



IEEE Guide for Overhead AC Transmission Line Design

IEEE Standards Association

Developed by the
Corporate Advisory Group

IEEE Std 1863™-2019



STANDARDS

IEEE Guide for Overhead AC Transmission Line Design

Developed by the

Corporate Advisory Group
of the
IEEE Standards Association

Approved 7 November 2019

IEEE SA Standards Board

Abstract: Methods for designing 110 kV to 1000 kV ac overhead transmission lines are provided and may also be used as reference for the design of lower voltage overhead transmission lines. The principles and procedures for designing weather-resistant conductor, ground wire, insulator, structure, and foundation of ac transmission overhead lines are specified.

Keywords: AC overhead transmission line, conductor, electrical design, fitting, foundation, ground wire, IEEE 1863™, insulator, lightning protection, load, radio interference, structure design, weather loads

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

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PDF: ISBN 978-1-5044-6319-5 STD23985
Print: ISBN 978-1-5044-6320-1 STDPD23985

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Introduction

This introduction is not part of IEEE Std 1863-2019, IEEE Guide for Overhead AC Transmission Line Design.

This guide is for the design of 110 kV to 1000 kV ac overhead transmission lines and can also be used as reference for the design of lower voltage overhead transmission lines.

The main content in this guide is divided into five parts:

- Clause 3 defines terms.
- Clause 4 shows requirements of each component and explains how to choose them.
- Clause 5 proposes methods of determining designs to withstand wind velocity and icing thickness. Also, it puts forward the relative reliability level of different overhead transmission lines.
- Clause 6 through Clause 8 introduce several electrical, foundation, and structure designs. The designers can choose the design methods suitable for the line's geography, environment, and importance.

The annexes give exact limit values and some calculation methods of electric parameters.

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IEEE Guide for Overhead AC Transmission Line Design

1. Overview

1.1 Scope

This guide applies to three-phase overhead ac transmission line (110 kV to 1000 kV) design and construction, and it can be used as reference for lower voltage levels. This guide specifies design methodologies of the overhead transmission line conductors and ground wires, insulators and fittings, insulation coordination, lightning protection and grounding, conductor arrangement, as well as tower types, loads, materials, structure, and foundations.

1.2 Purpose

This guide applies to the design of ac overhead transmission lines, and gives primary methods for electrical, structural, and foundation design. The design engineer can choose the appropriate design methods based on the location, ambient conditions, and importance of the line.

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).

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

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

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.

ASCE MOP 74, Guidelines for Electrical Transmission Line Structural Loading.³

ASCE/SEI 10-15, Design of Latticed Steel Transmission Structures.

IEC 60071-2, Insulation Co-ordination—Part 2: Application Guide.⁴

IEC/TS 60815, Selection and Dimensioning of High-Voltage Insulators Intended for Use in Polluted Conditions—Part 1: Definitions, Information and General Principles.

IEC/TS 60815, Selection and Dimensioning of High-Voltage Insulators Intended for Use in Polluted Conditions—Part 3: Polymer Insulators for A.C. Systems.

IEEE Std 80™-2013, IEEE Guide for Safety in AC Substation Grounding.^{5, 6}

IEEE Std 516™-2009, IEEE Guide for Maintenance Methods on Energized Power Lines.

IEEE Std 691™, IEEE Guide for Transmission Structure Foundation Design and Testing.

IEEE Std 738™-2006, IEEE Standard for Calculating the Current-Temperature Relationship of Bare Overhead Conductors.

IEEE Std 1243™-1997, IEEE Guide for Improving the Lightning Performance of Transmission Lines.

IEEE Std 1862™-2014, IEEE Recommended Practice for Overvoltage and Insulation Coordination of Transmission Systems at 1000 kV AC and Above.

IEEE Std C95.6™-2002, IEEE Standard for Safety Levels with Respect to Human Exposure to Electromagnetic Fields, 0–3 kHz.

GB 50545-2010, Code for Design of 110kV–750kV Overhead Transmission Line.

GB 50665-2011, Code for Design of 1000kV Overhead Transmission Line.

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3. Definitions

3.1 Definitions

For the purposes of this document, the following terms and definitions apply. The *IEEE Standards Dictionary Online* should be consulted for terms not defined in this clause.⁷

anchor bolts: Bolts that are pre-embedded at the top of the foundation to connect the foundation and base plate.

drilled foundation: A foundation which is formed by directly casting the reinforcing bars and concrete into a pit drilled or excavated by manual or mechanical means.

equivalent salt deposit density (ESDD): Amount of sodium chloride (NaCl) that, when dissolved in demineralized water, gives the same volume conductivity as that of the natural deposit removed from a given surface of the insulator divided by the area of this surface, generally expressed in mg/cm².

icing stress product: The product of the ice, snow, or rime accretion per cm of insulator length, and the electrical conductivity of the melted accretion corrected to 20 °C, (g/cm) × (μs/cm).

leakage distance: The shortest distance, or the sum of the shortest distances, along the insulating parts of the insulator between those parts which normally have the operating voltage between them.

