

IEEE Guide for the Application of Insulation Coordination

Sponsor

**Technical Council
of the
IEEE Power Engineering Society**

Reaffirmed 9 June 2005

Approved 26 June 1999

IEEE-SA Standards Board

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

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

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

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Print: ISBN 0-7381-1761-7 SH94764
PDF: ISBN 0-7381-1762-5 SS94764

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Introduction

(This introduction is not a part of IEEE Std 1313.2-1999, IEEE Guide for the Application of Insulation Coordination.)

This guide is the second part of a major revision of ANSI C92.1-1982. The guide is divided into two parts: IEEE Std 1313.1-1996 (Part 1) presents the definitions and the procedure for insulation coordination. IEEE Std 1313.2-1999 (Part 2) is an application guide, which presents practical examples. The technical content of Part 2, particularly 6.2 and 6.3, is taken with permission from the book *Insulation Coordination for Power System* by Andrew R. Hileman, published by Marcel Dekker Inc., New York, NY.

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

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

This standard is prepared by the Insulation Coordination Working Group, under the sponsorship of the Technical Council of the IEEE Power Engineering Society. At the time this application guide was completed, the Insulation Coordination Working Group had the following membership:

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IEEE Guide for the Application of Insulation Coordination

1. Overview

1.1 Scope

The insulation coordination standard and guide apply to three-phase ac systems above 1 kV and are divided into two parts.

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

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

1.2 Purpose

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

2. References

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

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

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

IEEE Std 4-1995, IEEE Standard Techniques for High Voltage Testing.²

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

3. Voltage stresses

3.1 Origin and classification of voltage stresses

IEEE Std 1313.1-1996 identifies classes and shapes of different types of overvoltages. In addition, Part 1 identifies the continuous (power frequency) voltages that are the result of normal operation of the power system. There are many possible causes for each of the different types of overvoltage. Some of the common overvoltages are

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

3.1.1 Continuous power frequency voltages

The designated maximum system voltage is identified in ANSI C84.1-1995 and ANSI C92.2-1987 and is used for insulation coordination. For systems whose maximum system voltage exceeds that given in the standards, the actual maximum system operating voltage should be used.

3.1.2 Temporary overvoltages

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

3.1.2.1 Fault overvoltages

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

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

3.1.2.2 Load rejection overvoltages

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

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

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

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

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

Shunt reactors, static VAR compensators, or special (grouped) arresters can control these overvoltages.

3.1.2.3 Resonance and ferroresonance overvoltages

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

3.1.2.4 Transformer energization caused overvoltages

The energization of a transformer causes in-rush-current and overvoltages at the transformer terminal. These overvoltages may last for seconds and have magnitudes in the range of 1.5–2.0 pu.

3.1.2.5 Limitation of temporary overvoltages by surge arresters

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

3.1.3 Switching overvoltages

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

- Line energization,
- Faults and fault clearing,
- Load rejections, or
- Switching of capacitive or inductive currents.

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

The distribution of switching overvoltages is obtained using a transient program where the breakers are randomly closed or reclosed 200 to 400 times. These overvoltages are then statistically analyzed to obtain a probability distribution, which approximates the data. Several distribution functions have been used, e.g., Gaussian, extreme-value Weibull. However, a Gaussian or normal distribution is used most frequently. This distribution is defined by its 2% value, called the statistical switching overvoltage (E_2), and by its standard deviation σ in pu of E_2 . The standard deviation pu is: σ/E_2 . To clarify the definition, E_2 means that 2% of the switching overvoltages equal or exceed E_2 . The shape of the distribution may be affected by the surge controlling action of an arrester. Typically the gapless arrester modifies the reflected wave and reduces the voltage stress caused by the return wave.

3.1.3.1 Line energization and reclosing overvoltages

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

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

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

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

Line switching overvoltages may be reduced through the use of

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

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

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

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

3.1.3.2 Typical phase-ground switching overvoltages

Table 1 presents approximate values of reclosing produced overvoltages distribution; E_2 (2% probability) and σ/E_2 at the end of the line when no arresters are present. These values were calculated by the case-peak method. In addition, approximate values of the voltage profile are presented. The voltage profile is the ratio of the switching overvoltage at the switched end to that at the open end of the line (E_2).

Table 1—Typical overvoltage from reclosing on a trapped charge

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

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

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

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

3.1.3.3 Typical phase-phase switching overvoltages

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

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

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

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

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

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

The value of the statistical phase-phase switching overvoltage, E_{2p} , may be estimated from the value of the statistical phase-ground switching overvoltage, E_2 . The ratio of E_{2p}/E_2 only varies between 1.6–1.5 while the value of E_2 ranges between 2.0 to 3.0. A ratio of about 1.55 appears reasonable for all values of E_2 . As an example, for an E_2 of 2.8 pu, E_{2p} is 4.35 pu. Also, in general, the values for σ/E_{2p} are equal to the values of σ/E_2 . The maximum phase-phase switching overvoltage is approximately 1.0 to 1.5 standard deviations above E_{2p} . In addition, the values of voltage profiles are similar to those for phase-ground overvoltages.

