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(Revision of IEEE Std 1313-1993)

IEEE Standard for Insulation Coordination—Definitions, Principles, and Rules

Sponsor

Technical Council
of the
IEEE Power Engineering Society

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Abstract: The procedure for selection of the withstand voltages for equipment phase-to-ground and phase-to-phase insulation systems is specified. A list of standard insulation levels, based on the voltage stress to which the equipment is being exposed, is also identified. This standard applies to three-phase ac systems above 1 kV.
Keywords: atmospheric correction factor, basic lightning impulse insulation level (BIL), basic switching impulse insulation level (BSL), crest value, ground fault factor, insulation coordination, overvoltage, phase-to-ground insulation configuration, phase-to-phase insulation configuration, protective margin, protective ratio, standard withstand voltages, voltage stress

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Introduction

(This introduction is not a part of IEEE Std 1313.1-1996, IEEE Standard for Insulation Coordination—Definitions, Principles, and Rules.)

This standard is a revision of IEEE Std 1313-1993. This standard presents the definitions and the procedure for insulation coordination. A related draft standard, IEEE P1313.2, is an application guide, which presents practical examples.

A new concept in this standard is the addition of phase-to-phase insulation coordination, and longitudinal insulation coordination, which is the coordination of switching surges and 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 IEEE Std 1313-1993. The first step is the determination of voltage stresses using digital computer simulation, a transient analyzer, or mathematical methods. These analyses result in nonstandard overvoltage waveforms, which have to be converted to an equivalent standard waveshape. The second step is the selection of insulation strength to achieve the desired level of probability of failure. The standard considers both the BIL and BSL as either a conventional or statistical variable. For equipment in Class I (1–240 kV), use of the low-frequency withstand voltage and lightning impulse withstand voltage are recommended. For Class II (> 242 kV), use of the lightning impulse withstand voltage and switching withstand voltage are recommended.

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IEEE Standard for Insulation Coordination—Definitions, Principles, and Rules

1. Overview

1.1 Scope

This standard applies to three-phase ac systems above l kV. It specifies the procedure for selection of the withstand voltages for equipment phase-to-ground and phase-to-phase insulation systems. It also identifies a list of standard insulation levels, based on the voltage stress to which the equipment is being exposed.

1.2 Purpose

The purpose of this standard is to

a) Define applicable terms
b) Outline insulation coordination procedures
c) Identify standard insulation levels

1.3 Applications

The insulation coordination procedure described in this standard is generally applicable to all type of apparatus. However, alternative insulation levels and test voltages may be required or permitted by the appropriate apparatus standards.

The insulation coordination of rotating machines is not considered in this standard, but the basic concepts may be applicable.

Insulation levels (transmission line) may be different from those identified as standard insulation levels but the methods of insulation coordination are applicable.

2. References

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

ANSI C84.1-1989, American National Standard for Electric Power Systems and Equipment—Voltage Ratings (60 Hz).[1]

IEEE Std 4-1995, IEEE Standard Techniques for High-Voltage Testing (ANSI).[2]

IEEE Std 48-1990, IEEE Standard Test Procedures and Requirements for High-Voltage Alternating-Current Cable Terminations (ANSI).

IEEE Std 100-1992, The New IEEE Standard Dictionary of Electrical and Electronics Terms (ANSI).

IEEE Std 386-1995, IEEE Standard for Separable Insulated Connector Systems for Power Distribution Systems Above 600 V (ANSI).

IEEE Std 404-1993, IEEE Standard for Cable Joints for Use with Extruded Dielectric Cable Rated 5000–138 000 V and Cable Joints for Use with Laminated Dielectric Cable Rated 2500–500 000 V (ANSI).

IEEE 1312-1987 (Reaff 1993), American National Standard for Power Systems—Alternating-Current Electrical Systems and Equipment Operating at Voltages Above 230 kV Nominal Preferred Voltage Ratings (ANSI).

IEEE Std C37.04-1979 (Reaff 1988), IEEE Standard Rating Structure for AC High-Voltage Circuit Breakers Rated on a Symmetrical Current Basis (ANSI/DoD).

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

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.

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 (ANSI).

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

IEEE Std C62.11-1993, IEEE Standard for Metal-Oxide Surge Arresters for Alternating Current Power Circuits (ANSI).

IEEE Std C62.22-1991, IEEE Guide for the Application of Metal-Oxide Surge Arresters for Alternating-Current Systems (ANSI).