NOTE 1—The surface of cement or of any other non-insulating jointing material is not considered as forming part of the creepage distance.⁸

NOTE 2—If a high-resistance coating, e.g., semi-conductive glaze, is applied to parts of the insulating part of an insulator such parts are effective insulating surfaces and the distance over them is included in the leakage distance.

NOTE 3—Leakage distance is synonymous with creepage distance in IEC/TS 60815.

load: Forces applied on the transmission line system, which may be permanent load, variable load, or accidental load.

melted water conductivity: The electrical conductivity of water used to simulate ice, snow, or cold fog accretion on insulators, melted after accretion and corrected to 20 °C. The melted water conductivity can be higher than the applied water conductivity when accretion occurs on contaminated insulator surfaces. Melted water conductivity can also be lower than applied water conductivity for glaze ice accretion on clean insulators, through the process of water purification by crystallization.

non-soluble deposit density (NSDD): Amount of non-soluble residue removed from a given surface of the insulator divided by the area of this surface, generally expressed in mg/cm².

pad and chimney foundation: A foundation which is buried into a pre-excavated pit and then backfilled and compacted, where the disturbed backfill forms the anti-uplift soil to keep the uplift stability of the foundation.

pile foundation: A foundation comprising a pile or a pile with a cap connected at the pile top. Includes both single-pile foundations and group-pile foundations.

p-percent disruptive discharge voltage (flashover voltage): The prospective value of the test voltage that has a *p*-percent probability of producing a disruptive discharge.

⁷ *IEEE Standards Dictionary Online* is available at: <http://dictionary.ieee.org>.

⁸ Notes in text, tables, and figures of a standard are given for information only and do not contain requirements needed to implement this standard.

protected leakage (creepage) distance: The leakage distance of an insulator that is not wetted in a specified precipitation condition. The protected leakage distance of an insulator in any orientation may vary with precipitation type, intensity, wind speed and direction.

rock foundation: A rock anchor foundation in which the anchor bar is bonded to the rock through cementation of grout or fine-aggregate concrete in the rock holes; a rock embedded foundation in which the reinforcing bar and concrete are directly cast into the rock pit directly drilled (or excavated) by mechanical (or manual) means in the rock subgrade.

site pollution severity (SPS): Five levels of pollution characterizing the site severity are qualitatively defined, from very light pollution to very heavy pollution, as in IEC/TS 60815-1.

statistical switching overvoltage: The switching overvoltage is statistically analyzed to obtain a probability distribution, and the statistical switching overvoltage is generally defined by the 2% value of a Gaussian or normal distribution for reference, meaning that 2% of the switching overvoltage is equal to or exceeds U_s . In insulation coordination, this reference probability is generally taken as 2%.

NOTE—See subclause 3.1.3 of IEEE Std 1313.2™-1999 [B29] for the definition of *statistical switching overvoltage* (E_2).

stub: A short member that connects a leg member at one end and inserts into the foundation chimney at the other end to connect the support and foundation.

support: A general term of structures of various types to support the conductors and ground wires in overhead transmission lines.

unified specific creepage distance (USCD): The leakage distance of an insulator divided by the maximum operating voltage across the insulator. For ac systems, this is usually the highest rms voltage for equipment ($U_m/\sqrt{3}$). For dc systems, this is usually the rated voltage where the insulator is intended to be used. For insulators or bushings with combined dc voltage application, the voltage is equal to $Z \times V_d$ where Z is number of six-pulse bridges in series and V_d is the dc-rated voltage per valve bridge. USCD is generally expressed in mm/kV and specified as a minimum value.

NOTE 1—This definition in IEC/TS 60815 differs from that of *specific creepage distance* where the phase-to-phase value of the highest voltage for the equipment is used. For phase-to-earth insulation, this definition results in a USCD value that is $\sqrt{3}$ times that given by the definition of *specific creepage distance* in IEC/TS 60815.

NOTE 2—This definition retains the *specific creepage distance* definition in IEEE Std 100™ for dc conditions, meaning that the peak electrical stress on ac insulators is $\sqrt{2}/\sqrt{3}$ times the constant electrical stress on dc insulators at the same system voltage and USCD.

