riser pole with lower discharge voltage, riser pole type, or intermediate class will further reduce the magnitude of surge current discharged by the underground arresters by themselves discharging a larger proportion of the surge current.

When control of transients to lower values is desired to prolong cable life, arresters with lower discharge voltage characteristics, or possibly elbow or liquid-immersed arresters, can be used.

Although not yet proven effective, such applications have been made when “treeing” has been suspected of decreasing cable life.

Arresters installed directly on underground equipment may be either elbow arresters (for dead front equipment) or base- or bracket-mounted arresters (if equipment has mounting provisions). Also, liquid- immersed arresters are available mounted inside the transformers.

6.7.5 Contaminated atmospheres

Surveys (IEEE Working Group Report [B99]) have shown that failures of gapped silicon-carbide arresters due to operation in contaminated atmospheres are ~~quite~~ rare. Because metal-oxide distribution arresters are usually constructed without internal gaps, internally induced failures of these arresters due to external contamination should not be a factor. However, external failure (flashover) of the arrester housing may occur from the combined effect of accumulation of contaminants on the arrester and conditions of wet snow, frost, light rain, or fog.

The usual solution is periodic cleaning of the housing. In a few cases, application of nonconducting, nontracking, water-repellent greases to the insulating surfaces has been used. Overinsulating the arrester housings has also been used effectively to reduce the effects of external contamination.

6.7.6 Low-side (secondary) surges

Surges impressed on the secondary terminals of transformers can result in failure of the primary or secondary winding insulation.

Relatively small surge currents into the center tap of 120/240 V secondary windings can induce high primary winding layer-to-layer voltages. This secondary surge phenomenon is a major cause of distribution transformer failures (IEEE Transformer Committee Task Force Report [B91]). Interlaced transformer windings are believed to be less susceptible to this failure mode. Adequate secondary-side surge protection applied on non-interlaced transformers is believed to provide the same level of protection. There has been much industry debate regarding the impact of secondary surges on interlaced and noninterlaced distribution transformer designs. The phenomena are discussed in detail in Dugan and Smith [B43] and in the IEEE Transformer Committee Task Force Report [B91].

Lightning strikes to either the primary or the secondary system can produce secondary surges. Strikes to the primary system elevate the transformer secondary neutral potential above the neutral potential at the customer service, forcing surge current into the transformer. The configuration of the secondary system will affect the magnitude and characteristics of surges impressed on the transformer secondary. The relative impedances of customer service ground and transformer ground have a substantial effect on secondary surge current magnitudes. Open-wire service drops allow greater secondary surge currents to flow compared with a triplex service drop, due to decreased mutual coupling between the conductors.

Secondary surges can also occur as a result of direct strokes to the secondary service conductors or the connected load. Field coupling and ground potential rise will also induce secondary surges if lightning strikes nearby objects such as trees and structures. Surges impressed on the primary winding of the transformer also are reflected to the secondary by inductive and capacitive coupling, although this is not usually of concern to the integrity of the transformer secondary winding insulator (Barker et al. [B13]; Dugan and Smith [B43]; and IEEE Transformer Committee Task Force Report [B91]).

6.7.7 Protection of transformers from low side surges

Secondary winding protection can be achieved through the use of metal-oxide arresters or spark gaps located at the secondary terminals of the transformer (connected between each leg and neutral). The BIL of distribution secondary windings is 30 kV according to IEEE Std C57.12.00-2000, so it is relatively easy to coordinate the insulation withstand with the surge arrester protective level. Transformers on the underground distribution system are just as vulnerable to secondary surges as overhead transformers and are candidates for secondary arrester protection.

Several references (Dugan et al. [B42]; Dugan and Smith [B43]; IEEE Transformer Committee Task Force Report [B91]) recommend using either spark gaps or metal-oxide secondary arresters with a protective level of 4 kV to 6 kV for the transformer secondary in cases where the transformer may be exposed to a high level of surge activity (see Figure 15). There is considerable controversy on the need for secondary arresters. Some industry experts feel that transformers with interlaced secondary windings do not need secondary arresters to maintain reasonable service reliability (McMillen et al. [B134]). Because the transformer is located in an exposed environment relative to typical indoor or customer load applications, a surge protective device that is suitable for indoor or customer service applications may (and will likely) not have sufficient energy handling capability for an outdoor distribution transformer appli~~-~~cation. Only suitable secondary devices that meet the requirements per IEEE Std C62.34™-1996 should be utilized at the transformer. The surge arrester utilized at the transformer should have an MCOV and TOV capability that exceeds the maximum sustained and/or temporary secondary voltages, which can be expected at the transformer.

Where possible, the transformer secondary neutral terminal should be bonded to the primary neutral, which also should be bonded to the tank. This is very important because severe voltage potentials can develop between the secondary and primary windings during lightning surges, which can cause transformer failure even though all windings have arresters connected across the terminals.

Studies suggest that the use of secondary arresters at the distribution transformer, while ~~quite~~ effective in protecting the transformer, may actually increase the surge voltage that reaches the customer service connection (Dugan and Smith [B43]; IEEE Transformer Committee Task Force Report [B91]). As a result of this phenomena, some utilities install secondary protection at both the distribution transformer and the customer service entrance. Note that a secondary arrester at the customer service would generally have a much lower protective level than that which is recommended for the transformer because customer appliances can be damaged at surge voltages much less than 4 kV.

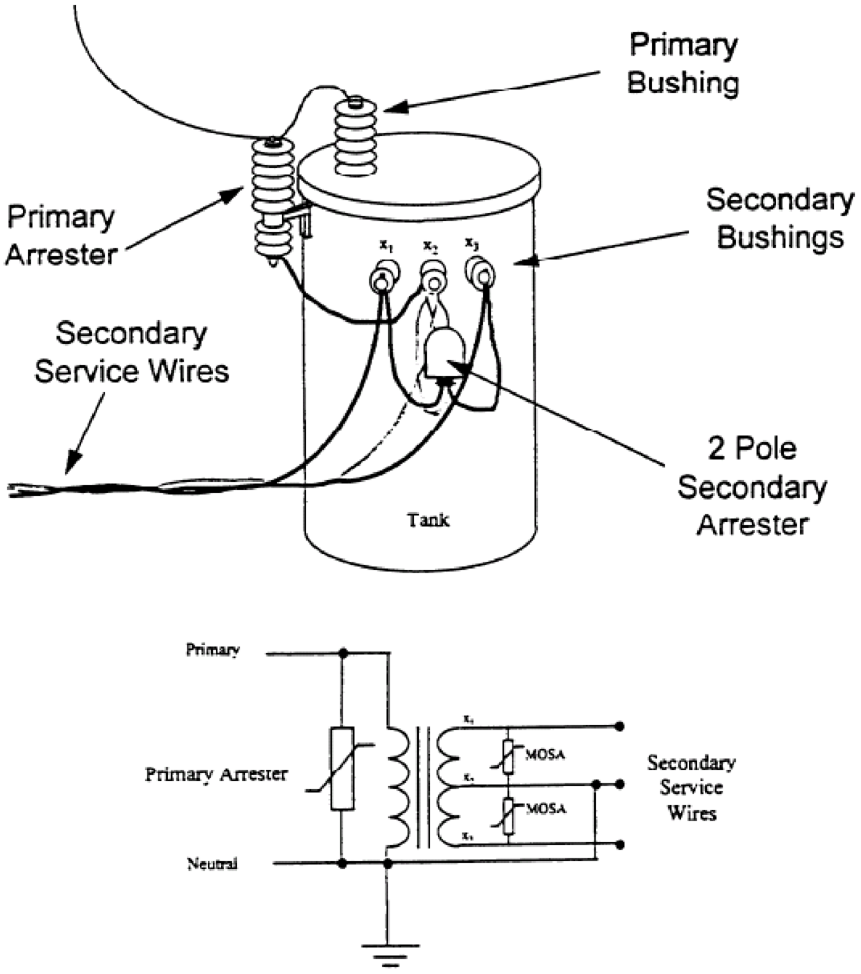


Figure 15—Typical transformer secondary surge protection

6.8 Isolation

6.8.1 Disconnectors and external gaps

Distribution arresters are sometimes furnished with external gaps that are placed between the line lead and the arrester terminal. Other arresters may be provided with disconnectors, which are usually mounted on the ground terminal of the arrester and connected between the ground terminal and the ground lead. The purpose of both devices is to isolate a failed arrester from the distribution system. In each case, a system fuse, recloser, or circuit breaker may operate to clear the fault if the arrester fails.

In the case of an arrester equipped with an external isolating gap, a failed, but intact, arrester remains connected to the system and continues to provide some measure of protection for the transformer on subsequent lightning surges. However, detection of a failed arrester from ground level may be difficult, but close inspection will usually reveal a burn mark or bubble of metal on the arcing horn from the passage of an abnormally high power-frequency current.

In the case of an arrester equipped with a disconnector, operation of the disconnector physically separates the arrester ground connection from the failed arrester and thus gives a visual indication of failure. Surge protection for the transformer is no longer provided. Care has to be taken to provide enough clearance ~~to ensure~~so that the separated ground lead is not thrown into an energized conductor. The ground lead should be flexible enough to allow the disconnector to separate from the arrester.

6.8.2 Current-limiting fuses

Current-limiting fuses are used to protect and isolate faulted distribution equipment as well as some single- and three-phase laterals. The principal advantage of these fuses is their ability to limit the let-through fault current (fault energy).

Because some current-limiting fuses can generate high arc voltage with peak magnitudes exceeding system voltage, ~~care~~ there should be ~~exercised to ensure~~ proper coordination between the fuse and the source-side arrester. Although experience with these applications for metal-oxide arresters is limited, distribution arrester dam~~-~~age as a result of current-limiting fuse operation has not been an application problem. In the event that arrester damage does occur, an arrester with a higher MCOV rating than would normally be applied could be required (i.e., conduction would start at higher arc voltages, reducing the number of arrester operations and, therefore, reducing the duty on the arrester). Should conduction occur, the energy (joules/kilovolts of rating) dissipated by the arrester would be reduced.

Additional information on the effects of current-limiting fuses can be found in a report by the IEEE Switchgear Committee and Surge Protective Devices Committee Working Group [B90]; Kershaw et al. [B114]; and Olive and Westrom [B144].

7. Protection of overhead lines

This clause addresses the use of surge arresters to protect overhead transmission and distribution lines.

7.1 General considerations

Many lightning and circuit response characteristics are common to both transmission and distribution line arrester applications. The behavior of insulation, grounding, arresters, and conductors is quite similar in both cases. The lightning environment is the same in both cases, although line height and right-of-way characteristics may affect the distribution of strokes that actually terminate on a line. Overhead shield wires have traditionally been used on transmission lines, but they have also been used on distribution lines. Likewise, the multigrounded neutral conductor has been typical of many distribution lines, but a transmission line with underbuilt distribution may have similar characteristics. The material, common to both transmission and distribution line lightning protection, is presented in this clause. Material specific to transmission lines is presented in 7.2, along with switching surge protection. Material specific to distribution lines is presented in 7.3.

7.1.1 Line insulation characteristics and performance metrics

Overhead line insulation is generally self-restoring. It is common and appropriate to use the CFO, at which a 50% probability of flashover exists. Because the S curve describing the insulation strength is so steep (low value of σ/CFO), it is common to take the CFO as a single-valued line insulation strength. That is, the probability of flashover is 0% for crest voltages less than the CFO, and 100% for crest voltages greater than the CFO. For switching surges, the σ/CFO value is higher, and the flashover probability should be treated as a function of voltage. The line insulation strength is also a function of the wave front and tail. In system studies of arrester applications, these time-dependent effects should be modeled using a volt-time curve, a destructive effect model, or a leader progression model (CIGRE Working Group [B29]). With self- restoring line insulation, it is not appropriate to use a fixed coordination current to calculate protective margins. Instead, the probability distribution of lightning stroke currents is applied to the line, and the probability of flashover is calculated. Combined with local ground flash density, this will produce a lightning flashover rate per unit length per year. This flashover rate is the lightning performance metric for the line. For transmission lines, a typical target might be 1 flashover per 100 miles per year. For distribution lines, a reasonable target may be somewhat higher. The effect of a flashover depends on protective relaying practices and on the possibility of arc quenching by wood. With line arrester applications, the arrester failure rate should also be considered in the line performance.

7.1.2 Lightning flashovers on overhead lines

Lightning flashovers are segregated into three main types, for stroke locations on a phase conductor, on an overhead shield wire, or to nearby ground.

7.1.2.1 Shielding failure flashovers

These events result from a lightning stroke terminating directly on a phase conductor. For shielded lines, these events should be very infrequent and of very low stroke current magnitude. For unshielded lines, these events will be much more common and will involve the full distribution of lightning stroke current magnitudes. Arresters can be used to address shielding failure flashovers by applying the arresters on the exposed phases. The arresters must be installed at every tower or pole to be effective at preventing shielding failure flashovers. For unshielded line applications, arrester energy requirements must be adequately addressed, since the stroke currents and durations, to which they will be exposed, are harsher than in shielded line applications.

7.1.2.2 Back flashovers

These events result from a lightning stroke terminating on the ground system (i.e., shield wires, tower tops, and pole tops) causing a potential across the insulation that causes a flashover to occur. The surge traveling on the shield wire will cause surge voltages to be induced in the phase conductors. The magnitude of the induced voltage is a function of the current magnitude, resistance, and geometry (Anderson [B4]). Stroke currents exceeding a critical current value will develop sufficient voltage between the structure and the phase conductor to cause an insulator flashover. The phase with the poorest coupling to the shield wire will be the most highly stressed and therefore most likely to flash over. Local grounding conditions have a major impact on back flashover performance. Arresters can be used to address these types of outages by placing them on the least coupled phases (e.g., bottom phases) or in high footing resistance areas. For applications in high footing resistance areas, it is important to apply the arresters not only in the areas of high footing resistances but also one or two structures away from the high footing resistance areas (Shih et al. [B162]).

7.1.2.3 Induced voltage flashovers

These events result from nearby lightning strokes inducing voltages on line conductors. Because the induced overvoltages measured on distribution lines rarely exceed 300 kV, it is common belief that this phenomenon has little effect at transmission voltage levels. However, the induced voltages tend to increase with line height. There may be some structures used at 34.5 kV through 69 kV (sometimes referred to as "subtransmission" voltages) that could be susceptible to induced voltage flashovers from nearby lightning strokes. For lines that are susceptible to induced voltage flashovers, arresters at relatively wide spacing may be used to reduce the effects of these events.

7.1.3 Special considerations related to standards and specifications

Line arresters are not specifically addressed in IEEE Std C62.11-2005, although the arresters used in these applications are part of the standard. Most of the test requirements that apply to line arresters are based on station requirements or distribution class requirements. When specifying line arresters, it should be noted that the following points are inherent to IEEE Std C62.11-2005:

a) Lightning energy handling capability can be a major factor in selecting line arresters, depending on their application. The requirement of lightning-related energy is typically much more significant for lines than stations. Although present standards do contain some lightning-related tests, there is not presently an accepted test to quantify the lightning energy handling capability of surge arresters. Published energy handling capability of arresters is typically based on switching-related tests.

b) Heavy-duty distribution arresters may be subjected to more severe lightning-related tests than station class or intermediate class arresters. Although it is common belief that arrester lightning energy capabilities increase from heavy-duty distribution to intermediate to station, the present standards do not necessarily prove this through testing.

c) The 100 kA test for heavy-duty distribution arresters should not be confused with an arrester surviving a 100 kA lightning stroke. First, the 100 kA test is a 4/10 wave that has much less energy than a typical 100 kA lightning stroke. Second, the 100 kA tests allow up to 5 min before the arrester is connected to MCOV to prove thermal stability.

d) Short-circuit tests permit polymer arresters to fall apart as long as the pieces fall within specific areas. The tests allow 2 min before the arrester must self-extinguish. These allowances in the present standards may not be acceptable for certain areas on a line right of way.