[1]ANSI publications are available from the Sales Department, American National Standards Institute, 11 West 42nd Street, 13th Floor, New York, NY 10036, USA.

[2]IEEE publications are available from the Institute of Electrical and Electronics Engineers, Service Center, 445 Hoes Lane, P.O. Box 1331, Piscataway, NJ 08855-1331, USA.

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

IEC 60-1 (1989), High-voltage test techniques, Part 1: General definitions and test requirements.[3]

IEC 71-1 (1993), Insulation co-ordination, Part 1: Definitions, principles and rules.

IEC 71-2 (1976), Insulation co-ordination, Part 2: Application guide.

3. Definitions

For the purposes of this standard, the following definitions apply:

3.1 atmospheric correction factor: A factor applied to account for the difference between the atmospheric conditions in service and the standard atmospheric conditions. (In terms of this standard, it applies to external insulation only.)

3.2 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.

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

3.4 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.

3.5 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.

3.6 conventional withstand voltage: The voltage that an insulation system is capable of withstanding without failure or disruptive discharge under specified test conditions.

3.7 crest value (peak value): The maximum absolute value of a function when such a maximum exists.

3.8 effectively grounded system: A system in which the neutral points are connected directly to the ground through a connection in which no impedance has been inserted intentionally.

3.9 external insulation: The air insulation and the exposed surfaces of solid insulation of equipment, which are both subject to dielectric stresses and to the effects of atmospheric and other external conditions such as contamination, humidity, vermin, etc.

3.10 front-of-wave lightning impulse voltage shape: A voltage impulse, with a specified rate-of-rise, that is terminated intentionally by sparkover of a gap that occurs on the rising front of the voltage wave with a specified time to sparkover, and a specified minimum crest voltage.

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

3.11 ground-fault factor: The ratio of the highest power frequency voltage on an unfaulted phase during a line-to-ground fault to the phase-to-ground power-frequency voltage without the fault.

NOTES

1—The ground-fault factor generally will be less than 1.3, if the zero-sequence reactance is less than three times the positive-sequence reactance, and the zero-sequence resistance does not exceed the positive-sequence reactance.

2—IEEE Std C62.1-1989[4] defines a "coefficient of grounding." This coefficient can be obtained by dividing the ground-fault factor by dividing the ground-fault factor by $\sqrt{3}$.

3.12 impedance grounded neutral system: A system whose neutral point(s) are grounded through an impedance (to limit ground-fault currents).

3.13 insulation configuration: The complete geometric configuration of the insulation, including all elements (insulating and conducting) that influence its dielectric behavior. Examples of insulation configurations are phase-to-ground, phase-to-phase, and longitudinal.

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

3.15 internal insulation: Internal insulation comprises the internal solid, liquid, or gaseous elements of the insulation of equipment, which are protected from the effects of atmospheric and other external conditions such as contamination, humidity, and vermin.

3.16 lightning impulse protective level of a surge-protective device: The maximum lightning impulse voltage expected at the terminals of a surge-protective device under specified conditions of operation.

NOTE—The lightning impulse protective levels are given by following: 1) Front-of-wave impulse sparkover or discharge voltage, and 2) the higher of either a 1.2/50 impulse sparkover voltage or the discharge voltage for a specified current magnitude and waveshape.

3.17 lightning overvoltage: A type of transient overvoltage in which a fast front voltage is produced by lightning or fault. Such overvoltage is usually unidirectional and of very short duration. A typical waveform is shown in figure 1.

3.18 longitudinal insulation configuration: An insulation configuration between terminals belonging to the same phase, but which are temporarily separated into two independently energized parts (e.g., open switching device).

3.19 longitudinal overvoltage: An overvoltage that appears between the open contact of a switch.

3.20 maximum system voltage, V_m: The highest root-mean-square (rms) phase-to-phase voltage that occurs on the system under normal operating conditions, and the highest rms phase-to-phase voltage for which equipment and other system components are designed for satisfactory continuous operation without deterioration of any kind.

3.21 nominal system voltage: The rms phase-to-phase voltage by which the system is designated and to which certain operating characteristics of the system are related.

NOTE—The nominal system voltage is near the voltage level at which the system normally operates. To allow for operating contingencies, systems generally operate at voltage levels about 5–10% below the maximum system voltage for which systems components are designed.

[4]Information on references can be found in clause 2.