3.2 Acronyms and abbreviations

AN	audible noise
EDS	everyday stress
EHV	extra-high voltage
HV	high voltage
ISP	icing stress product
OSHA	Occupational Safety and Health Administration

RI	radio interference
RTS	rated tensile strength
RTV	room temperature vulcanizing (silicone rubber)
SLA	A-weighted sound level
UHV	ultra-high voltage
U_n	nominal system voltage, rms, in kV
U_m	maximum system operating voltage, rms, in kV
U_s	statistical switching overvoltage, in kV
$U_{50\%}$	50% disruptive discharge (flashover) voltage, in kV
U_{rp}	representative overvoltage, in kV
U_{cw}	coordination withstand voltage, in kV
U_{rw}	required withstand voltage, in kV

4. Overview

4.1 Laws, regulations, and standards

The design of lines should comply with the requirements of applicable laws, regulations, and standards, including:

- International and national standards, such as the National Electrical Safety Code[®] (NESC[®])⁹
- Laws and regulations issued by relevant government bodies such as aviation, navigation, traffic, land, and environment
- Local laws and regulations: provisions applicable to the design of lines in laws or rules issued by local governments

4.2 Components and selection

4.2.1 Conductors

As one of the most important components of transmission lines, conductors are expected to fulfill the main function of lines: transmit power, operate safely and reliably, and meet environmental protection requirements. Therefore, the electrical and mechanical characteristics may be fully considered in the selection of conductors. For electrical characteristics, the environmental impacts caused by corona will be addressed through reasonable type selection and

⁹ The NESC is available from The Institute of Electrical and Electronics Engineers (<http://standards.ieee.org/>).

bundle configuration of conductors on the condition that the current carrying capacity is satisfied. For mechanical characteristics, conductors are required to demonstrate appropriate mechanical performance and safety. Particularly, the conductors used for high-altitude mountainous areas, heavy icing areas, significant elevation difference, or large spans may have a sufficient mechanical strength.

At present, the most common conductor used for transmission line is aluminum conductor steel reinforced (ACSR). It is also a trend to use three novel types of conductors as follow: 1) ACSR with a reduced power loss on conductors and enhanced anti-corrosion performance by increasing the conductivity of the aluminum base, 2) all-aluminum-alloy conductor (AAAC), and 3) aluminum alloy cored aluminum stranded conductor. Many other types including aluminum conductor, steel supported (ACSS), aluminum conductor, steel reinforced trapezoidal wire (ACSR/TW), all aluminum conductor trapezoidal wire (AAC/TW) and those various high-temperature, low-sag conductors presently available might be selected under specific conditions.

In principle, the following factors can be comprehensively taken into consideration:

- a) Transmission capacity of the system
- b) Permissible temperature rises of conductors
- c) Electric field effect
- d) Environmental impacts, including audible noise, radio interference, and light pollution
- e) Mechanical strength required
- f) Special environmental requirements, such as anti-corrosion
- g) Cost effectiveness within the whole life cycle

4.2.2 Ground wires

In addition to the purpose of lightning protection, ground wires can also reduce secondary arc current, power-frequency overvoltage of asymmetrical short circuit, interference to other communication lines, and can serve to carry optical communication units (optical fiber composite overhead ground wire [OPGW]). In principle, the following mechanical and electrical requirements may be comprehensively considered in the selection of ground wires:

- a) Mechanical characteristics: Ground wires shall have a design safety factor greater than that of conductors, sufficient over-load capacity, and an anti-vibration feature.
- b) Electrical characteristics: Ground wires in the span shall maintain a required distance from conductors for lightning protection and a required distance from conductors under uneven icing condition and satisfy thermal stability requirements in case of short circuit as well as requirements for current sharing of OPGW. For 750 kV and above lines, the corona of ground wires shall be checked.

4.2.3 Insulators

The materials and type of insulators may be determined through techno-economic comparison based on engineering features and the characteristics of the following: contamination and humidity along the lines, dust accumulation, construction, operation, and maintenance.