3.1.3.4 Longitudinal switching overvoltages

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

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

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

3.1.3.5 Fault overvoltages

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

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

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

where

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

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

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

3.1.3.6 Load rejection overvoltages

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

3.1.3.7 Inductive and capacitive currents switching overvoltages

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

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

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

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

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

3.1.4 Lightning overvoltages

Lightning overvoltages are caused by

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

Lightning overvoltages are fast front overvoltages with times to crest from 0.1–20 μ s.

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

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

For strokes close to the substations, lightning overvoltages between phases have approximately the same magnitude as those for phase-ground.

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

3.1.4.1 Lightning type overvoltages caused by switching

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

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

3.1.4.2 Limitation of lightning overvoltages

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

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

3.2 Characteristics of overvoltage protective devices

3.2.1 General

The following three basic types of surge arresters are used:

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

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

The voltage across the terminals of the arrester consists of a discharge voltage and a sparkover voltage if the arrester contains a gap. The discharge voltage is the voltage across the arrester when discharging a current. This voltage is defined as the crest voltage across the terminals of the arrester. The discharge voltage is a function of the magnitude and time to crest of the discharge current. For arresters employing a gap in series

with the valve block, the sparkover voltage is a function of the steepness of the front. For gapped arresters, both of these voltages must be considered.

3.2.2 Metal-oxide surge arresters

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

3.2.2.1 Lightning overvoltages

Manufacturers provide the discharge voltage for the following conditions:

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

Table 2—Lightning impulse classifying currents (IEEE Std 62.11-1999)

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

3.2.2.2 Switching overvoltages

The maximum discharge voltages are provided by the manufacturers for a discharge current having a time to crest of between 45 μ s and 60 μ s and a crest value equal to the switching impulse classifying current given in Table 3. The discharge voltage is insensitive to the variation of discharge current because of the extreme nonlinearity of the metal-oxide material. This discharge voltage is also known as the switching impulse protective level. The dependence of metal-oxide arresters' discharge voltage on the front time of the switching overvoltage is negligible.

Table 3—Switching impulse classifying currents (IEEE Std 62.11-1999)

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

3.2.3 Gapped metal-oxide arrester

The lightning protective level is the maximum of either the lightning impulse sparkover voltage or the discharge voltage.

3.2.4 Gapped silicon-carbide arresters

3.2.4.1 Lightning overvoltages

The manufacturers provide the discharge voltage for a 1.5–40 kA, 8/20 μ s discharge current. This results in a discharge voltage with a time to crest of about 1.2 μ s.

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

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

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

3.2.4.2 Switching overvoltages

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

3.2.5 Spark gaps

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

4. Insulation strength

4.1 General

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

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

4.1.1 Self-restoring insulation

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

4.1.2 Non-self-restoring insulation

In liquid insulation, particle impurities, bubbles caused by chemical and physical effects or by local discharges, can drastically reduce the insulation strength. An important aspect is also that the amount of chemical degradation of the insulation may tend to increase in time. The same is valid for solid insulation. However, in this case the mechanical stress may also affect the insulation strength.

4.2 Insulation behavior at power frequency voltages

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

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

Rain together with pollution can drastically reduce the insulation strength. Fog, dew formation, or light rain together with pollution or contamination usually causes the worst conditions.

The statistical description of the ambient conditions usually requires a large amount of data. The statistical description of aging is even more difficult. Therefore, statistical procedures are not recommended for estimation of the insulation behavior at power frequency voltages.

4.3 Influences of atmospheric conditions on external insulation

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

For atmospheric conditions other than the standard conditions, IEEE Std 4-1995 provides methods to estimate the insulation strength.

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

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

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

4.4 Probability of disruptive discharge

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

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

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

In addition, for evaluation of the switching surge flashover rate a statistical withstand voltage, V_3 , is used which is three standard deviations below the CFO. The truncation point is usually neglected. For self-restoring insulation, the value of the coefficient of variation is smaller for lightning impulses than for switching impulses. For lightning impulses, this coefficient is about 3%. For switching impulses for line or tower insulation, the coefficient increases to an average of about 5%. For station insulation, the coefficient of variation is generally assumed to be between 6% and 7%.

