



IEEE Guide for Recommended Electrical Clearances and Insulation Levels in Air Insulated Electrical Power Substations

STANDARDS

IEEE Power and Energy Society

Developed by the
Substations Committee

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(Revision of IEEE Std 1427-2006)



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Developed by

Substations Committee
of the
IEEE Power and Energy Society

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Abstract: This guide, covering three-phase ac systems from 1 kV to 800 kV, provides recommended electrical operating, safety clearances, and insulation levels in air-insulated electric supply substations; addresses insulation coordination procedures; provides design procedures for the selection and coordination of the insulation levels within the station as they relate to substation clearances; and addresses how reduced clearances in high-voltage ac substations will allow for compact bus arrangements and substation voltage uprating applications.

Keywords: basic lightning impulse insulation level (BIL), basic switching impulse insulation level (BSL), clearances, IEEE 1427™, insulation coordination, insulation levels, substation

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Introduction

This introduction is not part of 1427-2020, IEEE Guide for Recommended Electrical Clearances and Insulation Levels in Air Insulated Electrical Power Substations.

This guide was revised by members of Working Group D1 of the Substations Committee and is under the sponsorship of the Power and Energy Society.

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IEEE Guide for Recommended Electrical Clearances and Insulation Levels in Air Insulated Electrical Power Substations

1. Overview

1.1 Scope

This guide, covering three-phase ac systems from 1 kV to 800 kV, provides recommended electrical operating, ~~and~~ safety clearances, and insulation levels in air-insulated electric supply substations; addresses insulation coordination procedures; provides design procedures for the selection and coordination of the insulation levels within the station as they relate to substation clearances; and addresses how reduced clearances in high-voltage ac substations will allow for compact bus arrangements and substation voltage uprating applications. This guide addresses insulation coordination procedures, including the choice of insulation levels and arrester specification, in limited detail and only as relevant to clearance requirements. Detailed and expanded coverage of insulation coordination procedures is provided in other ANSI and IEEE guides and standards (see Clause 2). This guide focuses on open-air bus assemblies and configurations and excludes apparatus clearances (i.e., bushing clearances for transformers, and breakers). Detailed coverage of apparatus clearances is provided in other applicable guides and standards.

1.2 Purpose

Proper electrical clearances are necessary for the design, construction, and operation of electric supply substations. This document develops guidelines for the application of recommended electrical clearances and insulation levels in air-insulated substations. The recommended clearances incorporate both design/operating clearances and safety clearances.

1.3 Word usage

The word *shall* indicates mandatory requirements strictly to be followed in order to conform to the standard and from which no deviation is permitted (*shall* equals *is required to*).^{1,2}

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

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

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

2. Normative references

The following referenced documents are indispensable for the application of this document (*i.e., they must be understood and used, so each referenced document is cited in text and its relationship to this document is explained*). For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments or corrigenda) applies.

IEEE Std 1313.2TM~~-1999~~, IEEE Guide for the Application of Insulation Coordination^{3,4}.

¹The use of the word *must* is deprecated and cannot be used when stating mandatory requirements, *must* is used only to describe unavoidable situations.

²The use of *will* is deprecated and cannot be used when stating mandatory requirements, *will* is only used in statements of fact.

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IEEE [Std C62.82.1](#) ~~1313.1~~TM~~1996~~, IEEE Standard for Insulation Coordination—Definitions, Principles, and Rules.^{~~2,3~~}

3. Definitions

For the purposes of this [document](#) ~~guide~~, the following terms and definitions apply. The ~~Authoritative Dictionary of IEEE Standards~~ [Dictionary Online Terms](#) ~~[B68]~~⁴ should be [consulted](#) ~~referenced~~ for terms not defined in this clause.^{~~5~~}

air-insulated substation: An assembly of [structural](#) ~~structures~~ supporting equipment and buses exposed to atmospheric conditions that uses air as the external insulating medium.

ambient air temperature: The temperature of the surrounding air that comes in contact with the substation.

atmospheric correction factor: A factor applied to account for the difference between the atmospheric conditions in service and the standard atmospheric conditions.

NOTE—In terms of this guide, it applies to external insulation only.^{~~65~~}

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.

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.

⁵[IEEE Standards Dictionary Online is available at: <http://dictionary.ieee.org>.](#)

^{~~65~~}Notes in text, tables, and figures are given for information only and do not contain requirements needed to implement the standard.

bus support: An insulating support for a bus. It includes one or more insulator units with fittings for connection to the support structure and for receiving the bus.

clearance, center-to-center phase spacing: The distance between centerlines of the energized parts of adjacent phases of bus.