7.1.4 Effects of a shield wire

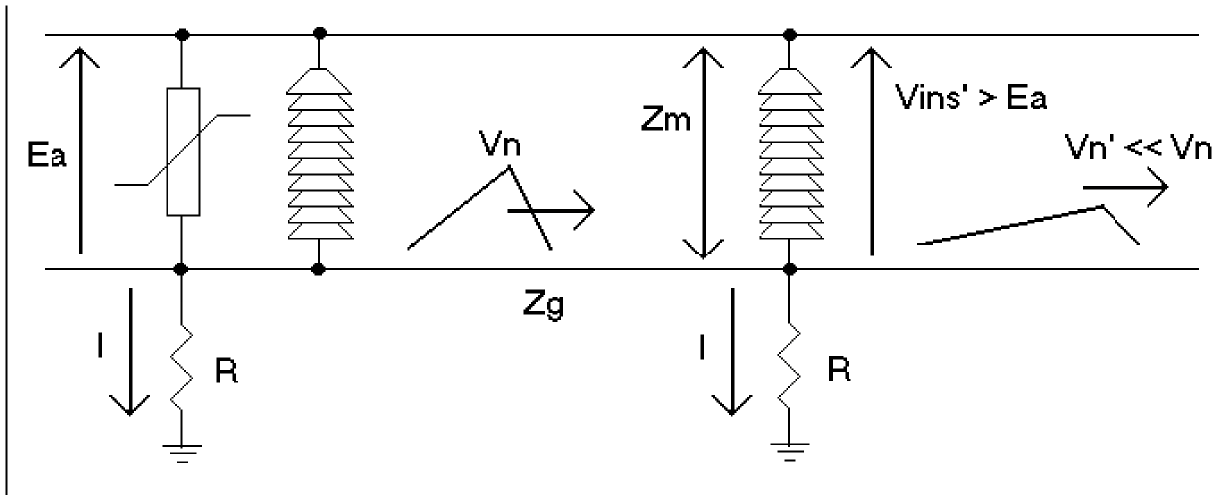
When a stroke terminates on the phase conductor, most of the current will discharge to ground through the nearest line arrester. Adjacent arresters will discharge some of the energy, limited by the span inductance. If the struck pole or tower ground resistance is reduced due to soil ionization, the energy sharing is less effective. There is no energy sharing to account for on the tail of the surge, due to the very high nonlinearity of the V-I characteristics of the line arresters for lower current amplitudes.

An overhead shield wire is designed to intercept most lightning strokes that would otherwise hit the phase conductors. Most of the current will discharge through the tower and pole grounds, with relatively little current flowing through any line arresters. This reduces the energy duty on the line arresters. Some lightning strokes may terminate directly on a phase conductor, but these should have low current magnitudes (5 kA to 20 kA) according to the present theory of shielding. Therefore, line arresters may be
applied to shielded lines to improve the back flashover performance, with little concern for energy duty on the arresters (Tarasiewicz et al. [B173]).

7.1.5 Effects of ground resistance

It is almost an article of faith among power system engineers that ground resistances should be kept as low as possible. For shielded lines with no line arresters, it is generally true that lower ground resistance at the towers and poles will improve the backflash performance. When line arresters are applied, however, a lower ground resistance may have no impact on the lightning performance, and in some cases, they may worsen the lightning performance. These paradoxes can occur because the arrester is protecting insulation between two conductors, and the grounding connection is external to the arrester-insulation loop circuit. Grounding can also adversely affect the current flows through the arresters, especially if there are differences in the ground resistance between adjacent towers or poles.

In Figure 16, a stroke to the pole with an arrester results in most of the current discharging through the pole ground, with coupled surges traveling to the next pole. The voltage across insulation at the struck pole is held to the arrester discharge voltage, E_a, ignoring lead length. At the next pole, most of the remaining current on the neutral conductor discharges through the pole ground, which reduces the voltage on the neutral conductor. By coupling, the voltage on the phase conductor is also reduced by a lesser amount.



The insulator voltage at the next pole in Figure 16 is as follows:

$$V'_{ins} = E_a + V_n\left[1 - {(2R+Z_m)}\big/{(2R+Z_g)}\right] \tag{37}$$

However, the voltage between the two conductors, which is the insulation stress, increases above the arrester discharge voltage. The situation is worse when the adjacent pole ground resistance decreases.

For example, let E_a = 40 kV, Z_m = 179.82 ∧, Z_g = 428.48 ∧, and V_n = 1000 kV. Then the adjacent insulator voltage as a function of ground resistance is given in Table 11.

Table 11 —Adjacent insulator voltage as a function of ground resistance

R **[∧]**	***V'***$_{ins}$ **[kV]**
–	40
1000	142
100	436
25	560
0	620

The insulation stress has been transferred to the adjacent pole that has no arrester. This phenomenon is the reason for at least two important application guidelines, as follows:

a) If line arresters are applied only on a section of line with poor grounds, then they must also be applied on at least the next one or two towers that have good grounds.

b) Some distribution poles may have a grounded neutral conductor with no existing arresters protecting a transformer, riser pole, or other equipment. These poles are good candidates for line arresters to improve the flashover rate.

This effect does not justify a lack of attention to grounding, because there are other reasons to keep the ground resistance low. It simply illustrates that one cannot always rely on lower ground resistance to improve the lightning performance of an overhead line with arresters.

7.1.6 Disconnector devices

The risk of a line arrester failing due to excessive energies from lightning strokes is higher than for applications in substations. Although the failure rate of these arresters is low, the user should consider that arresters typically fail in a short-circuit mode. After failure, the arresters should be disconnected from the line to allow for successful line reclosing.

Line arresters hanging directly on the line usually have the disconnector mounted on the ground terminal of the arrester and connected between the ground terminal and the ground lead. Line arresters mounted directly in the tower or parallel to insulators typically have the disconnector mounted on the high-voltage clamp between the high-voltage terminal and the line clamp. Operation of the disconnector physically separates the arrester ground connection from the failed arrester and gives a visual indication of failure. The ground lead should be flexible enough to allow the disconnector to separate from the arrester. Care must be taken to provide both enough clearance of the shorted arrester and to keep the separated ground lead from being thrown into an energized conductor.

7.1.7 Analytical methods

Most line arrester applications for lightning protection should be studied with computer simulation. Studies are especially recommended when:

a) Energy duty is of concern, as will be the case for unshielded lines. b) Only certain sections of

a line will be protected with arresters.

c) Only the top phase, or only the bottom phases, will be protected with arresters. d) Circuits of

different voltage levels are on the same tower or pole.

e) Only one circuit of a multicircuit line will be protected with arresters.

The IEEE Working Group on Estimating the Lightning Performance of Transmission Lines [B89] provides a free software package that can simulate shielding and backflash performance, but it does not currently simulate line arresters. Some users may have access to a commercial software package tailored to lightning

performance simulation, including arrester effects. For most, however, the EMTP, the Alternative Transients Program (ATP), or a similar package is the best choice. The EMTP/ATP is widely available, and knowledge of its application is also widespread. Results from EMTP/ATP will also be replicable by the arrester manufacturer in case of questions about the arrester energy duty; this may not be true of a commercial program.

The EMTP/ATP model should begin with at least 10 pole or tower spans and possibly more. The line model can begin with a constant-parameter modal transformation calculated at high frequency, with all phase conductors and shield wires retained. All modal propagation velocities are near the speed of light in this model. Second-order effects like frequency dependence and corona may be added later. However, attention should be given to insulator time dependence and ground resistance dependence on both time and current magnitude.

It is not possible to do the study with a single coordination current magnitude, nor is it possible to linearly scale the performance results with current magnitude. Instead, many EMTP/ATP cases must be run to determine a critical current level for both flashovers, and arrester energy duty. The critical currents are also likely to depend on the struck conductor. The electro-geometric model can be used to estimate the relative frequency at which each conductor is struck (IEEE Std 1243™-1997 [B82] and IEEE Std 1410™-2004 [B83]). These results may be used with stroke current probability distributions and ground flash density to obtain flashover and arrester failure rates (Hileman [B65] and Stenstrom and Lundquist [B170]). To calculate arrester energy discharge from realistic lightning wave shapes, the simulation must run for several hundred microseconds. Even if the stroke current is modeled with an exponential tail, the arrester current will extinguish at a time dependent on the discharge characteristic and the alternative ground paths. The simulation time step for this energy calculation could be as long as the span travel time. Shorter time steps must be used for the flashover calculation, but these simulations only need to run for at most 30 µs. For efficiency, therefore, it may be helpful to run separate simulations for flashover and energy duty, using the same model but different time steps. Another option is to increase the simulation time step after approximately 30 µs, if the software supports that function.

7.2 Transmission-line protection

A surge arrester installed on a transmission line is termed a transmission line arrester (TLA). TLAs are commonly used to address lightning-related phenomena with the intent to improve the overall reliability of transmission lines. TLA may also be used to help control switching overvoltages on EHV transmission lines rather than using closing resistors or controlled closing schemes. TLA may also be used as part of a compact transmission-line design. TLA can have a wide range of MCOV ratings and can range from normal-duty distribution class all the way to station class arresters as classified in IEEE Std C62.11-2005. The majority of TLAs currently used in North America are gapless, metal-oxide arresters in polymeric housings, although there may be some that have gaps and/or porcelain housings. This clause of the application guide is limited to gapless, metal-oxide arresters with polymeric housings.

7.2.1 Lightning overvoltage control

The possibility of a flashover of the line insulation and subsequent service interruption may be significantly reduced through the application of line arresters (Babik and Lamb [B9]; Brewer [B20]; Furukawa et al. [B50]; Kastrup et al. [B108]; Matsumoto et al. [B126]; Sadovic et al. [B159]; and Short et al. [B165]). Line arresters may also be applied on one circuit of a double-circuit line in order to reduce double-circuit interruptions due to lightning (Yamamoto et al. [B191]). Line arresters may be installed phase to ground, either in parallel with the line insulators (Koch et al. [B115]) or built into the insulators (Yamada et al. [B190]).

Other factors to consider to evaluate lightning performance include grounding conditions, insulation levels, ground flash density, tower dimensions, shield wire locations, and so on. IEEE Std 1243-1997 [B82] should be reviewed for more details on lightning performance parameters. Properly applied TLAs can help reduce the number of back flashovers and shielding failure flashovers a transmission line may experience. TLAs have also been used where an overhead shield wire was not present, and the arresters are used to protect the topmost phase from flashover and effectively act similar to a shield wire when the topmost phase intercepts a lightning stroke.

The rating of a TLA is chosen so that its protective level is below the CFO of the line insulators. Many times, this leads to higher ratings than what is used for substation protection. The selection of energy requirements depends on the application and whether the system uses shield wires. Protection against lightning on shielded lines leads to station or intermediate class arresters, depending on system parameters and acceptable overloading percentage. Protection with line arresters of unshielded lines often leads to station class arrester types, as these have a higher probability of being subjected to direct strokes. In cases where provision of shield wires are very expensive and/or complicated to install, arresters in all phases on each tower eliminate the need for both shield wires as well as good footing resistance. In areas with moderate ground flash densities, one arrester in the top phase may be used instead of shield wires.

7.2.1.1 Protecting the lowest phase

For vertical conductor configurations, the lowest phase will experience the lowest coupled voltage and the highest insulator voltage stress. TLAs may be applied on just the bottom phases. These arresters will operate during a prospective backflash event, effectively creating another grounded conductor and improving the coupling to the remaining phases. This increased coupling reduces the probability of a backflash on the phases that do not have arresters. A system study should be performed to determine whether this scheme provides acceptable line flashover performance.

7.2.1.2 Grounding effects in an unprotected line section

Line arresters may be installed on just the sections of line that have poor grounding due to soil conditions or that have exceptional exposure to lightning strokes (e.g., river crossings). As shown in 7.1.5 and by Shih et al. [B162], it is very important to install line arresters on towers adjacent to the protected line section. Otherwise, flashovers are likely to occur at these adjacent towers. A system study should be performed to determine how many adjacent towers need arresters.

7.2.2 Selection and installation

There are numerous factors to consider when applying TLAs that may differ from traditional uses in stations and distribution lines. Some of these include the following:

a) The TLAs are typically applied to protect line insulation at a particular structure. Because the lead length and separation distances are practically zero at the tower and the insulation levels are typically higher than stations of the same voltage level, it is possible to select an MCOV that is higher than the MCOV of arresters applied in stations.

b) The TLAs may need to be coordinated with existing gapped silicon carbide station arresters to be sure the TLAs do not unintentionally operate during switching operations (e.g., capacitor restrikes).

c) TLAs are typically installed with isolation devices that will allow a failed arrester to be separated from the phase conductor and will allow the transmission line to successfully reclose. Consideration must be given during the installation of how the arrester will interact with the system following an arrester failure (Melchior et al. [B136]).

d) TLAs may be physically less robust than other equipment used on transmission lines. Special precautions for handling, storage, and transportation should be made. Also, the hardware, tools, torque requirements, and so on may be vastly different than what transmission-line crews are accustomed to. Thus, special precautions should be taken to make sure that the TLAs are installed properly.

e) The protective level of the line arresters should be greater than the protective levels of the adjacent substation arresters. This will reduce the energy absorbed by the line arresters due to switching surges and therefore reduce the possibility of a line arrester failure. Selection of TLAs with a somewhat higher switching surge protective level than the arresters applied in stations will reduce failures.

7.2.3 Switching overvoltage control

Switching overvoltage flashovers are typically associated with reclosing on EHV transmission lines. Strategically placed surge arresters have been used instead of closing resistors or controlled switching schemes to control switching overvoltages on EHV transmission lines. With the increasing use of compact line designs, this application is no longer reserved just for EHV levels. For switching overvoltage control, line arresters are usually installed in all phases. The number of line arresters needed is dependent on the length of the line. For shorter lines, it is sufficient to have line arresters at both line ends only. For longer lines, arresters are added at one or two locations along the line. Typically, this is close to the middle, or at 1/3 plus 2/3 of the line length. Compact lines, or those with upgraded voltage levels, may require line arresters in every tower for one or all phases. System studies on a transient network analyzer (TNA) or digital computer (EMTP/ATP) will show how many are needed. Protection against switching typically requires one energy class lower for line arresters than what is used for arresters installed at the substation.

7.2.4 Station entrance protection

By locating line arresters in the towers closest to a substation, the incidence of back flashovers near the substation can be greatly reduced. This results in a reduction of steepness and amplitude of incoming surges. This improves the protection performance of the station arresters for air-insulated substations and may eliminate the need for metal-enclosed arresters even for large GIS.

7.2.5 Other applications

TLAs may also be used to protect transmission-line structures with insulation levels lower than the majority of the line (e.g., switching structures). TLAs may be used on certain open points on the system exposed to voltage surge doubling. At least one utility has used TLAs to intentionally reduce the insulation on certain structures resulting in increased clearances along the span. Arresters are also used in association with underground transmission cable, but this is outside the scope of this clause.

7.3 Distribution-line protection

Surge arresters are a very common method to improve the lightning performance of distribution lines and have been used for several decades throughout the utility industry. They are usually found on transformers, cable terminations, and other points along the distribution circuit. Surge arresters help control induced voltages from nearby lightning strikes and can help prevent back flashovers on shielded distribution lines. Distribution circuits are typically designed to withstand induced voltages from nearby lightning strikes but not for direct lightning strikes. It is expensive to design a distribution circuit to withstand a direct lightning strike to a phase conductor or overhead shield wire. A direct strike to a phase conductor will almost certainly cause a flashover. If the lightning strike is in high enough magnitude and duration, it is also possible to fail some surge arresters.

The effectiveness of overhead shield wires is dependent on the connected grounding systems and insulation levels of the phase conductors. Shield wires are an effective method to control lightning-related outages on transmission lines, but they are not as effective on distribution circuits because of the extremely low insulation levels used. A shielded distribution circuit has little chance of surviving a direct lightning stroke unless the ground resistance of the structures is very low (e.g., less than 10 ∧), which can be very difficult and expensive for distribution structures. Also, a wood pole with single downlead will have a higher surge impedance (or inductance) than the typical transmission tower.