4.5 Influence of polarity and overvoltage shape

When the more highly stressed electrode in air is positively charged, the breakdown voltage is lower than if the electrode is negatively charged. For the majority of gaps, the high voltage conductor is more stressed and is the more irregularly shaped electrode. If the grounded electrode of a gap is more highly stressed, the dielectric strength to negative impulses is lower. For air-porcelain insulation, e.g., tower or line insulation, positive polarity impulses produce the lower insulation strength. For self-restoring station insulation, apparatus standards specify that the polarity which results in the lower insulation strength be used to establish the BIL or BSL. Although not specified, this polarity is almost universally positive.

The breakdown voltage of the insulation depends on the impulse shape. For switching impulses, the strength of external insulation depends primarily on the impulse front. Only in the case of pollution does the tail of the impulse become important. Both the crest and shape of the impulse affect the strength of internal insulation.

For switching impulses, there exists a critical wavefront (CWF) or time to crest value, which results in a minimum CFO. This CWF varies with the gap spacing. The approximate value of the CWF (μs), for positive polarity, is numerically equal to 50 times the gap spacing in meters. For larger gap spacing the change in the insulation strength at the CWF is more pronounced than for shorter gaps. For normal strike distances and clearances in high-voltage (HV) and extra high-voltage (EHV) systems, the CWF ranges from about 100–250 μs . In weak systems or in systems where low-side switching is employed, the wavefront time is in the range of 1000–2000 μs . In these cases, both the CFO and standard deviation increase, which results in about a 10% increase, in insulation strength.

The insulation strength for lightning impulses is normally only available for the standard lightning impulse, i.e., 1.2/50 μs . However, this wave shape seldom occurs on the utility system. Therefore, either some approximations or a mathematical model of the breakdown process are frequently necessary to evaluate the strength of the insulation for nonstandard wave shapes. This is of primary importance in evaluating the insulation strength for surges resulting from a backflash, and in evaluating the insulation strength of station insulation.

In contrast to the switching impulse, the tail or time to half value of the lightning impulse generally determines the CFO.

The flashover voltage of gaps, with close to uniform electric field distribution and the gaps under high-pressure gas in a GIS system, is almost independent from the applied voltage shape and duration.

4.6 Phase-phase and longitudinal insulation

The phase-phase and longitudinal insulation strength depends on the relationship of the voltage components at the two terminals. This dependency is particularly important for external insulation in EHV systems and for three-phase metal enclosed substations.

For phase-phase insulation, the test specified by IEC 60071-1 (1993) [B2]⁵ to establish the phase-phase BSL consists of two synchronized switching impulses, each of equal value, but of opposite polarity. The positive switching impulse applied to one electrode has the standard switching impulse wave shape. The negative switching impulse, applied to the other terminal, has a wave shape with a time to crest and a time to half value, which are not shorter than the wave shape on the positive polarity terminal. Therefore, in evaluating the required BSLs, the results of the calculation must be converted to the above test specifications of equal crest surge voltage on each of the terminals.

The standard deviations for either method of defining the phase-phase strength are essentially identical, about 5% for the usual gap, decreasing to about 2% for a 300–400 m conductor-conductor gap.

5. Performance/reliability criterion

The fundamental performance or reliability criterion is the acceptable failure rate. This criterion is based on the consequence of failure and on the expected life of the equipment. Therefore, the failure rate of transmission lines and substation equipment may be different.

5.1 Transmission lines

The performance/reliability criterion for lightning is normally specified as the number of flashovers per 100 km-years. For switching surges, the flashover rate is normally specified in terms of flashovers per number of switching operations. However, the highest magnitude switching surges normally occur when reclosing, which is normally caused by a fault associated with lightning. Thus, the two separate criteria may not be appropriate in specifying the line reliability. Another criterion, denoted as the storm outage rate, is the number of unsuccessful reclosures per year and is obtained by multiplying the lightning flashover rate for the line in units of flashovers per year by the switching surge flashover rate in terms of flashovers per switching operation. For example, assuming the lightning flashover rate to be two per year and the switching surge flashover rate to be one per 100 switching operations, the storm outage rate is two per 100 years assuming one reclosing operation per year. Both the storm outage rate and the lightning flashover rate may be important since the lightning fault creates voltages “dips” or depressions in power frequency voltage, which may affect customer power quality.

For transmission lines, lightning flashover rates vary with system voltage and may range from 0.5 for EHV systems to 20 per 100 km-year for HV systems. Although lines are being designed for switching surge flashover rates between 1 and 10 flashovers per 100 switching operations, due to other conservative assumptions, switching surge flashovers are relatively rare.

5.2 Substations

The commonly used reliability criterion for lightning is the MTBF.

⁵The numbers in brackets correspond to those of the bibliography in Annex A.