NOTE—Cautionary differentiation should be made between surface-to-surface clearance and bus-to-bus centerline distance.

clearance, minimum phase-to-ground: The shortest distance between any energized part(s) and the adjacent grounded part(s).

clearance, minimum phase-to-phase: The shortest distance between any energized parts where the parts are of different phases, including phases of different voltages.

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

energized parts: Those parts that are designed to operate at voltage different from that of the earth.

external insulation: The distances between electrodes in open air and across the surfaces of the solid insulation of equipment in contact with open air that are subjected to dielectric stresses and to the effects of atmospheric and other external conditions, such as contamination, animals, etc.

insulation configuration: The complete geometric configuration of the insulation, including all elements (insulating and conducting) that influence its dielectric behavior. The following insulation configurations are identified:

- Phase-to-ground: An insulation configuration between an energized part and the neutral or ground.
- Phase-to-phase: An insulation configuration between two phases of energized conductors or parts.

- Longitudinal: An insulation configuration between energized conductors or parts belonging to the same phase, which are temporarily separated into two independently energized parts (e.g., open switching device).

insulation coordination: The process of bringing the insulation strengths of electrical equipment and buses into the proper relationship with expected overvoltages and with the characteristics of the insulating media and surge protective devices to obtain an acceptable risk of failure.

lightning overvoltage: A fast front voltage produced by lightning. Such overvoltages are usually unidirectional and of very short duration.

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

nominal system voltage: The root mean square (rms) phase-to-phase power frequency voltage below the maximum system voltage by which the system is designated and to which certain operating characteristics are related.

non-self-restoring insulation: An insulation that loses its insulating properties or does not recover completely after a disruptive discharge. This type of insulation is generally, but not necessarily, internal insulation.

overvoltage: Any time-dependent voltage between one phase and ground or between phases having a value exceeding the maximum system voltage. Unless otherwise indicated, such as for surge arresters, overvoltages are expressed in per unit with reference to $\sqrt{2}V_m / \sqrt{3}$ (maximum system crest voltage). Overvoltages are classified by their shape and duration. *See also:* temporary overvoltage; transient overvoltage.

protective margin (PM): The protective ratio (PR) minus one, expressed as a percentage. $PM = (PR - 1) \times 100$.

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

self-restoring insulation: Insulation that completely recovers its insulating properties after a disruptive discharge. This type of insulation is generally, but not necessarily, external insulation.

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% and 0.1%).

switching overvoltage: A slow front, short duration, unidirectional or oscillatory, highly damped voltage. These overvoltages are usually generated by switching or faults.

temporary overvoltage: An oscillatory overvoltage that is of relatively long duration and undamped or only slightly damped. Temporary overvoltages usually originate from switching operations or faults (for example, load rejection and single-phase faults), nonlinearities (ferro-resonance effect and harmonics), or both. Load rejection overvoltages may arise in the substation mainly due to a fault in the distant substation. Depending on the protection scheme, either all parts, or the parts between circuit breaker and transformer will be stressed.

transient overvoltage: A short-duration highly damped, oscillatory or non-oscillatory overvoltage, having a duration of few milliseconds or less. *See also:* **lightning overvoltage; switching overvoltage; very fast front overvoltage.**

very fast front overvoltage: A transient overvoltage with a very fast rise time, usually of short duration, and unidirectional voltage (often by [gas insulated switchgear](#) ~~GIS~~ disconnect switch operation or when switching motors). High-frequency oscillations are often superimposed on the unidirectional wave.

withstand voltage: The voltage that the insulation is capable of withstanding with a given probability of failure. *See also:* **conventional withstand voltage; statistical withstand voltage.**

4. Criteria

The proper electrical clearance levels for each user can be based on several criteria. Although initial clearance levels will probably be based on insulation coordination studies (see Clause 5), additional factors can influence the final levels selected, such as the latest regulatory requirements, added clearance for worker safety, animals/birds on conductors or structures, and an unacceptable level of clearance-related outages at existing installations. Acceptable minimum clearances will incorporate even greater concerns. Typical criteria may incorporate regulatory requirements, corporate policy, frequency and duration of outages, cost of each occurrence, safety issues, severity of damage, applicable equipment standards, potential impact on nearby customers, substation location, and quality-of-service requirements. The following criteria outlined in 4.1 through 4.6 should be considered when evaluating the minimum clearance requirements.