Surge arresters may improve a distribution line's lightning performance if applied properly (Marshall and Angeli [B124]; McDermott et al. [B129]; Nakada et al. [B139] and [B140]; and IEEE Task Force Reports [B174], [B175]). Specialized arresters have been designed for distribution systems (Fujiwara et al. [B49] and Podporkin and Sivaev [B151]). Consult IEEE Std 1410-2004 [B83] for more information on other factors affecting a distribution line’s lightning performance.

7.3.1 Selection and installation

Line arrester voltage ratings on distribution systems are selected the same way as for distribution transformers and other equipment. Temporary overvoltages during faults, distributed generation backfeed, and ferroresonance should be considered. Ground lead disconnectors should be provided.

The existing distribution transformer primary arresters will provide some line protection. These should be included in the line performance evaluation. If adding line arresters to improve the line flashover rate, then the new arresters should be applied first on the following:

a) Poles with a grounded neutral, which do not already have an arrester.

b) Poles with lower than normal insulation strength, such as dead-end and guyed poles.

7.3.2 Separation distance guidelines

In order to eliminate direct-stroke flashovers on distribution lines, the arresters must be installed on every pole. Some improvement will result if arresters are installed every second or third pole, provided there is no grounded neutral conductor on the intermediate poles. These widely spaced arresters will only provide protection for direct strokes close to the arrester location.

For induced-voltage flashovers due to nearby strokes, the line arresters can be effective at wider spacings (IEEE Std 1410-2004 [B83] and McDermott et al. [B129]). One method to help reduce the effects of induced voltages on distribution circuits is to increase the basic insulation levels of the poles to 300 kV BIL or higher. The use of guy strain insulators on guy wires and fiberglass standoff brackets assists in this effort. When adding arresters to improve the line flashover rate, users should include the impact of increased arrester failures in the economic evaluation.

7.3.3 Top-phase arrester application without a shield wire

Some unshielded subtransmission or distribution lines will have one phase conductor significantly higher than the others. This occurs with vertical conductor arrangements or horizontal arrangements with the center conductor higher than the others. It is sometimes possible to apply line arresters on just the top-most phase.

The best protection from direct-stroke flashovers will result from arresters on all phases. If the pole ground resistance is very low and the top phase conductor provides a shielding angle of at least 45° (preferably lower), arresters on just the top phase at every pole may provide good performance. This application should be analyzed like a backflash case, because when the top-phase arresters operate, the top phase effectively becomes a shield wire.

It may be necessary to lower a crossarm or otherwise move the conductors to cause most strokes to terminate on the arrester-protected phase. The pole ground resistance must also be kept low to reduce the backflash rate.

7.3.4 Underbuilt distribution circuits

If a distribution line shares a tower or pole with a shielded transmission circuit, then the underbuilt distribution conductors are not likely to be struck directly. However, the distribution line is most vulnerable to a backflash, because the coupling between distribution conductors and shield wires is the weakest. The insulation strength on the distribution line is also weaker. Once a distribution conductor flashes over, coupling to the transmission conductors will increase and make a backflash less likely on the transmission circuit. The transmission circuit's lightning performance may improve at the expense of the distribution circuit's lightning performance. The situation can be remedied with line arresters on the distribution circuit. Usually arresters are needed at every tower or pole, on at least one phase.

7.3.5 Induced voltages from nearby strokes

One of the most significant differences between the lightning performance of distribution and transmission systems is the importance of induced voltages from nearby lightning strikes. Two primary methods are available to mitigate the effects of induced voltages on distribution circuits. The first method is to obtain at least 300 kV CFO line insulation strength, typically by using a porcelain or polymer insulator in series with wood or fiberglass. The second method is to use arresters along the feeder to help suppress induced voltages.

Induced voltages tend to increase with a conductor's height. If the line has a multigrounded neutral, then the voltage stressing insulation is the difference between voltages induced on the phase and neutral conductors. Without a grounded neutral, the voltage stress between phases is the difference between the voltage induced on each conductor. The insulation voltages, therefore, are typically much less than the voltage induced on any one conductor.

The accurate calculation of induced voltages requires specialized software, which may be coupled with the EMTP (Nucci [B142]).

8. Protection of electrical machines, 1000 V and greater

This clause is applicable to ac rotating machines rated 1000 V and greater. *It does not apply to motors used in solid-state switched adjustable speed drives.* Test standards IEEE Std 522™-2004 and IEC 60034-15:1995 apply to both motors and generators with form-wound multiturn coils. Test standard NEMA MG-1-2006 applies to induction motors and generators and to synchronous motors with form- wound multiturn coils. In this clause, single-turn or bar coils are not considered; the emphasis is on surge protection of motors with form-wound multiturn coils. For more complete guidance on protecting ac rotating machinery from surges, see IEEE Std C62.21™-2003, which contains a bibliography relevant to surge protection of ac rotating machinery.

Some rotating machines may require surge protection, especially if exposed to lightning or capacitor switching, started frequently, or critical to a process. The coil insulation of the stator winding of ac rotating machines has a relatively low impulse strength. The insulation consists of groundwall insulation and turn insulation. The groundwall insulation surrounds all the turns in the coil, insulating between the coil and the stator iron. Turn insulation is around each turn so as to insulate between the several turns in a coil. Stator winding insulation systems of ac machines are exposed to stresses due to the steady-state operating voltages and to steep-fronted surges

of high amplitudes. Both types of voltages stress the groundwall insulation. Steep-fronted surges also stress the turn insulation. If the rise time of the surge voltage is steep (0.1 µs to 0.2 µs), then most of the surge will appear across the line end-coil, closest to the line terminal. This is a nonlinear voltage distribution that can damage the turn insulation even though the magnitude of the surge is limited to a value that can be safely withstood by the groundwall insulation.
Steep-fronted surges appearing across machine terminals are caused by lightning strikes, normal circuit breaker operation, switching of power factor correcting capacitors, and for motors, starting, aborted starts, bus transfers, and switching windings (or speeds) in two-speed motors. Turn insulation testing also imposes a high stress on the insulation system.

The crest value and rise time of the surge at the machine depend on the transient event taking place, on the electrical system design, and on the number and characteristics of all other devices in the system. These include, but are not limited to, the machine, the cables connecting the machine to the switching device, the conduit and conduit grounding, the type of switching device, the length of the connected switchgear bus, and the number of other circuits connected to that bus. Because of the many variables involved, the surge magnitudes and rise times can be unpredictable. Even though surge withstand capability levels are specified for the windings, it may be desirable for critical applications that surge protective devices also be installed at or very close to the machine terminals. These will slope back (i.e., lengthen) the rise time of the incoming surge so it will distribute more evenly throughout the winding. The relatively low impulse strength of rotating machines indicates that they may need their own surge protective equipment even though they may be partially protected from connected exposed overhead line(s) through apparatus (transformers, regulators, reactors, or cables) whose line side is adequately protected by a surge protective device.

The material presented in this clause may be used as guidance in estimating the surge withstand capability and switching surge exposure of ac rotating machinery in usual, not extreme exposure, installations. The manufacturer should be contacted for specific withstand values for machinery of particular interest or importance.

8.1 Insulation withstand tests

NEMA, IEEE and IEC have established standard tests to prove the surge voltage withstand strength of motors. The surge voltage withstand strength test consists of two tests, one to test the groundwall insulation and the other to test the turn insulation.

From NEMA MG-1-2006, stator windings of ac machines, unless otherwise specified, shall be designed to have a surge withstand capability of 2 pu (per unit) at a rise time of 0.1 µs to 0.2 µs and 4.5 pu at a rise time of 1.2 µs or longer. One pu is the crest of the rated motor line-to-ground voltage, which is as follows:

$$1 \text{ pu} = V_{P-P} \quad 2 \; 3 \qquad (38)$$

From IEEE Std 522-2004, the overall surge withstand strength of coil insulation in a machine can be defined as follows:

The coils should have groundwall and turn insulation sufficient to withstand an impulse voltage wave shape falling within the envelope bounded by straight lines between three points on a linear plot with ordinate in per-unit volts and abscissa in microseconds:

↓ 1.0 pu V at front rise time of 0.0 µs

↓ 3.5 pu V at front rise time of 0.1 µs

↓ 5.0 pu V at front rise time of 1.2 µs or longer

For testing turn insulation, the rise time of applied impulses should be between 0.1 µs and 0.2 µs.

IEC 60034-15:1995 specifies two tests.

For the ground wall insulation BIL: wave shape = 1.2/50 , and the wave crest voltage = BIL, where the IEC BIL is as follows:

$$\text{BIL} = 4V_L + 5\ \text{kV} \tag{39}$$

where V_L = rated voltage.

For the turn insulation: wave shape = oscillatory, first crest rise time = 0.2 µs; tolerance = +0.3 µs and –
0.1 µs; crest voltage = 0.65 BIL. The IEC "rise time" is about 1.25 times the NEMA "rise time."

The equivalent 1.2 µs rise time withstand kilovolts by present standard tests, for commonly used motor voltages, are given in Table 12.

Table 12 —Equivalent surge strengths for rise times 1.2 µs or longer by present standard tests for commonly used motor voltages

Rated volts	NEMA withstand	IEC BIL
2 400	9 kV	15 kV
4 160	15 kV	22 kV
13 800	51 kV	60 kV

8.2 Methods of surge protection for motors started across the line (full voltage start)

It is desirable, because of the unpredictable nature of the surge magnitudes and rise times, that for critical applications, surge protective capacitors and gapless MOSA be installed at or very close to the motor terminals. These may lengthen the rise of the incoming surge thereby making it more evenly distributed across the entire winding and will limit the maximum surge voltage.

For 50 ns to 200 ns rise times, the $L(di/dt)$ of the capacitor inductance and its leads can isolate the capacitor from the surge so as to allow 75% to 90% of this surge peak to reach the motor. Such motor starting steep front transient peaks may exceed the NEMA tested withstand of 2.0 pu at 0.2 µs for usual motor lead configurations, unless:

a) The motor horsepower is quite large (i.e., the motor has a low surge impedance). b) The

motor leads have quite low surge impedance.

c) The capacitor leads are very short (< 2 m), and the rise time is slower than 200 ns.

If one or more of the following surge protective elements exist for a particular motor application, the need for additional surge protection may not be necessary:

1) Effective shielding from lightning strokes to overhead lines supplying the building or plant can reduce the probability of a lightning surge overstress.

2) Gapless metal-oxide surge arresters at the motor terminals can limit the magnitude of voltage stress while avoiding introducing a steep-front change caused by gap sparkover.

3) Single-phase surge capacitors at the motor terminals with short leads (<2 m). Surge arrester lead length is not as critical when machine protective arresters are applied together with short lead length capacitors, because the capacitors will lengthen the rise time applied to the arrester lead inductance.

4) Low grounding resistance at the motor-starting switchgear, in the order of one fifth of the phase mode surge impedance of the motor supply cable. The usual cable phase mode surge impedances will vary between 7 ∧ and 70 ∧. Low grounding resistance, to be effective, should be in the order of 1.5 ∧ for low impedance cables and less than 15 ∧ for high impedance cables.

5) Interconnected bonds to ground from the motor frame, the surge arrester, and the surge capacitor.

6) The motor supply cables are individually shielded with outer jackets that effectively isolate the shields from the raceway, and the shields are bonded at only one end, only at the motor end of the motor supply cables, to the metallic raceway, and to the motor frame and to a low impedance ground or earthing system. (This shield bonding configuration can reduce the surge at the motor by as much as 60% compared with bonding the shields at both ends.)

IEEE Std C62.21-2003 provides the following two methods for determining whether surge protection is required for motors started across-the line:

– A table look-up procedure

– Equations for a personal computer or pocket calculator

Annex A

(informative)

Lightning flashes, lightning stroke currents, traveling waves, and station shielding

A.1 Lightning flashes and strokes

A lightning flash is composed of one or more lightning strokes, each flash having three strokes on the average. In general, the first stroke has a higher current, but the rate of rise is less steep than subsequent strokes. To determine the incoming surge voltage to a station for analyzing protection of station equipment, usually only the surge voltages caused by the first stroke are considered. However, to determine the energy discharged by an arrester, subsequent strokes should also be considered.

As shown in Anderson and Eriksson [B6] and Berger~~, Anderson, and Kroninger~~ et al. [B15], the lightning stroke parameters for negative downward strokes are considered to be approximated by the log-normal distribution, whose probability density function is as follows:

$$f(x) = \frac{1}{xB\sqrt{2\pi}} e^{-\frac{1}{2}\left[\frac{\ln\frac{x}{M}}{B}\right]^2}$$

where

$f(x)$ is the probability density function
M is the median value of distribution
B is the logarithmic standard deviation

Table A.1 and Table A.2 show values of M and B derived from measurements of Berger et al. [B15]. P is the correlation coefficient.

~~The measurements of Berger, Anderson, and Kroninger [B13] show the following values of M and B for first and subsequent strokes:~~

Table A.1—First-stroke statistics

Parameter	***M***	***B***	***P***
Crest current (kA)	31.1	0.48	0.38
Maximum steepness (kA/μs)	24.4	0.60	0.38
Front (μs)	1.28	0.61	
Tail (μs)	77.5	0.58	

Table A.2—Subsequent stroke statistics

Parameter	***M***	***B***	***P***
Crest current (kA)	12.3	0.53	0.56
Maximum steepness (kA/μs)	39.9	0.85	0.56
Front (μs)	0.31	0.71	
Tail (μs)	30.2	0.93	

As noted, the steepness and crest current are correlated; the correlation coefficient is denoted by *P*. The front is derived on a statistical basis from the other two quantities and the correlation coefficient.

The first-stroke crest current data in Table A.1 obtained by Berger et al. [B15] was combined with other data. The resultant distribution is piecewise log-normal whose parameters are shown in Table A.3 (see CIGRE WG 33-01 [B29]).

Table A.3—Piecewise log-normal parameters

Range	***M***	***B***
20 kA and below	61	1.33
20 kA and above	33.3	0.60

The distribution may also be approximated (Anderson [B4]) as follows:

$$P(I_S) = \frac{100}{1 + \left[\dfrac{I_S}{31}\right]^{2.6}}$$

where

$P(I_S)$ is the probability of peak current that is equal to or exceeds I_S (in percent)
I_S is the peak first-stroke current (in kA)

The lightning severity within a specific area is generally specified by the ground flash density N_g in flashes per kilometer _squared._ However, currently within the United States, data on the average _N_g _are not generally available, and the lightning severity has to be based on the annual keraunic level or on the number of thunderstorm days per year, T_D. In the United States, these levels vary from 5 or less on the West Coast to greater than 100 in Florida, with an average between 35 and 40 (IEEE Working Group Report [B95]). The value of N_g may be approximated from T_D as follows:

$$N_g = 0.04 T_D^{1.25}$$

where both N_g and T_D are average yearly values (Eriksson and Meal [B46]). The coefficients of variation of both N_g and T_D are large, about 60% for low values of T_D and about 30% for high values of T_D [B66]. (An exponent of 1.35 for this equation appears in an IEEE Working Group Report [B95]. The 1.25 exponent has since been accepted and approved by the developers of an IEEE Working Group Report [B98].

A.2 Arrester currents due to lightning strokes

As a general rule, arrester currents due to lightning strokes are less than the current in the stroke itself. In the case of direct strokes to lines, traveling waves are set up in opposite directions from the point of contact. Flashover of line insulation provides a parallel path to ground through which a portion of the stroke is diverted from the arrester. In the case of strokes to more than one conductor or flashovers between conductors, two or more surge arresters may operate and share the current. Only in the case of a direct stroke very near to the terminal of the arrester, with no flashover occurring before arrester operation, is the arrester called on to discharge most of the lightning stroke current. The probability of such an occurrence can be significantly reduced by the use of shielding. Evaluation of arrester currents is discussed in 5.2.2.2.