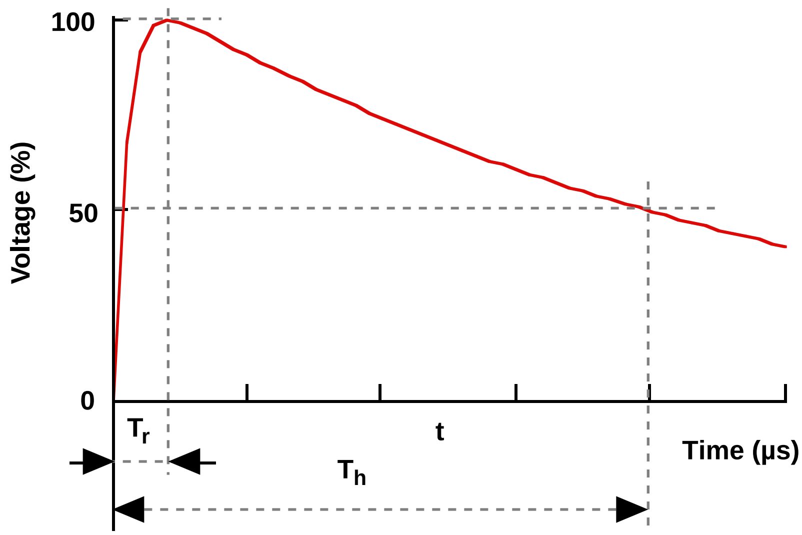

Figure 1—Lightning overvoltages (T_r = 0.1–20 μs, Th < 300 μs, where T_r is the time-to-crest value, T_h is the time-to-half value)

3.22 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.

3.23 overvoltage: Voltage, between one phase and ground or between two phases, having a crest value exceeding the corresponding crest of the maximum system voltage. Overvoltage may be classified by shape and duration as either temporary or transient.

NOTES

1—Unless otherwise indicated, such as for surge arresters, overvoltages are expressed in per unit with reference to V_m $(\sqrt{2})/(\sqrt{3})$.

2—A general distinction may be made between highly damped overvoltages of relatively short duration (transient overvoltages) and undamped or only slightly damped overvoltages of relatively long duration (temporary overvoltages). The transition between these two groups cannot be clearly defined.

3.24 performance criterion: The criterion upon which the insulation strength or withstand voltages and clearances are selected. The performance criterion is based on an acceptable probability of insulation failure and is determined by the consequence of failure, required level of reliability, expected life of equipment, economics, and operational requirements. The criterion is usually expressed in terms of an acceptable failure rate (number of failures per year, years between failures, risk of failure, etc.) of the insulation configuration.

3.25 phase-to-ground insulation configuration: An insulation configuration between a terminal and the neutral or ground.

3.26 phase-to-phase insulation configuration: An insulation configuration between two-phase terminals.

3.27 protective margin (PM): The value of the protective ratio (PR), minus one, expressed in percent. PM = (PR–1) · 100.

3.28 protective ratio (PR): The ratio of the insulation strength of the protected equipment to the overvoltages appearing across the insulation.

3.29 resonant grounded neutral system: A system in which one or more neutral points are connected to ground through reactors that approximately compensate the capacitive component of a single-phase-to-ground-fault current.

NOTE—With resonant grounding of a system, the fault current is limited such that an arc fault in air will be self-extinguishing.

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

3.31 standard chopped wave impulse voltage shape: A standard lightning impulse that is intentionally interrupted on the tail by sparkover of a gap or other equivalent chopping device. Usually the time to chop is 2–3 μs.

3.32 standard lightning impulse voltage shape: An impulse that rises to crest value of voltage in 1.2 μs (virtual time) and drops to 0.5 crest value of voltage in 50 μs (virtual time), both times being measured from the same origin and in accordance with established standards of impulse testing techniques. It is described as a 1.2/50 impulse.

3.33 standard power-frequency short-duration voltage shape: A sinusoidal voltage with frequency between 48 Hz and 62 Hz, and duration of 60 s.

NOTE—Some apparatus standards (e.g., transformers) use a modified waveshape when practical test considerations or particular dielectric strength characteristics make such modification necessary.

3.34 standard switching impulse voltage shape: A full impulse having a time-to-crest of 250 μs and a time-to-half value of 2500 μs. It is described as a 250/2500 impulse.

NOTE—Some apparatus standards use a modified waveshape where practical test considerations or particular dielectric strength characteristics make some modification imperative (see IEEE Std 4-1995).