4.1 Safety codes and regulations

Due to the nature of the National Electrical Safety Code[®] (NESC[®]) (Accredited Standards Committee C2) [\[B1\]](#) and other governmental regulations, some clearance levels determined through the use of this guide could come into conflict with governmental regulations or overlapping jurisdictions. Determination of the acceptable operating and safety clearances should include [the](#) application of applicable laws and regulations, such as the NESC.

4.2 Basic lightning impulse insulation level criteria

The performance criterion upon which the insulation strength or withstand voltages and clearances are selected 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.

4.3 Radio interference voltage and corona criteria

As phase-to-ground and phase-to-phase clearances in substations are reduced, the higher electric gradients surrounding conductors, especially at bus hardware and irregular-shaped equipment parts, may initiate corona generation and corresponding radio interference voltage (RIV). Audible and visible (at night) corona, as well as RIV, may be environmentally objectionable to the community or nearby residents. In general, buses should be designed in accordance with IEEE Std 605™ ~~1998~~ [B52 69]^Z to limit electric gradients below corona/RIV onset. If specific problems develop at fittings or irregular parts due to reduced (minimum) substation clearances, bolt covers or corona rings/shields can be installed.

4.4 Operating history

If an unacceptable level of clearance-related outages has been identified, the specific causes need to be determined. Outage records, maintenance reports, and routine inspections of facilities will afford information as to the cause and extent of the problem. Typical information found in these reports includes facility name, date, time, equipment affected, outage cause and duration, and [the](#) number of customers affected.

4.5 Economic aspects

Economic aspects can be considered when determining which alternative design to employ, and severe cost constraints may result in the use of a less-effective design.

4.6 Community acceptance

Community acceptance of the potential increased noise levels when reduced clearances are used should also be considered, as reduced clearances (i.e., compact designs) can result in increased corona-related audible or RIV noise. The acceptability of certain levels of noise is intangible and may be dictated by company policies, community acceptance, customer relations, and so on. The impact on adjacent property owners should be addressed. See IEEE Std 1127™ ~~2004~~ [B53 72].

^{Z 4}The numbers in brackets correspond to those [of](#) ~~in~~ the bibliography in Annex A.

5. Substation insulation coordination

Electrical clearances in air-insulated substations, from an operational viewpoint, are closely tied to the insulation levels in the station. For example, the strike distance across a station post insulator can be directly correlated to its BIL. Establishment of recommended operating clearances necessitates an understanding of the insulation coordination process and the selected insulation levels for a given system voltage.

Insulation coordination is a method for providing [an](#) adequate protective margin between the insulation withstand levels of the equipment, bus, ~~and~~ insulators, and the voltage stresses that can arise in the substation. At a basic level, insulation coordination becomes a selection of the BIL and BSL withstand ratings for various pieces of major equipment and substation bus/insulator assemblies that will provide the desired protective margin(s). The protective margin for a given BIL/BSL withstand voltage is usually tied closely to the rating of the surge arrester employed. A lower arrester rating provides a greater protective margin or (at the user's discretion) allows for the use of lower BIL/BSL levels. Lower BIL and BSL levels can translate into reduced capital costs.

The complete methodology is [exceptionally](#) ~~very~~ complex and probabilistic in nature, and often involves analog studies or computer simulations of the proposed system. It involves [a number of](#) ~~many~~ detailed steps, many of which are beyond the scope of this guide. For a detailed description of the methods available, the user is encouraged to study IEEE Std [C62.82](#) ~~1313.1-1996~~ TM and IEEE Std [1313.2](#) ~~TM-1999~~ ^{8 6}

Substation insulation coordination comprises the following activities:

- Selection of the arrester maximum continuous operating voltage (MCOV) rating and establishment of the minimum protective margin requirements.
- Selection of BIL/BSL levels that provide the required protective margin.
- Establishment of electrical clearances based on BIL/BSL levels.

^{8 6}Information on references can be found in Clause 2.

5.1 Protective margins and arrester maximum continuous operating voltage

Historically, the minimum protective margins have been set at 15% for the BSL and 20% for the BIL. However, with the application of modern metal oxide surge arresters, protective margins of 50% or greater are common. The quantity and location of arresters within the substation is also important, and the BIL/BSL selection should take into account the voltage level, the separation distance between the arresters, and the protected equipment/assemblies. For large separations, it may be necessary to increase the protective margins.