A.3 Line shielding

Overhead lines may be protected against direct lightning strokes to the conductors by the use of shield (overhead ground) wires, which are positioned to intercept lightning strokes and to direct the stroke current to ground via metallic tower or pole structures. Where wood pole structures are used, low-impedance conductors are used to connect the shield wires to the ground.

Almost all direct strokes to line conductors are eliminated by the use of shield wires. When such a direct stroke (shielding failure) does occur, line flashover is almost certain. When a lightning stroke terminates on a shield wire, the stroke current is diverted to ground through the structure-connecting conductors. The impedance of the current path together with ground resistance results in a voltage at the top of the line structure, a portion of which is coupled to the phase conductor. The difference between the phase conductor potential and structure top potential is impressed directly across line insulation and may result in flashover. This type of flashover is called a backlash. The incidence of backlashes is controlled by selection of a proper insulation level; by keeping the structure ground resistance at an acceptably low value; and by providing adequate clearance from conductor to structure ground, conductor to shield wire, and conductor to conductor.

A.4 Station shielding

Procedures analogous to those used for shielding lines may also be used for shielding stations. Shielding methods include overhead ground wires, metallic masts without ground wires, and lightning rods supported from the station structure. These methods may be used in many combinations. Refer to IEEE Std 998™-
1996.

A.5 Uses of shielding in station protection applications

The purpose of shielding in station applications is to reduce the risk of insulation failure to an acceptable level. In certain applications, this may be achieved by shielding the station alone. In other cases, it may be necessary to shield all incoming lines to the station. As pointed out in A.6, shielding of the lines for a relatively short distance from the station may be all that is required for station protection.

With well-designed shielding, insulation, and grounding systems, the probability of direct strokes to phase conductors is reduced to a low level, and the voltages across insulation in the event of strokes to the shielding system are reduced below flashover levels. As a result, arrester discharge currents are reduced, thereby permitting the arrester to provide better protection to equipment insulation (see 5.2.5).

A.6 Traveling waves

Lightning strokes to lines, as well as switching operations, set up traveling waves that move along the line (Bewley [B16]). Crest voltage can double when the wave arrives at the terminals of an open line switch or circuit breaker. A reflected voltage approaching double the incident wave occurs at line-terminating transformers.

As a wave initiated by lightning moves along a line, the crest is reduced and the time to crest is increased (Wagner et al. [B182]). Effective shielding of a line for as little as 800 m (1/2 mile) from the station can reduce a high percentage of incoming surges to a tolerable level (Bewley [B16]).

Annex B

(informative)

COG for various conditions

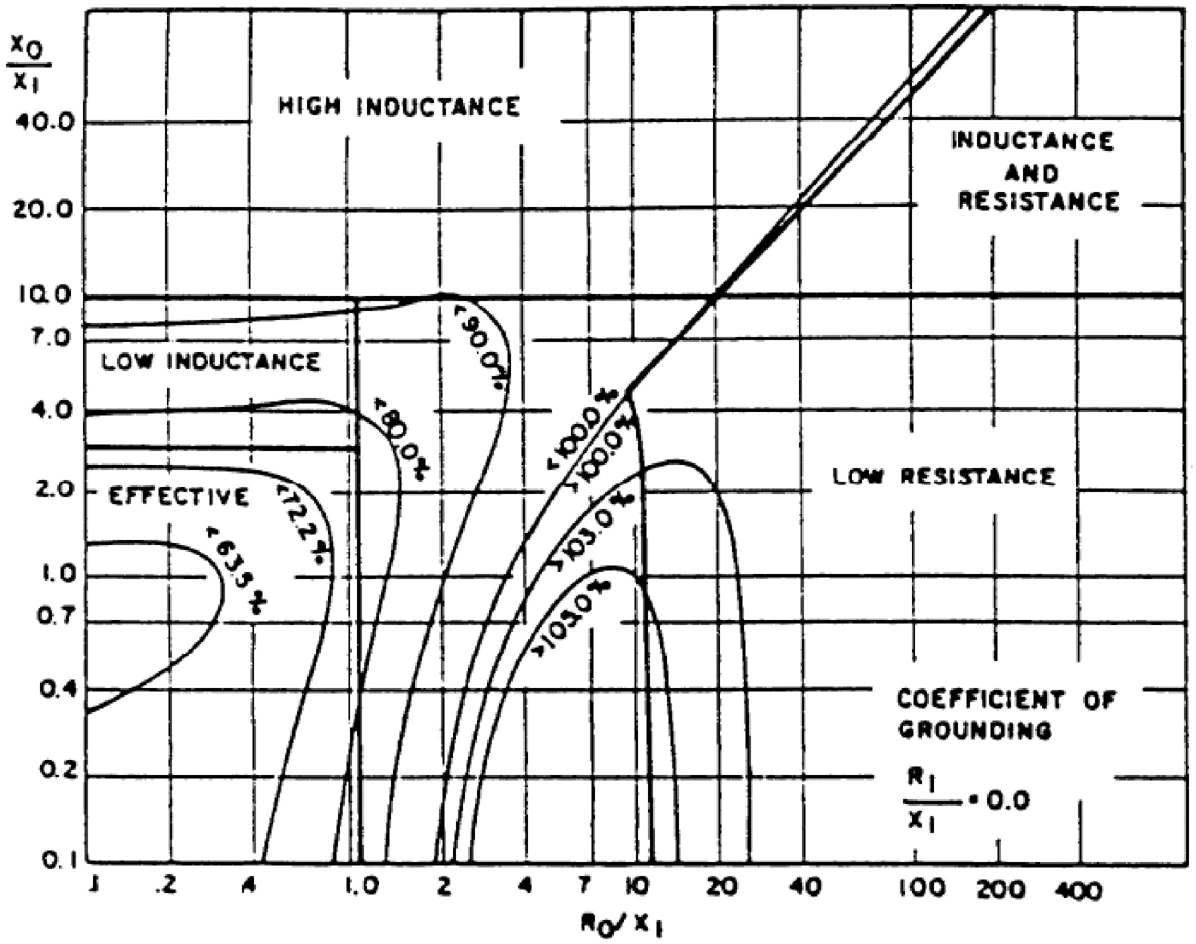


Figure B.1—Coefficients of grounding for $R_1/X_1 = 0$

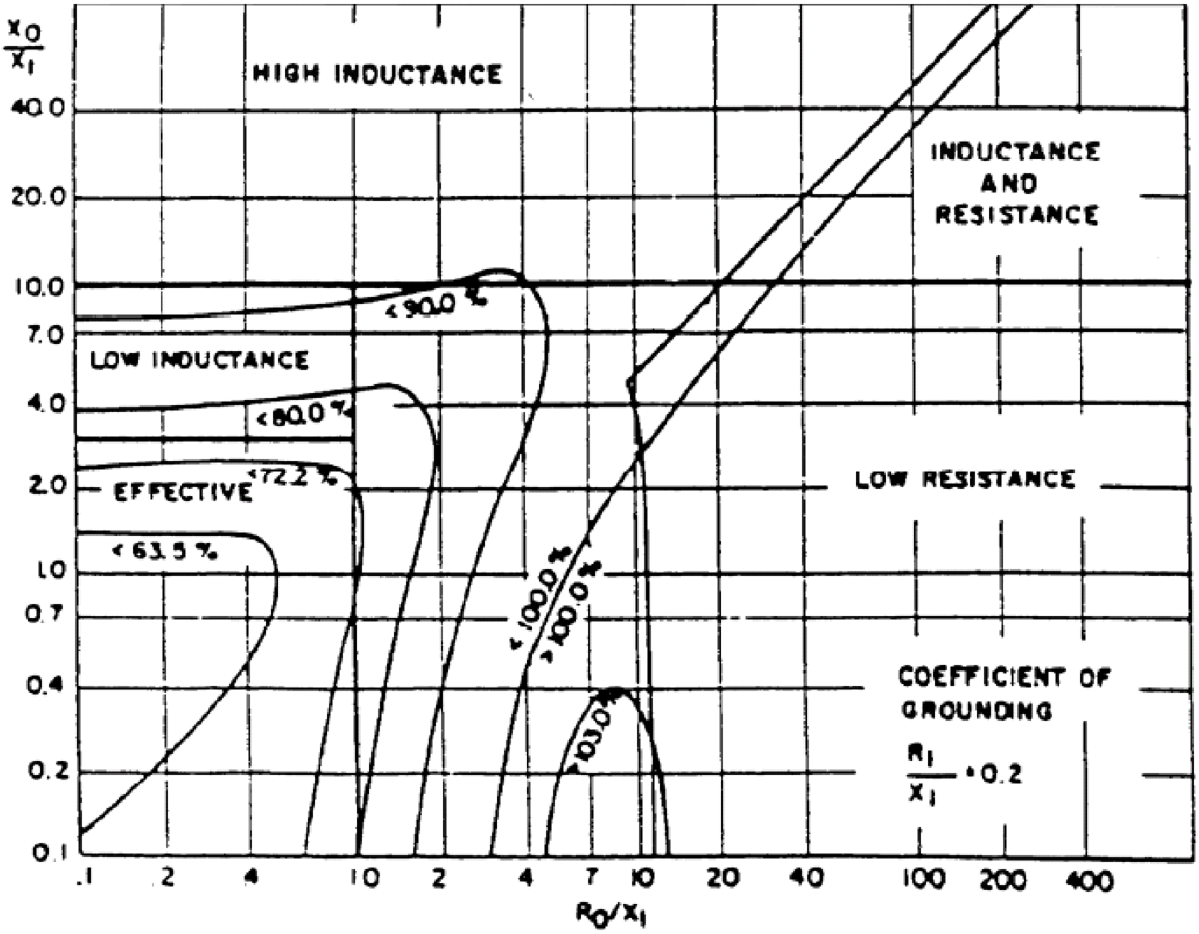


Figure B.2—Coefficients of grounding for $R_1/X_1 = 0.2$

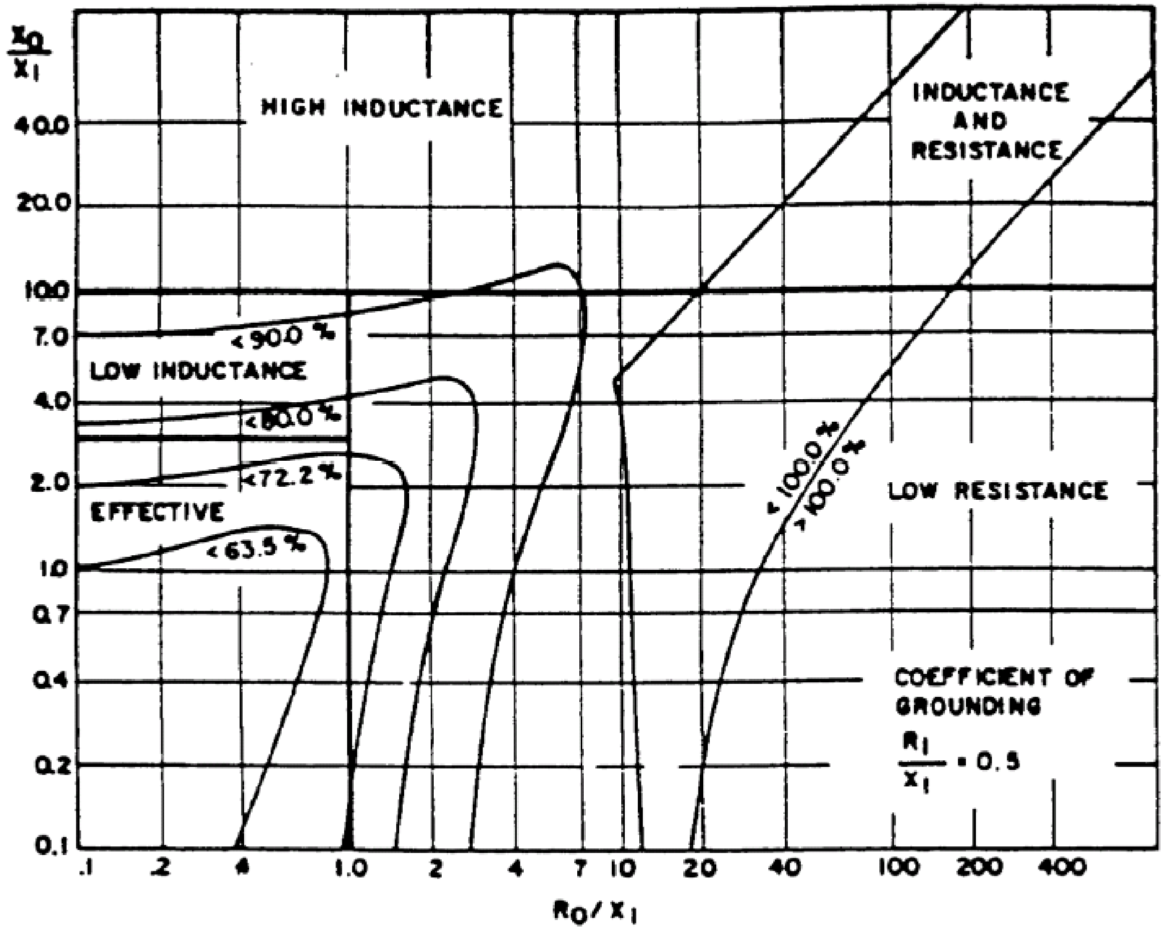


Figure B.3—Coefficients of grounding for $R_1/X_1 = 0.5$

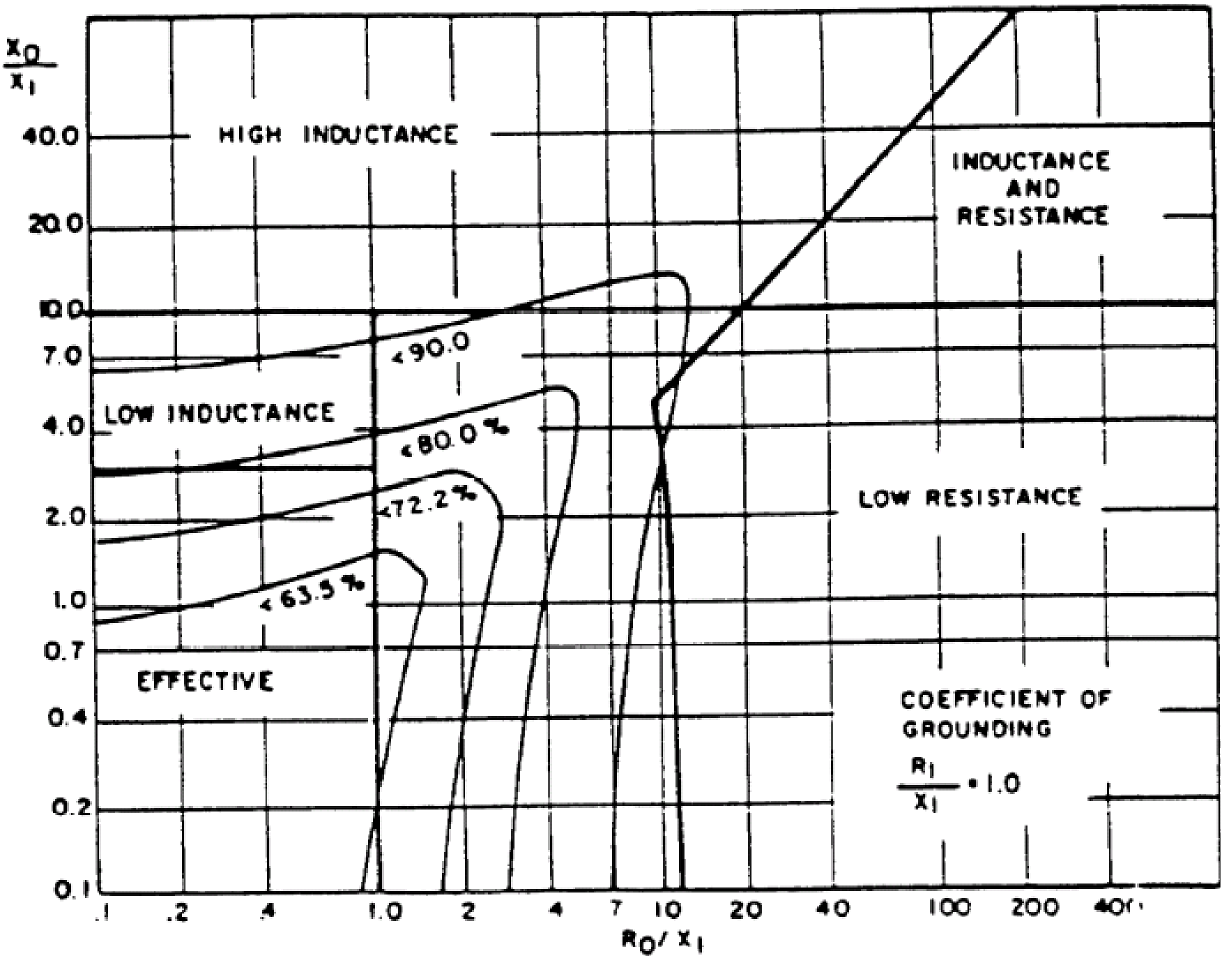


Figure B.4—Coefficients of grounding for $R_1/X_1 = 1$

NOTE—Parameter values given against Figure B.1 through Figure B.5 indicate limiting values of COG (see