Porcelain, glass, and composite insulators are mainly used in transmission lines. The insulating ceramic parts of porcelain and glass insulators is able to resist aging, corona, arc erosion, and chemical corrosion, but they are easily wetted and conduct leakage current that varies with the accumulated pollution level. Besides, glass insulators have

the feature of self-explosion while the resistance of insulator is low. Compared with porcelain insulators, composite insulators are lighter and hydrophobic and thus more resistant to pollution flashover, but are more prone to aging problems. The silicone rubber coatings applied to ceramic insulators offer some advantages of both ceramic and composite insulating materials. Additionally, the following factors may be considered in selection of insulators:

- a) Frog-profile cap-and-pin disc insulators have long ribs under sheds and a large creepage distance. The protected leakage distance reduces the effect of moisture, giving the frog-profile a high pollution withstand voltage property. They are suitable for coastal, foggy, damp, and saline-alkali areas. Outer-rib-and-aerodynamic-type insulators, featuring good self-cleaning performance, little natural dust accumulation, and high pollution withstand voltage, may perform more outstanding than other types of insulators in dusty environments. They are suitable for various operating conditions, especially in heavily polluted, high-altitude, desert, and dry areas.
- b) Some additional measures, such as application of room temperature vulcanizing (RTV, silicone rubber) coating may be required when porcelain or glass insulators are used in coastal areas (no more than 3 km from the sea), salt lake, salt-treated roadway, or other heavily polluted areas.
- c) Composite insulators that can retain excellent hydrophobicity and hydrophobicity transfer performance through pollution layers are easier to operate and maintain in areas with medium or heavier pollution severity, but less suitable for use in dusty environments, such as a cement plant.
- d) When composite insulators are used in icing areas, the icing performance may be enhanced by enlarging the shed in a limited range to inhibit bridging through icicles.
- e) The following measures against icing flashover may be taken for insulator strings in heavy icing areas: alternate-diameter strings, V-type and inverted-V-type insulator strings. These measures can minimize the probability of bridging of insulators through icicles and the probability of icing flashover. Farzaneh et al. [B16] lists many other available methods to improve performance of insulators under icing conditions.

4.2.4 Fittings

The fittings of transmission lines shall meet the special requirements placed in a specific project, and allow for ease of transportation, installation, maintenance, and replacement. The general requirements are as follows:

- a) The fittings may have high reliability to maintain the safe and stable operation of transmission lines.
- b) The structure of fittings as well as the structures connecting the fittings with insulators, conductors, and other fittings may be reasonable and optimally designed.
- c) In the selection of materials, the requirements specified in a) and b) above shall be fully considered, and decisions made through comprehensive comparison from the aspects of strength, cost, workability, etc.
- d) For fittings with the corona issue, the basic requirement that no visible corona is generated under the highest power-frequency voltage shall be satisfied. Therefore, its structure may be specially designed, and can be optimized with three-dimensional finite element simulation software. The theoretically calculated peak value of operating field strength on the surface of fittings shall not exceed 26 kV/cm for altitudes of 1000 m and below, and shall meet altitude correction requirements for higher altitudes.
- e) The fittings can be interchangeable for ease of line maintenance.
- f) The fittings used in regions with a low extreme temperature may be made of low-temperature-resistant materials. The fittings used in regions where strong wind occurs frequently and lasts for a long time may be made of wear-resistant materials. For fittings made of ferrous metal, the surface can be hot galvanized or treated with other proper anti-corrosion measures.

4.2.5 Support structure

The design of support structures of transmission lines shall meet the following requirements:

- a) Support structures shall satisfy the requirements of the ultimate limit states and serviceability limit states under normal operation load (including such natural loads as wind and ice, and potential artificial loads) within the specified design service life. They shall be able to bear various loads imposed during construction and maintenance. Their reliability level should be determined in accordance with local laws and regulations; if not specified, the relative reliability criteria recommended in this guide may be adopted.
- b) The design of supporting structures should consider the requirements on public safety, endurance, safety, environmental friendliness, cost effectiveness, and maintainability. In addition, the visual appearance can also be considered based on the requirements of the construction environment.
- c) The support structures may be towers or poles. Towers can be composed of angle steel or steel tube, and poles can be made of steel, wood, reinforced concrete, composite material, etc.
- d) Based on practical engineering experience and accident investigation results, the selection of tower type for heavy icing areas shall also confirm to the following principles:
 - 1) Self-supporting towers with conductors symmetrically arranged can be used.
 - 2) Lines in heavy icing areas often feature large elevation difference, uneven span, uneven icing, and ice shedding, which may lead to high tension or torsion load in the line direction. Therefore, the tower body should have satisfactory longitudinal rigidity and torsional rigidity.
 - 3) The structural type of towers may be determined through comprehensive techno-economic comparison in view of the characteristics of lines in heavy icing areas.
- e) The arrangement of tower heads shall satisfy requirements for the electrical clearances on tower heads, spacing between conductors in a span, shielding angle of ground wires, etc. Operational experience of existing lines in heavy icing areas has revealed that when a conductor is de-iced earlier than adjacent conductors or ground wire and is thus elevated, the adjacent conductors or adjacent conductor and ground wire in the mid-span will statically or dynamically approximate each other and therefore flashover will occur. As such, the horizontal displacement and vertical spacing between adjacent conductors—or between ground wire and adjacent conductor—in icing areas shall meet relevant requirements.