In the simplest of terms, selection of the surge arrester MCOV rating for any given system voltage is based on the lowest rating possible for which the arrester will survive the expected system overvoltages. Arrester energy dissipation capabilities for lightning and switching surge conditions may govern the MCOV rating at higher voltages (230 kV and above). However, it is the capability of the surge arrester to handle long-term sinusoidal temporary overvoltages (temporary system overvoltages for metal-oxide arresters and unfaulted phase overvoltages during faults for silicon carbide arresters), which will usually establish the minimum MCOV rating at which the arrester can survive. See IEEE Std C62.1-1997 22TM [B57 77] for proper application.

5.2 Selection of basic lightning impulse insulation level and basic switch impulse insulation level

5.2.1 Statistical insulation levels

Statistical methods are used to classify and analyze insulation withstand levels and various overvoltages, as described in 5.2.2. These methods are generally applied when first establishing the insulation levels for a given system and later at specific substations where unusual conditions or proposed modifications warrant detailed study.

The basic lightning impulse insulation level may be either a conventional BIL or a statistical BIL, classified as follows:

- Conventional BIL: 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, which is applicable specifically to non-self-restoring insulations.
- 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, which is applicable specifically to self-restoring insulations.

The basic switching impulse level may be either a conventional BSL or a statistical BSL, classified as follows:

- Conventional BSL: 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, which is applicable to non-self-restoring insulations.
- 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, which is applicable to self-restoring insulations.

Switching impulses often represent the more severe air insulation withstand condition at system voltages 362 kV and ~~higher~~ ~~over~~.

5.2.2 Standard insulation levels

Based on many years of historically successful operating experience, standard BIL and BSL have been established for given maximum system voltage levels. Table 1 and Table 2 (from IEEE Std [C62.82 1313.1-1996](#)) ~~-2014~~ show several possible withstand voltages for a given maximum rated voltage. The withstand voltage selected should be based on the results of the user's insulation coordination analysis.

For example, in Table 1, 650 kV BIL has been established as the historical, conservative insulation level at 145 kV. With improvements in surge protection, and for other reasons, [145 kV system's](#) successful operation is possible, at a BIL of 550 kV or 450 kV depending on user criteria and the desired protective margin. When other considerations are incorporated (see Clause 8), even further reductions in BIL may be possible.

The withstand voltages in Table 1 and Table 2 are phase-to-ground voltages. To establish the phase-to-phase withstand voltage, and associated clearances, it is necessary to continue the insulation coordination analysis. With some equipment, the phase-to-phase withstand voltage (based on test voltages) can be the same as the phase-to-ground withstand voltage (for example, three-phase transformers). With other equipment, the phase-to-phase insulation level is undefined (for example, support insulators) and the withstand voltage is dictated by the design of the assembly (i.e., air clearances between phases and from phase-to-ground).

Table 1—Standard withstand voltage for $1 \text{ kV} \leq V_m \leq 242 \text{ kV}^a$

Maximum system voltage (phase-to-phase) V_m kV, rms	Low-frequency, short-duration withstand voltage ^b (phase-to-ground) kV, rms	BIL (phase-to-ground) kV, crest
1.2	—	30 45
5	—	60 75
15	34	95 110
26.2	40 50	125
	50	150
36.2	50 70	150 200
48.3	95	250
72.5	95 140	250 350
121	140 185 230	350 450 550
145	185 230 275	450 550 650

[\(New\)](#)

Maximum system voltage (phase-to-phase) V_m kV, rms	Low-frequency, short-duration withstand voltage ^b (phase-to-round) kV, rms	BIL (phase-to-ground) kV, crest
1.2		30
		45
5		60
		75
15	34	95
		110
26.2	50	150
36.2	70	200
48.3	95	250
72.5	95	250
	140	350
121	140	350
	185	450
	230	550
145	185	450
	230	550
	275	650
169	230	550
	275	650
	325	750
242	275	650
	325	750
	360	825
	395	900
	480	975
		1050

(Deleted)

Table 1—Standard withstand voltage for $1 \text{ kV} \leq V_m \leq 242 \text{ kV}^a$ (continued)

Maximum system voltage (phase-to-phase) V_m kV, rms	Low-frequency, short-duration withstand voltage ^b (phase-to-ground) kV, rms	BIL (phase-to-ground) kV, crest
169	230	550
	275	650
	325	750
242	275	650
	325	750
	360	825
	395	900
	480	975
		1050

(New)

^aFrom p. 11 of IEEE Std C62.82 1313.1–2014 1996, except for the 1.2 kV and 5 kV values.

^bSee relevant apparatus standards for specific equipment values.