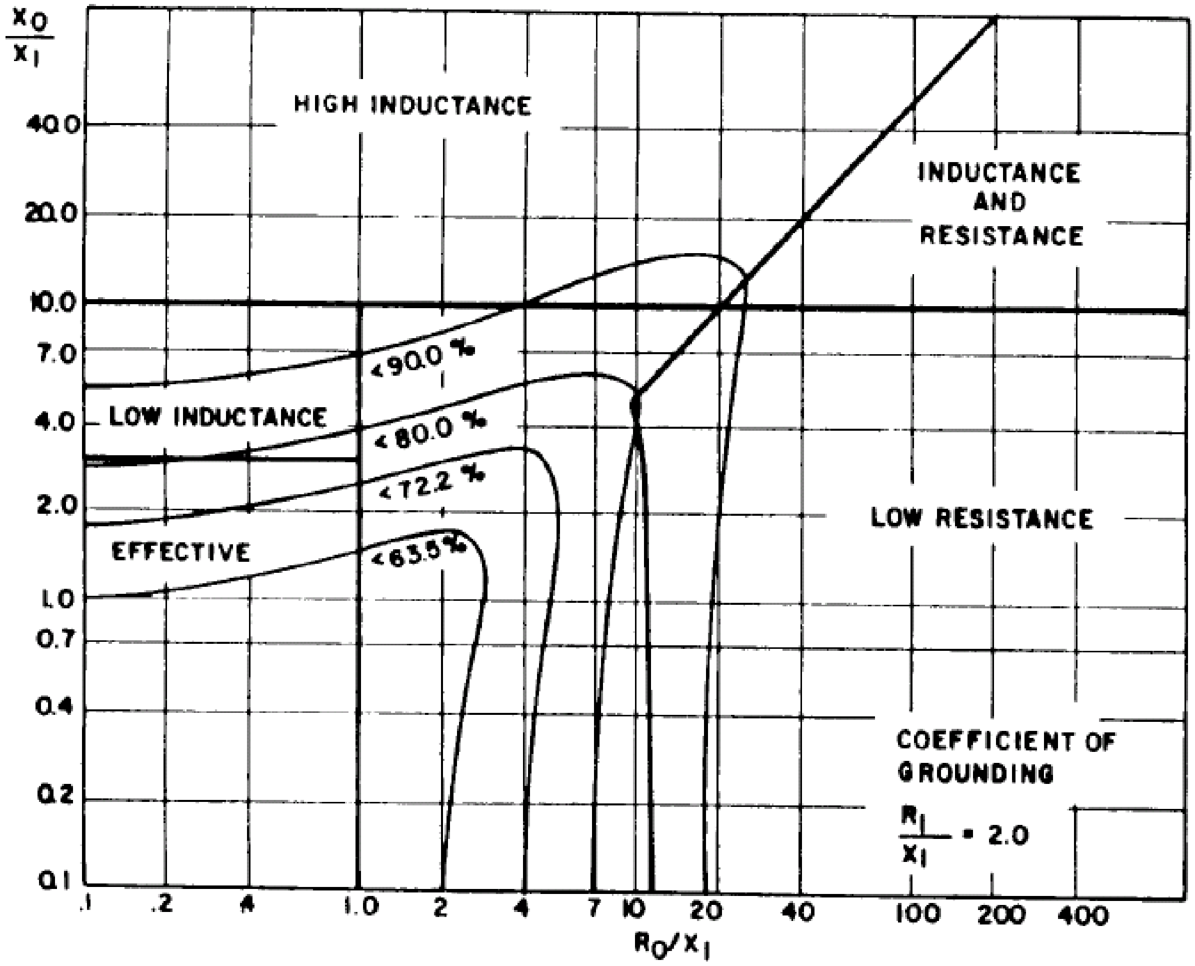


Figure B.5—Coefficients of grounding for $R_1/X_1 = 2$

3.1~~3~~.8) within the area circumscribed by the curve. Definitions of grounding class or means are indicated in each area. All impedance values have to be on the same kilovolt ampere base or in ohms on the same voltage base.

R_0 is the zero-sequence resistance
R_1 is the positive-sequence resistance
R_2 is the negative-sequence resistance
X_0 is the zero-sequence inductive reactance
X_1 is the positive-sequence inductive reactance X_2 is the negative-sequence inductive reactance Z_1 is equal to Z_2

All these quantities are components of the system impedance as seen from the point of fault. See 5.2.1.2.1.

The effect of fault resistance was taken into account. The resistance that gives the maximum voltage to ground was the value used.

The COG for other parameter values when $Z_1 = Z_2$ can be calculated using the equations in Figure 6. The curves of the figures in Annex B are from IEEE Std C62.92.1-2000. For assumptions in producing these curves, see IEEE Std C62.92.1-2000.

Annex C

(informative)

Calculations of surge arrester separation distances

C.1 Purpose

The purpose of this annex is to provide a relatively simple method for calculating the maximum allowable separation distances between surge arresters and equipment to be protected. This annex applies to properly shielded, air-insulated substations, rated 69 kV and higher, where all connected transmission lines are effectively shielded.

In the previous revisions of IEEE Std C62.22-1997, the calculations of arrester separation distances in this annex were based on a deterministic approach, with a set voltage wave steepness based on MCOV. Annex C has been modified to a statistical approach in this revision. The incoming surge steepness is now determined by the distance from the substation to a strike point. This distance is based on the MTBF of the station and the line flashover rate. The decrease in the surge based on the corona constant for the line type and the distance to the strike point is also a factor in the surge steepness at the station now. The separation distance between equipment with self-restoring insulation and the surge arrester has been added to this new version.

C.2 Introduction

The most effective location for any surge arrester is at the terminals of the equipment to be protected. For a variety of reasons, surge arresters are sometimes located some distance from the equipment. For example, a single arrester may be located to provide protection to more than one piece of equipment.

Locating a surge arrester remote from the equipment to be protected reduces the protective margin. Depending on a number of factors, the surge voltage at the equipment ~~can easily be more than~~ may exceed twice the surge arrester protective level. ~~An analysis has to be made to determine how far a surge arrester can be located away from the equipment and still provide adequate protection~~Therefore, some analysis is necessary to determine the maximum allowable separation distance between the arrester and the equipment to be protected.

C.3 Definitions of symbols

The symbols used to calculate surge arrester separation distances are defined in this clause. Figure C.1 helps illustrate the use of some of these symbols.

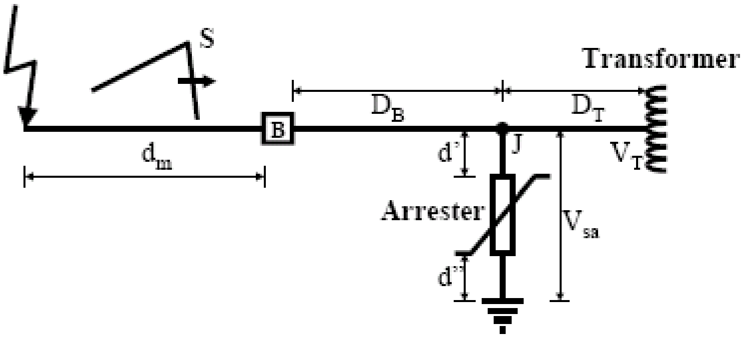


Figure C.1—Definition of symbols

B A piece of equipment that has self-restoring insulation (disconnecting switch, bus support, etc.) located in front of the surge arrester

BIL Basic lightning impulse insulation level of the transformer or equipment *B* (kV)

c Velocity of light, 300 m/µs

CWW 3-µs chopped-wave withstand of transformer or equipment B (kV)

For transformer: CWW = 1.10 × BIL (IEEE Std C57.12.00-2000, Table 6)

For circuit breaker: CWW = 1.15 × BIL (ANSI C37.06-2000, Table 4). This is also a conservative estimate
for disconnecting switches and bus supports.

d' Conductor length between junction *J* and surge arrester terminal (meters)

d'' Conductor length between surge arrester and ground (meters)

d Total surge arrester lead, *d'* + *d''* (meters)

d_m Distance from station to flashover (kilometers)

δ Relative air density factor used for derating air insulation for higher altitudes

D Separation distance (meters)

D_B Maximum allowable separation distance between junction *J* and equipment B (meters)

D_T Maximum allowable separation distance between junction *J* and transformer terminal (meters)

di/*dt* Rate of rise of surge current = 2 *S* / *Z* (in kiloamperes per kA/µs) FOR Flashover rate of lines (flashovers/100 km-year)

J Common point among transformer lead, surge arrester lead, and surged line

K_c Corona constant that determines steepness of incoming surge (kV – km/µs)

L Inductance of surge arrester lead d (µH) (Assume 1.3 µH/m)

MTBF Mean time between failures (years). A failure in this context is an overvoltage event that exceeds the maximum voltage stress allowable (see V_B and V_T below), which includes a protective ratio.

N Number of transmission lines, including the surged line, connected to a substation bus

n 1 for the equipment B case and for a nonsymmetrical substation layout case. Equal to N for the symmetrical substation layout case.

~~S' is rate of rise of incoming surge on the transmission line (kV/µs) (Use 11 kV/µs per kV MCOV~~
~~rating to a maximum of 2000 kV/µsÑIEEE Std C62.11-1993)~~ (~~in kilovolts~~)

~~V_T is maximum voltage stress allowable at the transformer (in kilovolts):~~

PR_T Protective ratio of transformer. PR_T should be equal to or greater than 1.15.

PR_B Protective ratio of equipment with self-restoring insulation and is either 1.00 or 1.05.

S' Rate of rise (steepness) of incoming surge on the transmission line (kV/µs)

S Rate of rise (steepness) of incoming surge at junction

J (volts per kV/µs) V_a Surge arrester FOW protective level at 0.5 µs (kV)

(See Table 1) V_{sa} Voltage across the surge arrester, from junction J to ground

~~V_T is CWW/1.15 if time to crest voltage is less than 2 µs~~

~~V_T isBIL/1.15 if time to crest voltage is more than 2 µs~~
V_B Maximum voltage stress allowable at self-restoring equipment B (kV)

V_T Maximum voltage stress allowable at the transformer (kV)

Z Surge impedance of line conductor or substation bus (△) (Refer to Z_L in Table 11 of IEEE Std C62.11-2005)

C.4 Study method

This annex provides a simplified procedure for calculating acceptable separation distances for simple air- insulated substations with shielded overhead lines. The procedure is illustrated in this annex using the following two examples:

a) A substation consisting of a single overhead line terminated with a single transformer b) A three-line, two-transformer substation

The calculation method is based on a desired reliability goal for the substation (IEEE Std 1313.2-1999 and Hileman [B65]). The goal reflects the importance of the substation in the system's service performance and is expressed in terms of MTBF in years. More complex studies could assign different MTBF goals for different equipment in the same substation. Transformers can be exposed to incoming surges at more than one voltage level and may be evaluated at each voltage level to develop a composite MTBF for the transformer. In most substation designs, there is one critical location or piece of equipment with the longest lead lengths, largest separation distances, lowest insulation levels, and/or highest required protective margins that will have the lowest theoretical MTBF of all the equipment in the substation. This piece of equipment would effectively determine the MTBF of the entire substation even if the MTBF was evaluated for every piece of equipment to determine the composite station MTBF. This type of detailed evaluation is beyond the scope of this annex. However, the simplified technique presented in the annex should evaluate the worst-case scenario in a substation that should yield results very similar to a more comprehensive analysis of station MTBF.

The equipment in air-insulated substations may have a useful life in the range of 30 years to 75 years. Therefore, a MTBF of 50 years to 150 years could be used for air-insulated substations. The flashover rate of all lines connected to the substation is obtained or assumed, i.e., flashovers per 100 km per year. This establishes the surge exposure of the substation. The steepness of the design surge entering the substation is derived from this and other parameters, as is described later. The steepness of this entering surge is the major factor in determining the permissible separation distance between the arrester and the protected equipment.

A reduction process is used in the second example to derive a single-line single-transformer substation that can be analyzed as shown in the first example.

For non-self-restoring insulation:

The voltage at the transformer, generated by use of the EMTP, is based on a single-line transformer station and is shown by the curve of Figure C.8. This curve may also be represented by the following equation:

$$\frac{V_T}{V_{sa}} = 1 + \frac{1.92}{1 + \frac{0.385}{K_1}} \quad \text{(C.1)}$$

where

$$K_1 = \frac{D_T S}{cV_{sa}}$$

Solving for D_T:

$$D_T = \frac{0.385cV_{sa}}{S}\frac{V_T - V_{sa}}{2.92V_{sa} - V_T} \quad \text{(C.2)}$$

The curve of Figure C.8 and Equation (C.1) and Equation (C.2) are valid for separation distances not exceeding 90 m. The transformer surge capacitance was varied from 1 nF to 5 nF, and the power frequency voltage was assumed as of opposite polarity to the surge voltage and set equal to the crest line-neutral voltage. The evaluation criterion of 5.2.5.4 placed in terms of the maximum permissible separation distance results in the following equations.

a) If the time to crest of the arrester voltage is less than 2 µs, V_T/V_{sa} is equal to or less than 1.10 and $PR_T = 1.15$, then the maximum separation distance D_T is given by:

$$D_T = \frac{(0.385)cV_{sa}}{S} \frac{(0.870\,\mathrm{BIL}) - V_{sa}}{(2.92V_{sa}) - (0.870\,\mathrm{BIL})} \tag{C.3}$$

b) If the time to crest of the arrester voltage is less than 2 µs, V_T/V_{sa} is greater than 1.10 and $PR_T = 1.15$, then the maximum separation distance D_T is given by:

$$D_T = \frac{(0.385)cV_{sa}}{S} \frac{(0.957\,\mathrm{BIL}) - V_{sa}}{(2.92V_{sa}) - (0.957\,\mathrm{BIL})} \tag{C.4}$$

c) If the time to crest of the arrester voltage is equal to or greater than 2 µs and $PR_T = 1.15$, then the maximum separation distance D_T is given by:

$$D_T = \frac{(0.385)cV_{sa}}{S} \frac{(0.870\,\mathrm{BIL}) - V_{sa}}{(2.92V_{sa}) - (0.870\,\mathrm{BIL})} \tag{C.5}$$

The “long-tail” criteria is used as a final check on the required minimum BIL and is as follows:

$$\mathrm{BIL} = \frac{1.15V_a}{0.83} \tag{C.6}$$

For self-restoring insulation:

A conservative equation for the voltage at the equipment B is as follows (IEC 60071-2-1997):

$$\frac{V_{\mathrm{B}}}{V_{sa}} = 1 + \frac{2SD_{\mathrm{B}}}{cV_{sa}} \tag{C.7}$$

Reformatting this equation to obtain D_{B}:

Using the evaluation criterion of 5.2.5:

$$D_B = \frac{c(V_B - V_{sa})}{2S}$$

a) If $V_B/V_{sa} \leq 1.15$ and $PR_B = 1.05$:

$$D_B = \frac{c}{2S}\left(\frac{\delta\ BIL}{1.05} - V_{sa}\right)$$

b) If $V_B/V_{sa} > 1.15$ and $PR_B = 1.05$:

$$D_B = \frac{c}{2S}\left(\frac{1.15\ \delta\ BIL}{1.05} - V_{sa}\right)$$

where δ is the relative air density and is given by:

$$\delta = e^{-A/8.6} \qquad \text{(C.11)}$$

where A is the altitude, in kilometers.