5. Meteorological design criteria

5.1 Basic wind speed and icing

5.1.1 Basic wind speed

The basic wind speed is associated with the return period and is obtained by probability statistics based on the data observed in 10 min at 10 m above ground in local flat and open terrains. Generally, a shorter wind acquire time corresponds to a higher wind speed. The conversion among different time intervals of wind speed is affected by various factors, typically, the smaller the average wind speed is, the larger the ratio is; and the more drastically the wind speed fluctuates, the larger the ratio is. ASCE MOP 74 gives the conversion relation among wind speeds with different time intervals, which can be applied in engineering design based on practical experience.

The basic wind speed is generally determined with a 50-year return period.

5.1.2 Icing

5.1.2.1 Investigation and observation of icing

An icing survey can be carried out in heavy icing areas within the transmission line right-of-way. Additionally, experience and data from areas with similar topography and climate—especially on windward slopes and wind gaps of cold wave areas, mountains close to lakes, and the boundaries between basins and mountains—may be taken into consideration.

The accurate basic data for the icing characteristics and icing distribution patterns of areas with different topologies and climates within the transmission line right-of-way may be obtained through icing observation. To this end, it is necessary to divide the transmission line right-of-way into various zones in terms of topography and climate, and to set relatively fixed icing observation stations in representative areas to collect icing data.

5.1.2.2 Ice thickness

Ice thickness may be determined according to local qualitative and quantitative icing data, topography and climate along the transmission line right-of-way, as well as the operation of nearby existing lines. A correction to the determined ice thickness should be made based on the return period corresponding to the transmission line, altitude, and transmission line diameter.

The maximum ice thickness data, accumulated over more than 10 years in the project area or areas with similar characteristics of topography and climate, may be used for the frequency calculation of design ice thickness by means of Pearson type III distribution model, type I extreme value distribution mode, or generalized Pareto distribution (GPD) model.

If the available maximum ice thickness data is recently observed (within one to five years) for the project area, the icing meteorological indices derived from the data obtained from the icing observation station and neighboring meteorological stations can be used for frequency analysis to determine statistical parameters and calculate the design ice thickness.

If no observed icing data is available in the project area, investigation of historical icing data may be carried out in the project area and areas with similar characteristics in terms of topography and climate to analyze and calculate the design ice thickness.

The design ice thickness may be selected based on the icing map and historical icing data, if the icing map for the project area is able to effectively show the accurate icing conditions, such as Figure 250-3 in Section 25 of ANSI C2-2017, National Electrical Safety Code®.

In some regions, the ice accretion model is also used as an aid for calculating the ice thickness.

The classification of icing areas should be in line with the local conditions. For example, the classification in the United States is: Very light < 1 mm reference ice level on rotating cylinder; Light < 6 mm; Moderate = 6 mm to 10 mm; Heavy > 10 mm. Rationale: Freezing fog/hoar frost occurs in areas with no icing, leading to widespread cold fog flashovers (Farzaneh and Chisholm [B17]). In China, the classifications are: Areas where conductors are subject to no icing are non-icing areas; areas with a design ice thickness of conductors of 10 mm or less are light icing areas; areas with a design ice thickness of conductors of more than 10 mm are medium or heavy icing areas.

When a transmission line passes through a watershed, mountain crest, cliff, wind gap, or other microtopographical and micrometeorological area, the design wind speed and design ice thickness may be increased appropriately based on practical experience.

If necessary, the anti-icing performance of a transmission line may be checked against rare icing conditions to improve the line reliability.

5.2 Reliability of overhead transmission lines

The design of transmission lines may ensure the desired reliability of the lines. The desired reliability may be expressed according to the return periods of different meteorological areas or the adjustment coefficient of return periods.

Calculation of the absolute reliability of overhead transmission lines is complicated. Therefore, the relative reliability, instead of the absolute reliability, may be used to measure the reliability of a line for engineering purposes. Level 1 reliability can be used as the reference level, while a higher reliability level may be calculated relative to the reference level.