3.35 statistical 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 insulation.

3.36 statistical 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 insulation.

3.37 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%, 0.1%).

3.38 switching impulse protective level of a surge-protective device: The maximum switching impulse expected at the terminals of a surge-protective device under specified conditions of operation.

NOTE—The switching impulse protective levels given by the higher of either: 1) the switching impulse discharge voltage for a specified current magnitude and waveshape, or 2) the switching impulse sparkover voltage for a specified voltage waveshape.

3.39 switching overvoltage: A transient overvoltage in which a slow front, short-duration, unidirectional or oscillatory, highly damped voltage is generated (usually by switching or faults). A typical waveform is shown in figure 2.

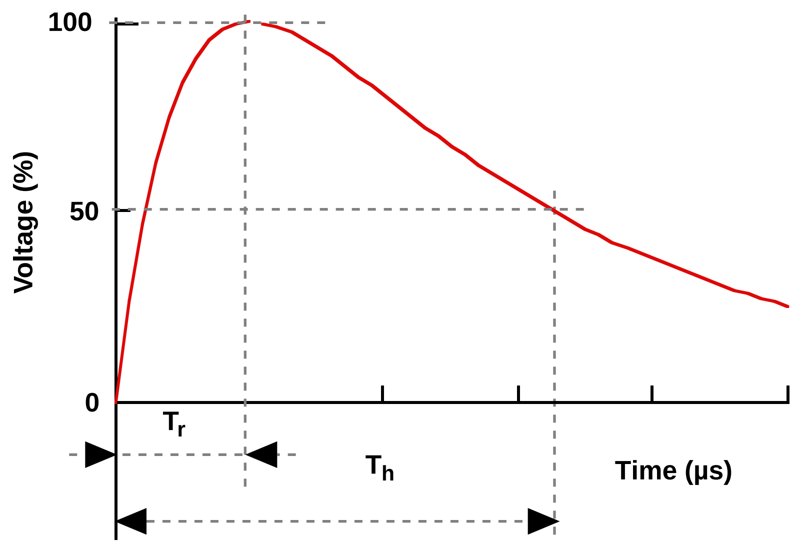

Figure 2—Switching overvoltages (T_r = 20-5000 μs, T_h < 20 000 μs, where T_r is the time-to-crest value, T_h is the time-to-half value)

3.40 temporary overvoltage: An oscillatory phase-to-ground or phase-to-phase overvoltage that is at a given location of relatively long duration (seconds, even minutes) and that is undamped or only weakly damped. Temporary overvoltages usually originate from switching operations or faults (e.g., load rejection, single-phase fault, fault on a high-resistance grounded or ungrounded system) or from nonlinearities (ferroresonance effects, harmonics), or both. They are characterized by the amplitude, the oscillation frequencies, the total duration, or the decrement.

3.41 time-to-crest value (T_r): The time that an impulse rises to crest value.

3.42 time-to-half value (T_h): The time that an impulse drops to 0.5 crest value.

3.43 transient overvoltage: A short-duration highly damped, oscillatory or nonoscillatory overvoltage, having a duration of few milliseconds or less. Transient overvoltage is classified as one of the following types: lightning, switching and very fast front, short duration.

3.44 ungrounded (isolated) system: A system, circuit, or apparatus without an intentional connection to ground, except through potential-indicating or measuring devices or other very-high-impedance devices.

3.45 very fast front, short-duration overvoltage: A transient overvoltage in which a short duration, usually unidirectional, voltage is generated (often by GIS disconnect switch operation or when switching motors). High-frequency oscillations are often superimposed on the unidirectional wave. A typical waveform is shown in figure 3.

3.46 very fast front voltage shape: This category has not been standardized at this time.