Depending on the transformer surge capacitance and the distance to equipment B, the actual voltage will be less and the distances will be greater than those given by Equation (C.8) through Equation (C.11). Special studies are required for complex substations using analytical tools such as the EMTP. It is not the intent of this annex to provide guidance in selecting cases for study or in interpreting the results obtained when using the EMTP or other analytical tools.

C.5 Selection of S', the steepness or rate of rise of the incoming surge

The steepness of the incoming surge may be estimated from the equation:

$$S' = \frac{K_c}{d_m}$$

where K_c is the corona constant per Table C.1 (IEC 60071-2-1997)

Table C.1—Estimated Values for K_c (IEC 60071-2-1997)

Type of line construction	K_c (kV-km/⌠s)
Distribution lines (phase-phase flashovers)[a]	
with grounded crossarms (flashover to ground at low voltage)	150
wood-pole lines (flashover to ground at high voltage)	400
Transmission lines (single-phase flashover to earth)	
single conductor	700
2-conductor bundle	1000
3 or 4 conductor bundle	1700
6 or 8 conductor bundle	2500

Per IEC 60071-2-1997, for these lines the corona constant, K_c, has been matched with service practice.

The distance d_m (in km) is determined from the equation:

$$d_m = \frac{1}{n(\mathrm{MTBF})(\mathrm{FOR}/100)} \tag{C.13}$$

where $n = N$, the number of lines for the symmetrical layout transformer case and where $n = 1$ for the equipment B case and the nonsymmetrical layout case. d_m is in kilometers and is the distance from the line flashover location to the station entrance. Realistically, this distance must equal an integer number of spans or towers from a station. That is, if d_m is not an integer number of towers, then d_m should be increased to the next further tower from the station if the specific tower locations are known. However, for studies where specific tower locations are not known, Equation (C.13) can be used without increasing to give a more conservative result.

In a symmetrical station layout, an incoming surge on each of the various lines results in nearly the same voltage at the transformer or piece of equipment. In a nonsymmetrical station layout, this is not the case as an incoming surge on one or more of the lines will result in a higher voltage at the transformer or piece of equipment.

The MTBF is primarily a function of the consequence of a failure and the life of the equipment. For air- insulated stations, MTBFs of 50 and 100 years have been used (Hileman et al. [B68]; Clayton and Young, [B33]), whereas in IEC 60071-2-1997, values of 400 years and 500 years are used. In contrast, because of the consequence of failure in gas-insulated stations, a higher MTBF of 400 years has been used, and MTBFs between 300 years and 1000 years have been suggested by Weck and Eriksson [B186].

C.6 Single-line, single-transformer substation, example 1

Refer to Figure C.1. Parameters in this example for a 115 kV system are as follows:

BIL	450 kV for transformer, and 550 kV for breaker
CWW	1.1 × BIL = 495 kV (see 5.2.5.1)
PR_T and PR_B	1.15

c	300 m/µs
d	d’ + d” = 7.6 m
Span length	200 m
FOR	2.0 per 100 km-years
MTBF	100 years
Conductors/phase	1
Surge arrester used	90 kV duty-cycle rated with a 70 kV MCOV

From Table C.1 for a single conductor, K_c = 700 kV-km/µs

and from Equation (C.13):

$$d_m = \frac{1}{(1)(100)(2/100)} = 0.5 \text{ km}$$

Because the span length is 200 meters, d_m is rounded up to integer 3 times 200 = 0.6 km, and therefore, from Equation (C.12):

$$S' = \frac{700}{0.6} = 1167 \text{ kV/µs}$$

where

S	S' in this example
V_a	226 kV for MCOV = 70 kV
Time to crest voltage	V_a/S' = (226/1167) = 0.19 µs, which is less than 2 µs
Use V_T	CWW/PR_T
Z	450 ^ from Table 11 of IEEE Std C62.11-2005

Calculate the following:

di/dt	2 S/Z = 2(1167) /450 = 5.2 kA/µs
L	(d’ + d”) × 1.3 µH/m = 7.6 × 1.3 = 9.9 µH
V_{sa}	$V_a + L(di/dt)$ = 226 + 9.9(5.2) = 277 kV
V_T	CWW/PR_T = 495/1.15 = 430 kV
V_T/V_{sa}	430 / 277 = 1.55

Since the time to crest < 2 µs, $V_T/V_{sa} > 1.10$, and $PR_T = 1.15$, use Equation (C.4) to calculate D_T:

$\delta = e_{-1.2/8.6} = 0.87$

CWW = 1.15 × BIL = 1.15 × 550 = 632.5 kV
V_B (internal) = CWW/PR_B = 632.5/1.05 = 602.4 kV
V_B (external) = ™ × CWW/PR_B = 0.87 × 632.5/1.05 = 524 kV (use this value for coordination)
di/dt = 2(S)/Z = 2 × 1167 / 450 = 5.2 kV/⌠s
V_{sa} = V_a + L(di/dt) = 226 + 9.9 (5.2) = 277 kV
V_B – V_{sa} = 524 – 277 = 247 kV
V_B / V_{sa} = 524 / 277 = 1.9

Since V_B / V_{sa} > 1.15 and PR_B = 1.05, use Equation (C.10) to calculate D_B:

$$D_{\mathrm{B}} = \frac{\mathrm{c}}{2S}\left(\frac{1.15\,\delta\,BIL}{1.05} - V_{sa}\right) = \frac{300}{2(1167)}\left(\frac{1.15\times 0.87\times 550}{1.05} - 277\right) = 31.8\,\mathrm{m}$$

This is the maximum allowable distance between the surge arrester junction and the transformer.

8 m

C.6.1 Calculated allowable separation distances.

Allowable separation distances between the arrester and the transformer for the single-line, single-transformer substation have been calculated using the above procedure for system voltages from 69 kV through 765 kV based on the following:

Typical values of BIL

—Station class surge arresters

— Minimum MCOV ratings

— Maximum value for the 0.5 µs FOW protective level from Table 1

— Surge arrester total lead length of 7.6 m

— Incoming steepness of 1000 kV/µs

— Protective margin of 15%

The allowable separation distances are given in Table 7 of 5.2.5.4.

C.7 Three-line, two-transformer substation

Figure C.2 shows a substation with three transmission lines, two transformers, and one set of surge arresters. Allowable surge arrester separation distances should be calculated for each transformer, assuming the incoming surge on each of the three lines, to determine the surge-protection adequacy of both transformers with one set of surge arresters.

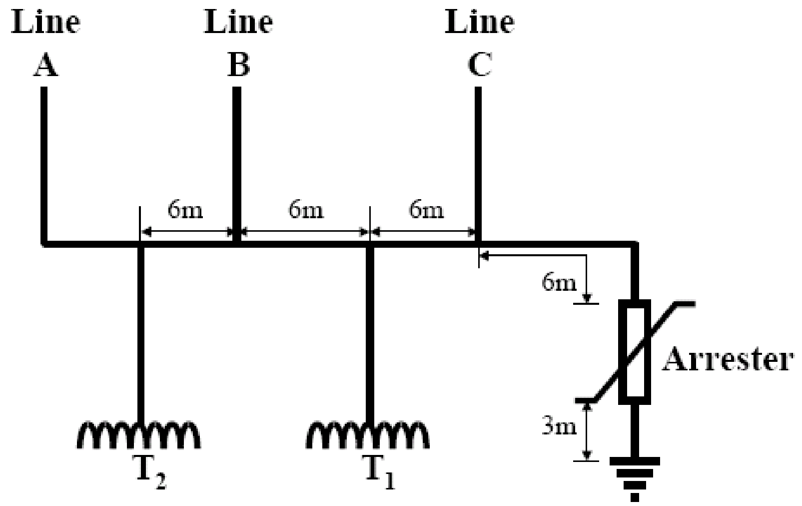


Figure C.2—An example of a three-line, two-transformer substation

To use the method of this annex, the three-line, two-transformer substation of Figure C.2 has to be reduced to a single-line, single-transformer substation similar to that of Figure C.1. The following procedure shows the reduction method (McNulty [B135]). The procedure should be repeated for each transformer, while assuming the incoming surge to travel on each line separately. Line-out conditions could also be investigated to identify the most severe case.

C.7.1 Step-by-step procedure for reduction process

— Step 1: Remove the transformer not being considered and identify the transmission line with incoming surge.

— Step 2:

i) Identify junction *J*, which is the common point among the transformer lead, surge arrester lead, and the surged line.

ii) Identify the separation distance *D* as the connection between junction *J* and the transformer terminal that would include the bus-bar length, if applicable.

iii) Identify the surge arrester lead *d’* as the connection between junction *J* and the surge arrester that would include the bus-bar length, if applicable.

— Step 3: Remove all lines connected to *d’* (connection between junction *J* and surge arrester).

—Step 4: The rate of voltage rise at junction *J* is as follows:

$S = (S') \times 3/(N + 2)$

where N equals the total number of lines (including the surged line) remaining after Step 3.

The three-line, two-transformer substation has been reduced, and the maximum allowable separation distance D can be calculated using the procedure used in C.6. This is a nonsymmetrical case.

C.7.2 Three-line, two-transformer substation—example 2

Refer to Figure C.2 and Figure C.3. Parameters used in this example for a 138 kV system follow:

FOR	2.0 flashovers per 100 km-years
BIL	550 kV for the transformer
c	300 m/µs
Conductors/phase	1
From Table C.1, K_c	700
MTBF	100 years
n	1 for nonsymmetrical layout
N	3 lines
PR_T	1.15
Span of line	200 m

Surge arrester used = 108 kV duty-cycle rated with a 84 kV MCOV From Equation (C.13):

$$d_m = \frac{1}{n(\mathrm{MTBF})(\mathrm{FOR}/100)} = \frac{1}{(1)(100)(2/100)} = 0.5 \text{ km}$$

$$d_m \,/\, \text{span length} = (500 \,/\, 200) = 2.5$$

Therefore, round up to three spans and use d_m = 3 × 200 m = 600 m = 0.6 km. From Equation (C.12):

$$S' = \frac{K_c}{d_m} = \frac{700}{0.6} = 1167 \text{ kV/µs}$$

Where

V_a 273 kV for MCOV = 84 kV
Time to crest voltage = V_a / S' = (273/1167) = 0.23 µs

This is less than 2 µs
Therefore use V_T = CWW/PR_T
Z 450 ∧ from Table 11 of IEEE Std C62.11-2005

C.7.2.1 Reduction of Figure C.2—for transformer 1 with incoming surge on line A

– Step 1: Remove the transformer not being considered, T2 in this case, and assume that the incoming surge is on line A; see Figure C.3.

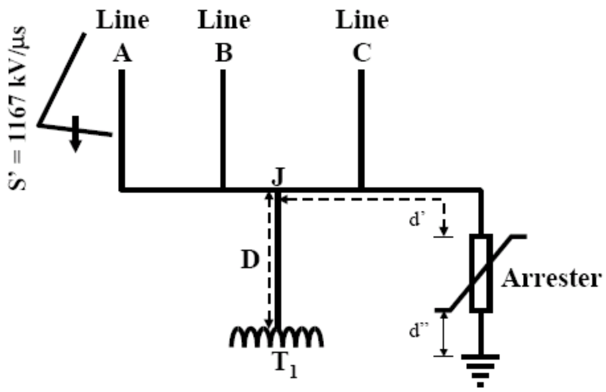


Figure C.3—Example 2—Three-line, two-transformer substation with an incoming surge on line A—transformer T2 is not being considered and is removed

– Step 2:

i) Identify junction J, where the dashed lines meet in Figure C.3 ii) Identify the separation distance *D*

iii) Identify the surge arrester lead length. d' = 12 m in this example (see Figure C.2), and

$d = d' + d'' = 12 + 3 = 15$ m

↓ Step 3: Remove all lines connected to d'; Line C in this case.

↓ Step 4: Calculate the voltage rate of rise at junction *J*.

Using Equation (C.14) with $N = 2$ (see Figure C.4):

$S = (S') \times 3/(N + 2)$
$= (1167) \times 3/(2 + 2) = 875$ kV/µs (see Figure C.4)

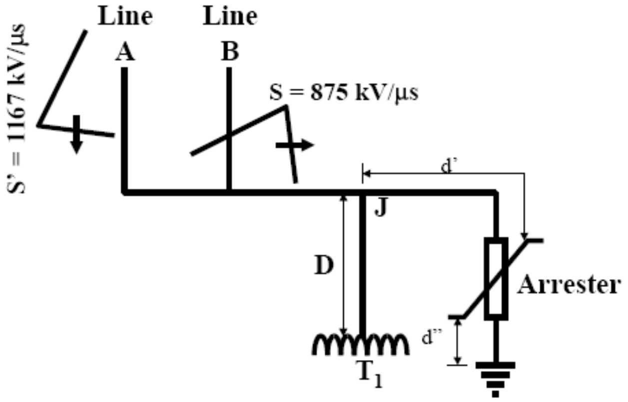


Figure C.4—Example 2—Three-line, two-transformer substation with an incoming surge on line A—all lines connected to *d'* are removed

The reduced single-line, single-transformer substation to be analyzed is shown in Figure C.5.

Calculate the following:
CWW 1.1 × BIL = 1.1 × 550 = 605 kV, for the transformer
di/dt $2(S)/Z = 2(875)/450 = 3.9$ kA/µs
L (d' + d") 1.3 µH/m = (15) 1.3 = 19.5 µH
V_{sa} $V_a + L(di/dt) = 273 + 19.5\ (3.9) = 349$ kV
V_T CWW/PR_T = 605/1.15 = 526 kV
V_T/V_{sa} 526/349 = 1.51

Using Equation (C.2) to solve for D_T [could also use Equation (C.4) for this example]:

$$D_T = \frac{0.385cV_{sa}}{S}\,\frac{V_T - V_{sa}}{2.92V_{sa} - V_T} = \frac{0.385(300)(349)}{875}\,\frac{526-349}{2.92(349)-526} = 16.5\ \text{m}$$

This is the maximum allowable distance between the junction *J* and the T1 transformer if line A is the surged line. Repeat the procedure with the incoming surge on each of the other lines; C.7.2.2 shows the incoming surge on line C.

$V_T - V_{sa}$~~= 1.42 on the curve of Figure C.8 is D (S)/(C × V_{sa}) = 0.108. Solve for: D = 0.108(984 × 302)/(554) = 58 ft (17.7 m)An incoming surge on Line A is more critical than one on Line C (D = 31 ft versus 58 ft or 9.4 m versus 17.7 m).Line B, and determine the maximum allowable separation distance D for transformer T1~~
~~A similar procedure should be followed to determine the maximum allowable separation distance D for transformer T2.~~

C.7.2.2 Reduction of Figure C.2—for transformer 1 with incoming surge on line C

↓ Step 1: Remove transformer not being considered, T2 in this case, and assume the incoming surge is on Line C. See Figure C.6.