Table 1—Relative reliability level

Relative reliability level	Return period (year)	Probability of overloading based on a 50-year return period (%)
1	50	64
2	150	28
3	300	15
4	700	7
5	1700	3

The relative reliability level can be determined based on local design experience, applicable laws and regulations, as well as the importance of the lines. The importance of lines can be judged based on the voltage class and transmission capacity of the lines, and the consequences of accidents. In general, a transmission line of a lower voltage class has a smaller transmission capacity, and therefore, a lower relative reliability level can be used. A transmission line of a higher voltage class has a larger transmission capacity and the economic losses resulting from accidents are unaffordable. Therefore, in this case, a higher relative reliability level can be used.

When using the factor to adjust the return period to express the relative reliability level, the type I extreme value distribution model can be used for the load calculation. The 50-year-return-period-based factor γ can be calculated using the following formula:

$$\gamma = \frac{\left[1 - 0.86 \times v \times \ln \left(-\ln \left(1 - \frac{1}{T} \right) \right) \right]^n}{\left[1 - 0.86 \times v \times \ln \left(-\ln \left(1 - \frac{1}{50} \right) \right) \right]^n} \quad (1)$$

where

- T is the return period
- n is the exponent coefficient, 1.0 for wind velocity, 2.0 is for wind pressure
- v is the coefficient of variation, i.e., the ratio of the standard deviation to mean value of the sample

6. Electrical design

6.1 Selection of conductor

6.1.1 Cross-section of conductor

The conductor should be capable of carrying the rated ampacity, as well as the short-circuit current. In addition, the requirements of the electromagnetic environment and economic effectiveness may be taken into consideration. Generally, for high-voltage (HV) lines, most commonly used conductors meet the requirements of the electromagnetic environment, therefore, the conductor cross-section may concern the ampacity combined with the economic effectiveness. The effects of the electromagnetic environment are non-negligible for extra-high-voltage (EHV) lines, and more prominent still for ultra-high-voltage (UHV) lines. The conductor cross-section and number of sub-conductors may be determined by the electromagnetic environment requirement rather than the ampacity requirement.

6.1.2 Conductor ampacity

The mechanical strength of conductors may be degraded when the temperature rises to a certain level, therefore, the heating of conductors should be limited. The maximum allowable conductor temperature under the ampacity rating corresponds to long-term continuous operation, which is related to the conductor material and is determined by the residual mechanical strength after long-term operation. The maximum temperature may be listed in standards or technical codes or can be determined with reference to guaranteed values from product tests. In addition, some other factors may be considered to determine the maximum allowable conductor temperature during long-term operation, including the issues caused by the heating of hardware, resistance losses resulting from conductor heating, and the increase of investment costs due to the increase in conductor sag, etc.

The minimum cross-section required for conductors can be calculated with the current required, the temperature allowed, and the duration.

The conductor ampacity can be calculated based on the heat balance principle. The allowable ampacity of overhead transmission line conductors can normally be calculated by Equation (2).

$$I = \sqrt{\frac{q_c + q_r - q_s}{R(T_c)}} \quad (2)$$

where

- I is the ampacity rating of conductor, in A

- T_c is the maximum allowable conductor temperature for long-term operation, in °C
- q_c is the convected heat loss rate per unit length of conductor, in W/m
- q_r is the radiated heat loss rate per unit length of conductor, in W/m
- q_s is the heat gain rate from the sun per unit length of conductor, in W/m
- $R(T_c)$ is the ac resistance of conductor at T_c , in Ω/m

The detailed calculation of conductor ampacity can be found in IEEE Std 738™-2006. The following factors, which affect conductor ampacity, are considered: the environmental conditions (wind speed, sunlight intensity, ambient temperature, etc.) and conductor parameters (the resistivity, heat absorption coefficient, radiation coefficient, allowable temperature, conductor diameter, etc.). Among these factors, the wind speed, ambient temperature, and maximum allowable conductor temperature have a greater impact on the ampacity. For environmental conditions, meteorological data collected in various regions or empirical design values are generally used. Refer to CIGRE 299 [B9] for more details.

6.1.3 Allowable short-circuit current of conductor

When a short-circuit fault occurs, a large current may flow through the conductor or ground wire. The thermal stability of the conductor or ground wire, especially the ground wire, should be guaranteed before the fault current is eliminated.

Calculation of short circuit current on a shielded overhead line should incorporate the asymmetrical current calculation (full decrement factor) and the symmetrical current calculation, which can be obtained from IEEE Std 80™-2013.