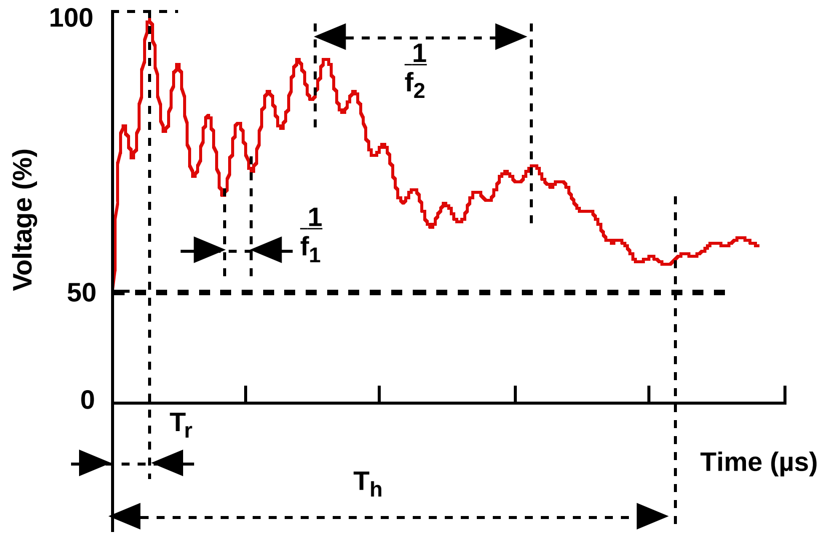

Figure 3—Typical very fast front short-duration overvoltages (T_r = 3–100 μs, T_h < 3 ms, f_1 = 0.3–100 MHz, f_2 = 30–300 kHz where T_r is the time-to-crest, T_h is the time-to-half value, f_1 and f_2 are the frequencies of the superimposed oscillation; f_1 and f_2 are defined in the figure)

3.47 voltage shape: A waveform of a voltage impulse that has been standardized to define insulation strength. The standardized voltage shapes are as follows: power-frequency short-duration, standard switching impulse, standard lightning impulse, very fast front, standard chopped wave impulse, and front-of-wave lightning impulse.

3.48 withstand voltage: The voltage that an insulation is capable of withstanding. In terms of insulation, this is expressed as either conventional withstand voltage or statistical withstand voltage.

4. Principles of insulation coordination

4.1 General outline of the insulation coordination procedure

The procedure for insulation coordination consists of

a) Determination of voltage stresses
b) Selection of the insulation strength to achieve the desired probability of failure

The voltage stresses can be reduced by the application of surge-protective devices, switching device insertion resistors and controlled closing, shield wires, improved grounding, etc.

4.2 Determination of the system voltage stress

System transient analyses that include the selection and location of the overvoltage limiting devices are performed to determine the amplitude, waveshape, and duration of system voltage stresses.

The overvoltage stress may be characterized either by

- The maximum crest values, or
- A statistical distribution of crest values, or
- A statistical overvoltage value [this is an overvoltage generated by a specific event on the system (lightning discharge, line energization, reclosing, etc.), with a crest value that has a 2% probability of being exceeded].

The results of the transient analysis should provide voltage stresses for the following classes of overvoltage:

- Temporary overvoltage (phase-to-ground and phase-to-phase)
- Switching overvoltage (phase-to-ground and phase-to-phase)
- Lightning overvoltage (phase-to-ground and phase-to-phase)
- Longitudinal overvoltage (an instantaneous combination of switching or lightning surge and a power-frequency voltage)

4.3 Comparison of overvoltages with insulation strength

To compare the overvoltages with the insulation strength, the insulation strength must be modified because of the (1) nonstandard waveshape of overvoltages and (2) nonstandard atmospheric conditions.

The dielectric strength of insulation for surges having nonstandard waveshapes is assessed by comparison to the dielectric strength as provided by standard chopped wave tests.

The rules for the atmospheric correction of withstand voltages for external insulations are specified in IEEE Std 4-1995. For insulation coordination purposes, wet conditions are assumed and only the relative air density corresponding to the altitude needs to be taken into account.

In addition, a safety margin may be necessary based on consideration of

- Statistical nature of the test results
- Factory or field assembly of equipment
- Aging of insulation
- Accuracy of analysis
- Other unknown factors

The overall protective margin is derived from experience and further described in IEEE P1313.2.[5]

4.4 Selection of standard insulation levels

The selection of the rated component insulation level consists of the selection of standard insulation withstand voltages that provide sufficient margin above the system overvoltage stress.

The tests required to verify the component rated maximum voltages are defined by the relevant apparatus standards. The component low-frequency, short-duration withstand voltage is selected from the list of standard withstand voltages provided in 4.5.

The standard BIL and BSL values are selected from the table in 4.6.

[5]This is an authorized IEEE standards project currently under development. For information on the status of this project, please contact the IEEE Standards Department, (908) 562-3800.

4.5 Low-frequency, short-duration withstand voltages

The following list of low-frequency, short-duration withstand voltages (rms values, expressed in kilovolts), are extracted from IEEE Std C57.12.00-1993 and IEEE Std C57.21-1990. The withstand value should be taken from this table.