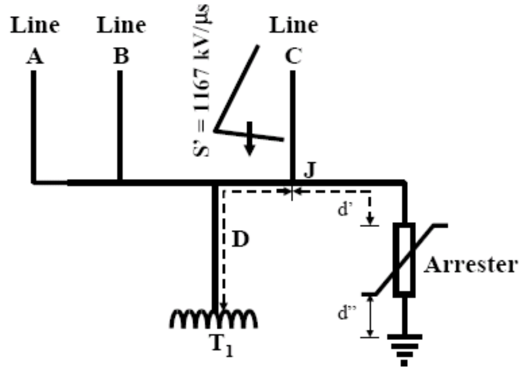


Figure C.6—Example 2—Three-line, two-transformer substation with incoming surge on line C—transformer T2 not being considered and is removed

– Step 2:

i) Identify junction J, where the dashed lines meet in Figure C.6

ii) Identify the separation distance D

iii) Identify the surge arrester lead length. $d' = 6$ m in this example (see Figure C.2) and

$d = d' + d'' = 6 + 3 = 9$ m

– Step 3: Remove all lines connected to d'; none in this case.

– Step 4: Calculate the voltage rate of rise at junction J.

$S = (S') \times 3/(N + 2)$; $N = 3$ (see Figure C.6)
$= (1167) \times 3/(3 + 2)$
$= 700$ kV/µs
~~= (924) × 3/(3+2)~~
~~= 554 kV/µs~~

The reduced single-line, single-transformer substation to be analyzed is shown in Figure C.7.

Calculate the following:

CWW	1.1 × BIL = 1.1 × 550 = 605 kV for the transformer
di/dt	$2(S)/Z = 2(700)/450 = 3.1$ kA/µs
L	$(d' + d'')$ 1.3µH/m = (9) 1.3 = 11.7 µH
V_{sa}	$V_a + L(di/dt) = 273 + 11.7\ (3.1) = 309$ kV

V_T CWW/PR_T = 605/1.15 = 526 kV
V_T/V_{sa} 526/309 = 1.7

Using Equation (C.2) to solve for D_T [could also use Equation (C.4) for this example]:

$$D_T = \frac{0.385cV_{sa}}{S}\frac{V_T - V_{sa}}{2.92V_{sa} - V_T} = \frac{0.385(300)(309)}{700}\frac{526 - 309}{2.92(309) - 526} = 29.4\ \text{m}$$

t should be noted that *D* in this example includes 6 m of bus-bar length, and the maximum allowable separation distance from the transformer to the main bus would be calculated as 23.4 m.

An incoming surge on line A is more critical than one on line C (16.5 m vs. 23.4 m).

Repeat the procedure with the incoming surge on line B and determine the maximum allowable separation distance *D* for transformer T1. Then, a similar procedure should be followed to determine the maximum allowable separation distance *D* for transformer T2. Table C.2 shows the results for all the combinations for the example three-line, two-transformer substation.

Table C.2—Results for example three-line, two-transformer substation

Case	**Transformer considered**	**Surge d line**	***d'* (*J* to arrester**	***d* (total lead length)**	***N* (after reductio n)**	***D* (*J* to transformer)**	**Distance from transforme**
1A	T1	A	12	15	2	16.5	16.5
1B	T1	B	12	15	2	16.5	16.5
1C	T1	C	6	9	3	29.4	23.4
2A	T2	A	24	27	1	4.0	4.0
2B	T2	B	18	21	2	12.6	6.6
2C	T2	C	6	9	3	29.4	11.4

Table C.2 shows that the maximum separation distances for T1 and T2 from the main bus are 16.5 m and 4.0 m, respectively.

C.7.2.3 Verification of BIL for long-tailed surges—example 2

$$\text{minimum BIL} = \frac{1.15\,V_a}{0.83} = \frac{1.15 \times 273}{0.83} = 378\,\text{kV}$$

Recall that V_a =
ng shows that the
378 kV).

$$\text{minimum BIL} = \frac{1.15\,V_a}{0.83} = \frac{1.15 \times 273}{0.83} = 378\,\text{kV}$$

C.8 Presentation of Figure C.8

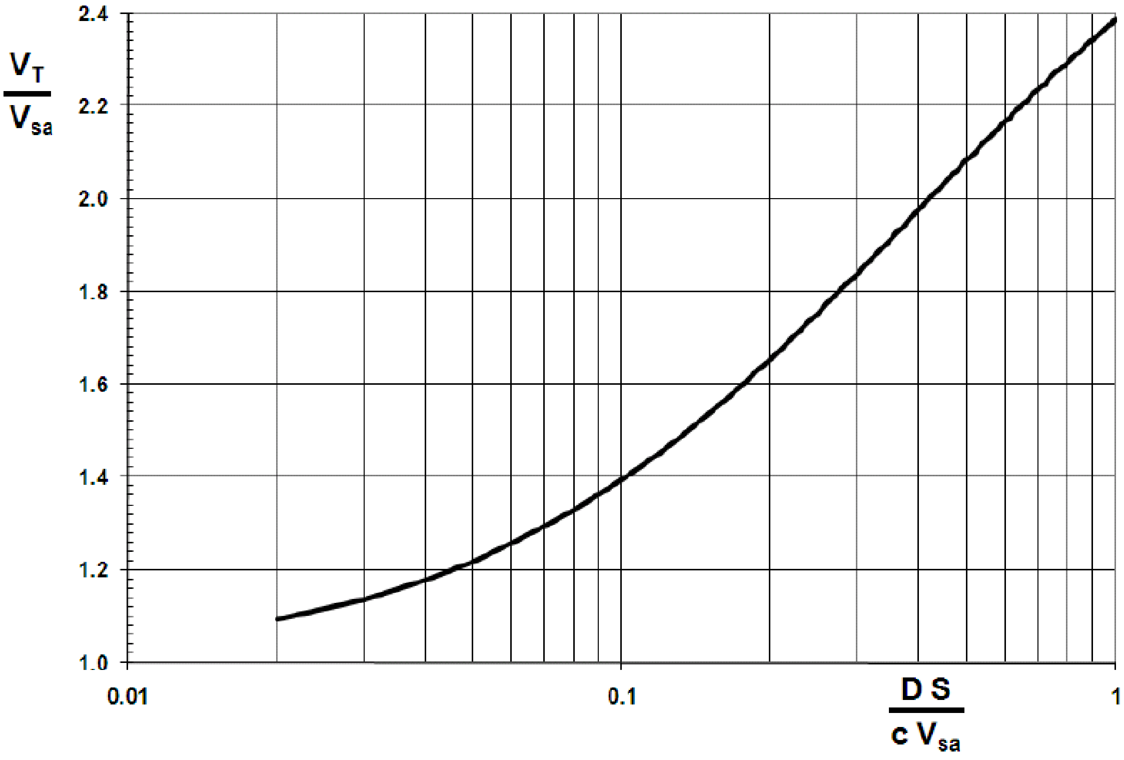
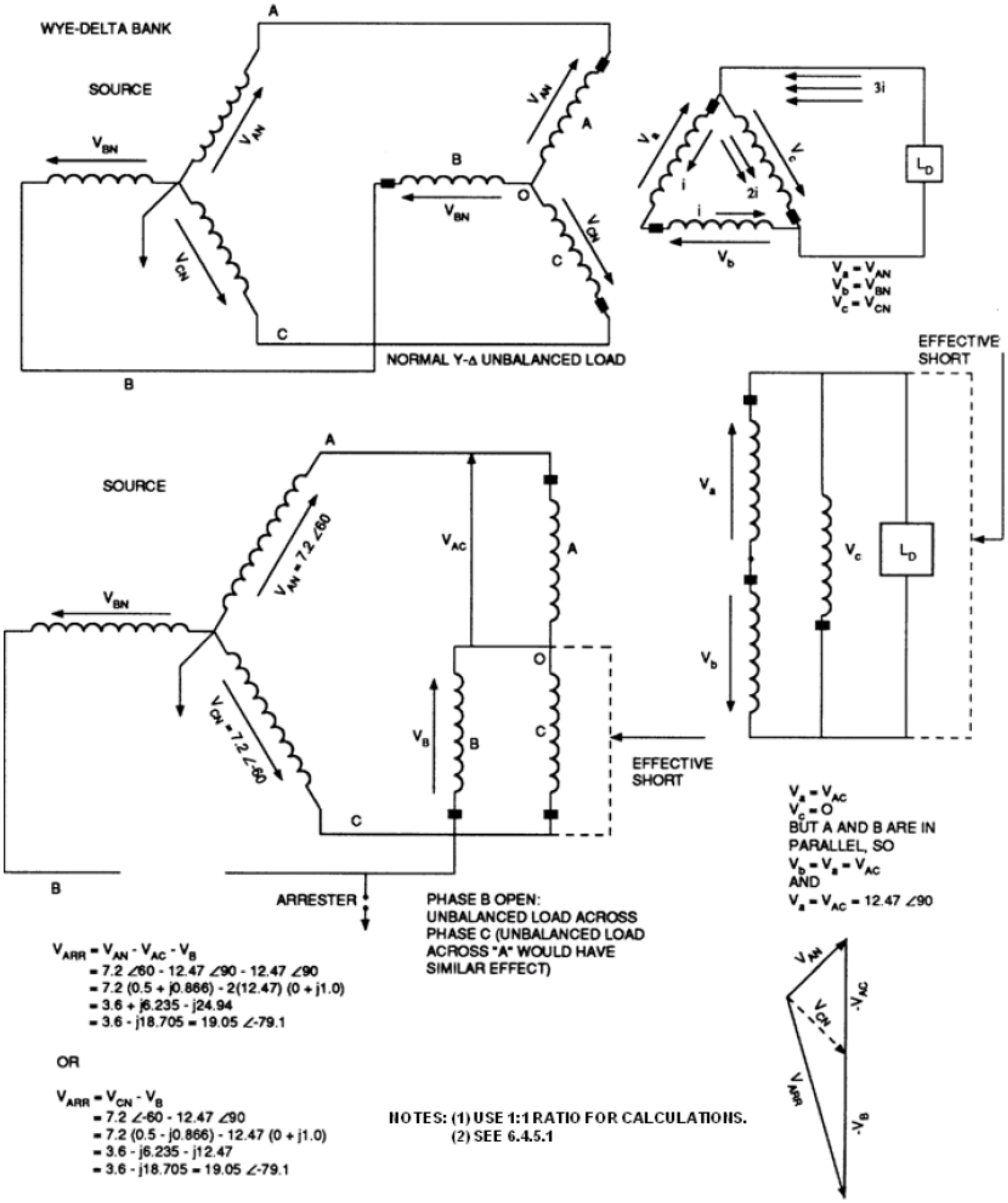


Figure C.8—Voltage at the transformer, V_T, in per unit of V_{sa} as given by Equation (C.1)

Annex D

(informative)

Distribution system overvoltage line diagrams



$V_a = V_{AN}$
$V_b = V_{BN}$
$V_c = V_{CN}$

$V_a = V_{AC}$
$V_c = 0$
BUT A AND B ARE IN PARALLEL, SO
$V_b = V_a = V_{AC}$
AND
$V_a = V_{AC} = 12.47 \angle 90$

PHASE B OPEN: UNBALANCED LOAD ACROSS PHASE C (UNBALANCED LOAD ACROSS "A" WOULD HAVE SIMILAR EFFECT)

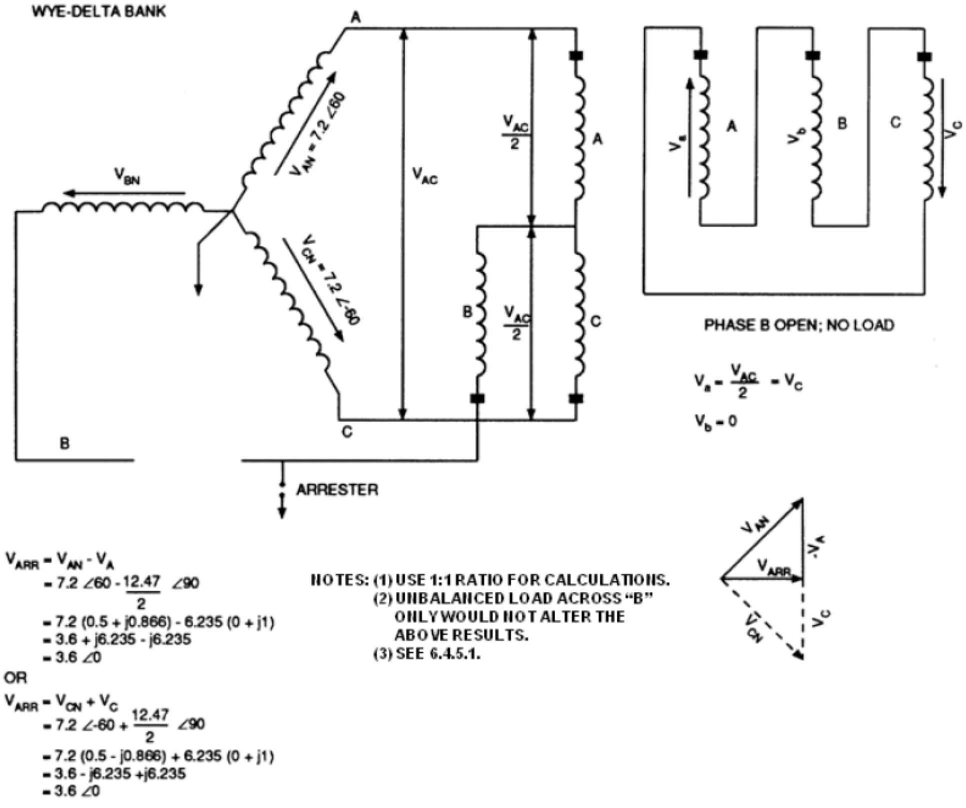
$$\begin{aligned}
V_{ARR} &= V_{AN} - V_{AC} - V_B \\
&= 7.2 \angle 60 - 12.47 \angle 90 - 12.47 \angle 90 \\
&= 7.2\,(0.5 + j0.866) - 2(12.47)\,(0 + j1.0) \\
&= 3.6 + j6.235 - j24.94 \\
&= 3.6 - j18.705 = 19.05 \angle -79.1
\end{aligned}$$

OR

$$\begin{aligned}
V_{ARR} &= V_{CN} - V_B \\
&= 7.2 \angle -60 - 12.47 \angle 90 \\
&= 7.2\,(0.5 - j0.866) - 12.47\,(0 + j1.0) \\
&= 3.6 - j6.235 - j12.47 \\
&= 3.6 - j18.705 = 19.05 \angle -79.1
\end{aligned}$$

NOTES: (1) USE 1:1 RATIO FOR CALCULATIONS.
(2) SEE 6.4.5.1

Figure D.1—Shorted secondary



$$V_a = \frac{V_{AC}}{2} = V_C$$

$$V_b = 0$$

$$
\begin{aligned}
V_{ARR} &= V_{AN} - V_A \\
&= 7.2\angle 60 - \frac{12.47}{2}\angle 90 \\
&= 7.2\,(0.5 + j0.866) - 6.235\,(0 + j1) \\
&= 3.6 + j6.235 - j6.235 \\
&= 3.6\angle 0
\end{aligned}
$$

OR

$$
\begin{aligned}
V_{ARR} &= V_{CN} + V_C \\
&= 7.2\angle -60 + \frac{12.47}{2}\angle 90 \\
&= 7.2\,(0.5 - j0.866) + 6.235\,(0 + j1) \\
&= 3.6 - j6.235 + j6.235 \\
&= 3.6\angle 0
\end{aligned}
$$

NOTES: (1) USE 1:1 RATIO FOR CALCULATIONS.
(2) UNBALANCED LOAD ACROSS "B" ONLY WOULD NOT ALTER THE ABOVE RESULTS.
(3) SEE 6.4.5.1.