For conductors made of a single material, the thermally permissible short-circuit current may be calculated with reference to the simplified formula in Equation (3) and Equation (4).

$$I = \sqrt{\frac{Q}{T}} = \sqrt{\frac{C}{\alpha_r R_r T} \ln \frac{\alpha_r (t_m - t_r) + 1}{\alpha_r (t_a - t_r) + 1}} \quad (3)$$

$$C = c_p \times \rho \times S \quad (4)$$

where

- I is the thermally permissible short-circuit current, in A
- Q is the thermally permissible short-circuit heat capacity, in $A^2 \times s$
- T is the equivalent duration of a short-circuit fault, in s
- C is the thermal capacity of the current carrying part, in $J/^\circ C/cm$
- C_p is the specific heat of the metallic material of the current carrying part, in $J/(g \times ^\circ C)$

ρ	is the density of the metallic material of the current carrying part, in g/cm^3
S	is the conductor cross section of the metallic material of the current carrying part, in cm^2
α_r	is the thermal coefficient of resistivity at reference temperature t_r , in $1/^\circ\text{C}$
R_r	is the resistance of the current carrying part at T_r , in Ω/cm
t_m	is the maximum allowable temperature during a short-circuit, in $^\circ\text{C}$; refer to IEC 60865-1 [B24] for determining its value
t_a	is the ambient temperature, in $^\circ\text{C}$
t_r	is the reference temperature for material constants, in $^\circ\text{C}$

The thermal capacity for most materials are listed or can be determined by calculation with reference to IEEE Std 80-2013.

6.1.4 Requirements for the electromagnetic environment

The electromagnetic environment of an HV overhead transmission line can be affected by the outer diameter and bundle configuration of conductors. Subclause 6.2 explains the underlying principles. The conductor type and configuration design should meet the requirements on radio interference, audible noise, and other electromagnetic environmental requirements.

6.1.5 Cost effectiveness

For transmission lines, the cross-section of conductors affects both the construction investment and the operating electric energy losses. When analyzing the cost-effectiveness of the conductor scheme, the local conditions can be considered. Generally, besides the construction investment, the costs of electric energy losses including resistance heating losses and corona losses, operation and maintenance costs, and time value of funds may be considered as well. The comparison of conductor schemes may be viewed in terms of cost-effectiveness throughout the whole life cycle.

When comparing the cost-effectiveness of conductor schemes, the estimate of construction costs of each scheme should be made as accurately as possible.

Some costs in the construction investment are sensitive to changes in the conductor scheme, such as conductor materials costs, tower materials costs, foundation costs, and costs of accessories. Such costs need to be calculated item by item. Some other costs are less or not sensitive to changes in the conductor scheme, which can be included as a small percentage of the investment or they can be ignored in comparisons.

From the perspective of engineering, the time value of each fund can be considered in the assessment of cost-effectiveness. The discount rate and economic life of a project are the main parameters related to the time value of funds in the economic assessment. Present-value cost method or annual cost method can be applied to economic comparisons of conductor schemes for a transmission line project. The principles of them are same, and the scheme with a lower present-value cost or a lower annual cost will be preferred.

6.2 Corona and electric field, magnetic field effects

6.2.1 Introduction

The electromagnetic environmental impacts produced by high-voltage transmission lines include power-frequency electric field and magnetic field, as well as radio interference and audible noise resulting from the conductors' coronas. See IEEE Std 539™ [B27] for definitions and terms regarding electromagnetic environmental impacts. They affect the quality of the human living environment to a certain extent and these effects can be restricted by taking proper technical measures. In addition, the corona of conductors also leads to the loss of electrical energy, which may be evaluated in the economic comparison of conductors.

6.2.2 Radio interference

6.2.2.1 Limits

The radio interference level of a transmission line varies significantly with weather conditions; thus, the values of statistical significance are often used to express the radio interference level of the line. In the CISPR 18 series publications from the International Special Committee on Radio Interference (CISPR) of the International Electrotechnical Commission (IEC), the statistics-based double 80% principle is specified, that is, the radio interference level of a transmission line does not exceed the specified limit in 80% of a year and has 80% confidence level.

CISPR 18 series publications specify that three technical requirements should be considered in determining radio interference limits for transmission lines, specifically: 1) the lowest radio signal level that should be protected; 2) the minimum signal-to-noise ratio (SNR) that can ensure the satisfactory reception; 3) the protection distance (or protection belt), i.e., the minimum distance from the outside-phase conductor to the location where the radio signal can be received satisfactorily.

The lowest protected radio signal level may be determined with reference to the values recommended by the International Telecommunication Union (ITU). For amplitude modulation audio modulation, the average SNR that can achieve the satisfactory reception quality recommended by CISPR is 26 dB ($\mu\text{V}/\text{m}$).