10, 15, 19, 26, 34, 40, 50, 70, 95, 140, 185, 230, 275, 325, 360, 395, 460, 520, 575, 630, 690, 750, 800, 860, 920, 980, 1040, 1090

The relevant apparatus standards recognize low-frequency, short-duration withstand voltages other than those listed above. Refer to these other standards for specific values.

4.6 Standard BIL and BSL

The BIL and BSL values should be taken from this table.

10, 20, 30, 45, 60, 75, 95, 110, 125, 150, 200, 250, 350, 450, 550, 650, 750, 825, 900, 975, 1050, 1175, 1300, 1425, 1550, 1675, 1800, 1925, 2050, 2175, 2300, 2425, 2550, 2625, 2675, 2800, 2925, 3050

Some apparatus standards recognize that a fixed relationship between BIL and BSL is appropriate for specific equipment and substation assemblies. Therefore the BSL may differ from the table values. In such cases, refer to the relevant apparatus standards for specific values.

4.7 Classes of maximum system voltage

The standard highest voltages are divided into the following two classes:

— Class I: Medium (1–72.5 kV) and high (72.5–242 kV) voltages: > 1 kV and ≤ 242 kV
— Class II: Extra high and ultra high voltages: > 242 kV

4.8 Selection of the equipment standard insulation level

The standard insulation level of equipment is generally given by a set of two standard withstand voltages.

For equipment in Class I (1–242 kV), the standard insulation withstand level is given by

— The low-frequency, short-duration withstand voltage
— The basic lightning impulse insulation level (BIL)

The standard withstand voltages for equipment in Class I are provided in table 1.

For equipment in Class II (> 242 kV), the standard insulation withstand level is given by

— The basic switching impulse insulation level (BSL)
— The basic lightning impulse insulation level (BIL)

The standard withstand voltages for equipment in Class II are provided in table 2.

Table 1—Standard withstand voltages for Class I ($15\ kV < V_m \leq 242\ kV$)

Maximum system voltage (phase-to-phase) V_m kV, rms	Low-frequency, short-duration withstand voltage[a] (phase-to-ground) kV, rms	Basic lightning impulse insulation level (phase-to-ground) BIL kV, crest
15	34	95 110
26.2	50	150
36.2	70	200
48.3	95	250
72.5	95 140	250 350
121	140 185 230	350 450 550
145	230 275 325	450 550 650
169	230 275 325	550 650 750
242	275 325 360 395 480	650 750 825 900 975 1050

[a]See relevant apparatus standards for specific values. Preferred values are provided in 4.5.

Tables 1 and 2 show for a given maximum rated voltage the possibility of choice from several withstand voltages. The choice should be based on the insulation coordination procedure.

The withstand voltages in tables 1 and 2 are phase-to-ground voltages. With some equipment, the phase-to-phase withstand voltage (i.e., test voltages) can be the same as the phase-to-ground withstand voltage (e.g., with three-phase transformers). With other equipment, the phase-to-phase insulation level is undefined (e.g., support insulators), and the withstand voltage is dictated by the design of the assembly (i.e., air clearances between phases and to ground). It is necessary to establish the phase-to-phase insulation level, or required clearances, by the insulation coordination procedure.

Table 2—Standard withstand voltages for Class II (V_m > 242 kV)

Maximum system voltage (phase-to-phase) V_m kV, rms	Basic lightning impulse insulation level (phase-to-ground) BIL kV, peak	Basic switching impulse insulation level[a] (phase-to-ground) BSL kV, peak
362	900 975 1050 1175 1300	650 750 825 900 975 1050
550	1300 1425 1550 1675 1800	1175 1300 1425 1550
800	1800 1925 2050	1300 1425 1550 1675 1800

[a]See specific BIL/BSL relationship in relevant apparatus standard. Preferred values are provided in 4.6.

In this standard the individual equipment BIL and BSL are considered. It is common in practice to refer to the BIL or BSL of an assembly of equipment such as the BIL or BSL of an entire station (e.g., a station BIL). This station BIL refers to the BIL of all apparatus comprising the station except possibly the transformer—or possibly, at high voltage, the circuit breaker, since only one BIL is available for each system voltage. It is also assumed when referring to a station BIL that the air clearances are set to maintain this BIL. This type of nomenclature is necessary when considering a gas-insulation substation.