Figure D.2—Open primary

Annex E

(informative)

Dual transformer station

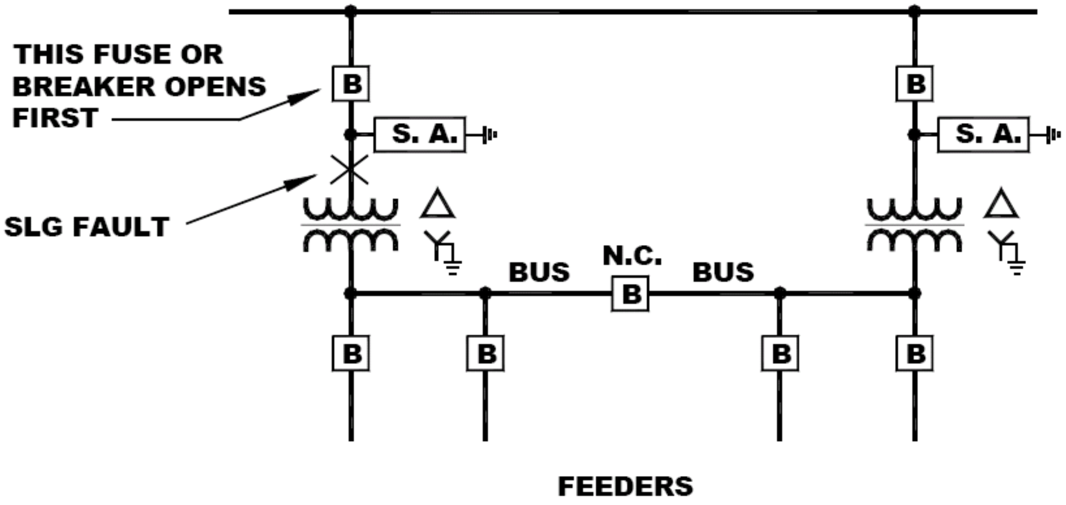


Figure E.1—Dual transformer station

Annex F

(informative)

Modeling of gapless metal-oxide surge arresters

F.1 Introduction

Data on the characteristics of surge arresters have been gathered to form a basis for modeling of surge arresters. The data indicate that metal-oxide arresters have dynamic (or frequency-dependent) characteristics that are significant for lightning and other fast wave front surges. The significant dynamic characteristics are that the voltage across a metal-oxide arrester increases as the time to crest of the arrester current decreases and that the arrester voltage reaches a peak before the arrester current reaches its peak. This would not be the case if the metal-oxide valve element performed strictly as a nonlinear resistance. Dynamic effects are significant considerations for surge arrester location and insulation coordination studies.

F.2 Recommended model for temporary overvoltage and switching surge studies

One objective of a transient study is to evaluate the performance of metal-oxide arresters during temporary and switching surge overvoltages on the system. These overvoltages have a slow wave front and therefore do not exhibit the dynamic effects mentioned previously. A metal-oxide arrester model suitable for these studies would be a simple, nonlinear V-I characteristic. The V-I characteristic should be chosen to be consistent with the range of currents expected in the simulation. Also, consideration should be given to manufacturing tolerances when choosing the appropriate V-I characteristic. For example, if a simulation is being made to determine the maximum voltage to which equipment will be subjected, the characteristic that gives the maximum voltage for a given current should be used. If the simulation is being made to determine the energy that the arrester should dissipate, then the characteristic that gives the minimum voltage for a given current should be used.

F.3 Recommended model for lightning studies

The time to crest for surges found in lightning studies can range from 0.5 μs to several microseconds. These are fast wave front surges for which a metal-oxide arrester exhibits the dynamic effects mentioned previously. A model that will represent these effects over this range of times to crest is shown in Figure F.1. In this model, the nonlinear resistance is designated A0 and A1. (See Table F.1, taken from Durbak [B45].) The two sections are separated by an R-L filter. For slow-front surges, this R-L filter has very little impedance, and the two nonlinear sections of the model are essentially in parallel. For fast-front surges, the impedance of the R-L filter becomes more significant. This results in more current in the nonlinear section designated A0 than in the section designated A1. Because characteristic A0 has a higher voltage for a given current than A1, the result is that the arrester model generates a higher voltage. Since metal-oxide arresters have a higher discharge voltage for fast-front surges, the model matches the overall behavior of a metal-oxide arrester.

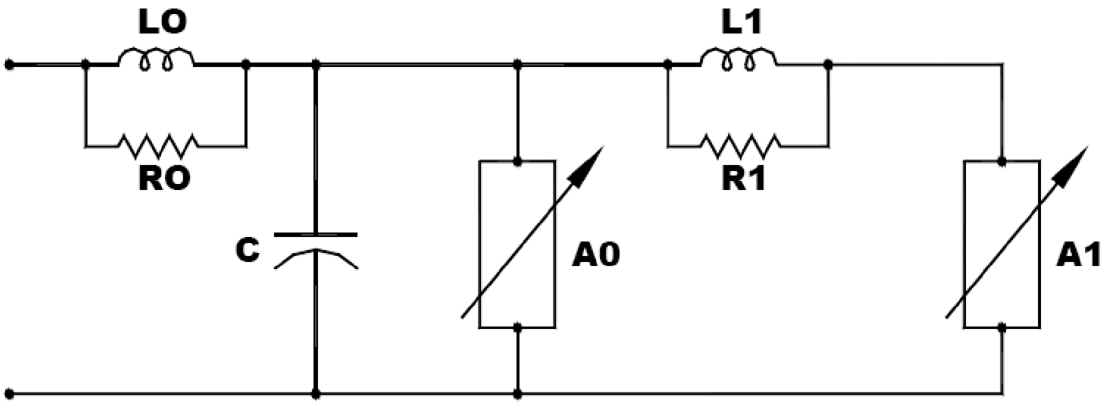


Figure F.1—Frequency-dependent model

The following formulas are suggested for choosing the parameters of the model based on an estimated height of _an arrester _and _the _number _of parallel columns of metal-oxide disks (Durbak [B45]). The inductance L1 and the resistance R1 of the model comprise the filter between the two nonlinear resistances. The formulas for these two parameters are as follows:

L1 is 15 d/n µH
R1 is 65 d/n Ω
where

d is the estimated height of the arrester in meters (use overall dimensions from catalog data)
n is the number of parallel columns of metal-oxide disks in the arrester

The inductance L0 in the model represents the inductance associated with magnetic fields in the immediate vicinity of the arrester. The resistor R0 is used to stabilize the numerical integration when the model is implemented on a digital computer program. The capacitance C represents the terminal-to-terminal capacitance of the arrester.

L0 is 0.2 d/n µH
R0 is 100 d/n Ω
C is100 n/d pF

The nonlinear V-I characteristics -A0 and -A1 can be estimated from the voltage-current points given in Table F.1.

Table F.1—Frequency-dependent model

Current (kA)	V-I characteristics of A0 V (pu) [a]	V-I characteristics of A1 V (pu)[a]
0.01	1.40	—
0.1	1.54	1.23
1	1.68	1.36
2	1.74	1.43
4	1.80	1.48
6	1.82	1.50
8	1.87	1.53
10	1.90	1.55
12	1.93	1.56
14	1.97	1.58
16	2.00	1.59
18	2.05	1.60
20	2.10	1.61

[a] pu is based on a model element that had a 1.6 kV IR at 10 kA. (See Durbak [B45] for greater detail.)

Efforts to match model results to laboratory test data have indicated that these formulas do not always give the best parameters for the frequency-dependent model. However, they do provide a good starting point for picking the parameters. Parameter L1 has the most impact, whereas the other parameters have little impact. The following procedure is recommended for choosing the parameters of the frequency-dependent model (IEEE Working Group Report [B98]):

a) Use the previously given formulas to derive initial values for L0, R0, L1, R1, C, and the nonlinear characteristics A0 and A1.

b) Adjust the per unit value on the curves for characteristics A0 and A1 to get a good match for the published discharge voltages associated with switching surge discharge currents (time to crest of approximately 45 µs).

c) Adjust the value of L1 to get a good match of published arrester discharge voltages for 8/20 ~~µs~~ disCharge currents.

~~Table G.1ÑFrequency-dependent model~~

~~kA~~	~~V-I characteristics of A¯~~	~~V-I characteristics of A1~~
	~~V(p.u.)~~[a]	~~V (p.u.)~~[a]
~~0.01~~	~~1.40~~	~~Ñ~~
~~0.1~~	~~1.54~~	~~1.23~~
~~1~~	~~1.68~~	~~1.36~~
~~2~~	~~1.74~~	~~1.43~~
~~4~~	~~1.80~~	~~1.48~~
~~6~~	~~1.82~~	~~1.50~~
~~8~~	~~1.87~~	~~1.53~~
~~10~~	~~1.90~~	~~1.55~~
~~12~~	~~1.93~~	~~1.56~~
~~14~~	~~1.97~~	~~1.58~~
~~16~~	~~2.00~~	~~1.59~~
~~18~~	~~2.05~~	~~1.60~~
~~20~~	~~2.10~~	~~1.61~~

[a] ~~pu is based on a model element that had a 1.6 kV IR at 10 kA. (See Durbak [B34] for greater detail).~~

The models recommended here apply to single arresters containing one or more columns of metal-oxide disks. If multiple arresters are used in parallel, then the models used must reflect the fact that the nonlinear characteristics are not identical.

Annex G

(informative)

"Rules of thumb" for some common arrester energy discharge cases

G.1 Switching surge energy discharge

$$W_{\mathrm{MCOV}} = 0.021 \times U_{l\text{-}g} \times L / Z \qquad \text{(G.1)}$$

where

W_{MCOV} is the energy discharged into the arrester, in kJ/kV of MCOV
$U_{l\text{-}g}$ is the maximum line-to-ground voltage of the line, in kV rms
L is the line length, in km
Z is the line surge impedance, in ohms

The value of Z can be taken from IEEE Std C62.11-2005, Table 11:

450 Ω for system voltages up to 150 kV
400 Ω for system voltages 151 kV to 325 kV
350 Ω for system voltages 326 kV to 400 kV
325 Ω for system voltages 401 kV to 600 kV
300 Ω for system voltages above 600 kV

This should give a conservative estimate of the energy discharged into the arrester because it is based on the low end of the range of published switching surge protective levels, k_2 (see Table 1) and on a relatively high switching surge level on the line, k_1 (2.6 pu). It applies to cases where the MCOV of the arrester is equal to the maximum line-to-ground voltage of the line. Use of a higher rated arrester (or an arrester with higher switching surge protective level) or a lower switching surge level on the line would result in lower discharge energy.

Example:

For a 362 kV line ($U_{l\text{-}g}$ = 209 kV rms), line length 320 km (200 miles), surge impedance 350 Ω

$$W_{\mathrm{MCOV}} = 0.021 \times 209 \times 320 / 350 = 4.01 \text{ kJ/kV MCOV}$$

G.1.1 Approach taken to arrive at "rule of thumb"

IEC 60099-4 [B74] provides a formula where W is the switching surge energy discharged by an arrester in joules:

$$W = U_{res} \times (U_L - U_{res}) \times 1/Z \times t \quad \text{J}$$

(G.2)

where

U_{res}	is the switching surge residual voltage (discharge voltage) of the arrester, in volts
U_L	is the voltage to which the line is charged, in volts
Z	is the surge impedance of the line, in ohms
t	is the duration of the switching surge, in seconds

For the transmission-line discharge test specified in IEEE Std C62.11-2005, the line charging voltage is
2.6 times the crest of the maximum line-to-ground voltage for systems up to 400 kV and 2.0 times the crest of the maximum line-to-ground voltage for higher system voltages. Generally:

$$U_L = \sqrt{2} \times k_1 \times U_{l\text{-}g}$$

(G.3)

where $U_{l\text{-}g}$ is the maximum rms line-to-ground voltage.

The switching surge discharge voltage of a station class arrester is typically in the range 1.64 to 1.85 times the MCOV of the arrester (see Table 1). Generally:

$$U_{res} = \sqrt{2} \times k_2 \times U_{\mathrm{MCOV}}$$

(G.4)

where U_{MCOV} is the rms MCOV of the arrester.

The duration of the switching surge can be approximated as twice the surge travel time along the line:

$$t = 2 \times L / \mathrm{c}$$

(G.5)

where

L	is the line length, in m
c	is the surge travel speed (approximately the speed of light), in m/s

If we choose an arrester whose MCOV is equal to the maximum line-to-ground voltage of the line, then

$$U_{\mathrm{MCOV}} = U_{l\text{-}g}$$

(G.6) Substituting Equation (G.3) through Equation (G.6) into the energy equation

[Equation (G.2)], the following is obtained:

$$W = U_{l\text{-}g}^{2} \times 4 \times L \times k_2 \times (k_1 - k_2) / (Z \times c) \quad \text{J} \qquad \text{(G.7)}$$

For a typical minimum value of k_1 (= 2.6) and a typical maximum value of k_2 (=1.64), using $c = 3 \times 10^8$ m/s, and with U_{MCOV} given in rms kV and L in km, this reduces to the following equation for arrester discharge energy in kilojoules:

$$W = 0.021 \times U_{l\text{-}g}^{2} \times L / Z$$

(G.8) With the arrester MCOV equal to $U_{l\text{-}g}$, the energy in kilojoules per kilovolt of MCOV can be expressed as follows:

$$W_{\mathrm{MCOV}} = 0.021 \times U_{l\text{-}g} \times L / Z \qquad \text{kJ/kV-of-MCOV} \qquad \text{(G.9)}$$

G.2 Arrester energy requirement for shunt capacitor application

Switching of shunt capacitor banks can result in significant currents being discharged through arresters connected close to the capacitor banks. Although switching surges of different origins can occur, a circuit breaker restrike during capacitor bank deenergization is likely to result in the highest arrester energy duty. Transient overvoltage on the capacitor due to a breaker restrike can approach 3 pu. The discharge voltage of a typical arrester applied at or close to the capacitor would be about 2 pu.

The arrester discharge energy in kilojoules can be roughly estimated as a function of capacitor size, as follows:

$$\text{Arrester energy (in kJ)} = 13.3 \times \text{MVAr per phase for 60 Hz systems}$$
$$= 16.0 \times \text{MVAr per phase for 50 Hz systems}$$

Example:

242 kV max system voltage, 60 Hz
3-phase shunt capacitor bank rating of 200 MVAr
Arrester energy (kJ) = 13.3 × 200/3 = 887 kJ
If arrester MCOV is 140 kV, energy requirement is 887/140 = 6.34 kJ/kV MCOV

G.2.1 Approach taken to arrive at “rule of thumb”

For an arrester connected across a capacitance *C*:

$W = ½\, C\, (V_C^2 – V_A^2)$ J

(G.10)

where

W is the energy discharged by the arrester in joules

V_C is the voltage that would appear across the capacitor in the absence of the arrester

V_A is the voltage across the capacitor with the arrester applied (i.e., arrester discharge voltage)

The reactive volt-amp rating (VAr) of the capacitor is defined by its system rms voltage V_M, capacitance C
and power frequency f:

M

$VAr = V\ ^2$

$\times 2\pi f \times C$ (G.11)

from which

M

$C = (VAr)/(2\pi f\, V\ ^2)$

(G.12) If the peak of the transient overvoltage in the absence of the arrester is as follows:

$V_C = k_3 \times V_M \sqrt{2}$

(G.13)

and the discharge voltage of the arrester is as follows:

$V_A = k_4 \times V_M \sqrt{2}$

(G.14) Substituting Equation (G.11) through Equation (G.14) in Equation (G.10), the following is

obtained:

M

$W = ½ \times (VAr) \times (k_3^2 – k_4^2) \times V\ ^2$

M

$\times 2 / \{(2\pi f \times V\ ^2\}$ (G.15)

which reduces to

$W = 0.16\, (k_3^2 – k_4^2)\, (VAr) / f$

(G.16)

If we assume the potential transient overvoltage due to a breaker restrike is 3 pu ($k_3 = 3$) and the arrester discharge voltage is 2 pu ($k_4 = 2$), then for a 60 Hz system:

$W = 0.0133 \times (VAr)$

(G.17) This is the energy discharged in joules, with the capacitor size expressed in reactive volt-amperes. If the capacitor size is expressed in MVAr, then

$$W \text{ (in kJ)} = 13.3 \times (MVAr) \qquad \text{(G.18)}$$

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