As the concept and specification for line corridor right-of-ways varies from different countries, CISPR has not yet specified a radio interference limit that can be adopted worldwide. Subclause A.1 gives the radio interference limits in some countries and regions.

6.2.2.2 Methods of prediction

6.2.2.2.1 Introduction

The methods for predicting radio interference mainly include the empirical formula approach and the excitation function approach.

6.2.2.2.2 Empirical formula approach

The empirical formula is derived from tests of the radio noise field on multiple HV test lines. The empirical formula recommended in CISPR 18-3 does not take account of the impact from the number of sub-conductors in a bundle, and the formula is suitable when conductor bundles have no more than four sub-conductors.

The formula recommended in CISPR to calculate the radio noise field strength is as follows:

$$RI_i = 3.5E_{\max i} + 12r_i - 30 + 33 \log \frac{20}{D_i} \quad (5)$$

where

RI_i is the radio noise field at the distance of D_i from phase- i conductor, in dB ($\mu\text{V}/\text{m}$)

$E_{\max i}$ is the maximum electric field strength on the surface of phase- i conductor, in kV/m (rms)

r is the sub-conductor diameter of phase- i conductor, in cm

D_i is the distance from phase- i conductor to the reference point, in m

If radio noise field strength of a certain phase is 3 dB more than the value of either of the other two phases, the radio noise field strength of the three-phase can be deemed as the field strength value of the phase with the largest value; otherwise, the radio noise field can be calculated by Equation (6).

$$RI = \frac{RI_1 + RI_2}{2} + 1.5 \quad (6)$$

where

RI is the radio noise field of an HV transmission line, in dB ($\mu\text{V}/\text{m}$)

RI_1 is the highest radio noise field among the three-phase conductors, in dB ($\mu\text{V}/\text{m}$)

RI_2 is the second highest radio noise field among the three-phase conductors, in dB ($\mu\text{V}/\text{m}$)

For the multiple circuits erected on a tower, the radio noise field produced by each phase conductor is calculated by Equation (6). Via adding together the radio noise field produced by the conductors of the same phase, the radio noise field of the three-phase line is formed.

The value calculated using Equation (5) is the average radio noise field for ideal weather and the frequency of 0.5 MHz, on which basis 6 dB to 10 dB need to be added to obtain the radio noise field for 80% of a year and with a confidence level of 80%.

The radio noise field increases at an increment of about Alt./300 with the rise of altitude, in which Alt. refers to the altitude in m.

When RI under 0.5 MHz is converted to that under the reception frequency of the affected object, the corresponding correction ΔRI to be applied is calculated by Equation (7), which is applicable to the frequency range from 0.15 MHz to 4 MHz.

$$\Delta RI = RI - RI_0 = 5 \left[1 - 2 \lg(10f)^2 \right] \quad (7)$$

where

RI_0 is the reference value of radio noise field under 0.5 MHz

f is the frequency expressed in MHz

6.2.2.3 Excitation function approach

The excitation function approach is based on the excitation function in heavy rain obtained through measurements on test lines or cages. The pulse currents of each phase conductor can be derived through certain modal transformation of the excitation function, and thus the electric field produced by these currents, i.e., the radio noise field, can be obtained. Many countries have obtained their empirical formulae of the radio interference excitation function for transmission lines through radio interference tests on their own HV corona cages and test lines. For voltages above 750 kV and conductors with more than four sub-conductors, the excitation function approach is preferred over the empirical formula approach as the latter results in a larger error.

In CISPR 18-3-1996, the method for calculating the radio interference of bundle conductors with the excitation function method is recommended, and the calculation steps include calculation of excitation function, correction of meteorological impacts, and calculation of the distribution of radio noise field based on the modal propagation principle.

The formula used for calculating the excitation function in heavy rain as recommended in CISPR 18-3 is as follows:

$$\Gamma_1 = 70 - \frac{585}{E_{\max}} + 35 \log(d) - 10 \log(n) \quad (8)$$

where

Γ_1 is the excitation function in heavy rain, in dB

E_{\max} is the average maximum electric field produced on the surface of sub-conductors (rms), in kV/cm

d is the sub-conductor diameter, in cm

n is the number of sub-conductors in a bundle

As proposed in CISPR 18, the radio noise field in 80% of a year and with a confidence of 80% can be obtained by subtracting 10 dB to 15 dB ($\mu\text{V}/\text{m}$) from that in heavy rain.

6.2.3 Audible noise

6.2.3.1 Limits

The main purpose for limiting noise is to protect human hearing and health, with the psychological effects of noise also being fully considered. The limits of audible noise from transmission lines can be determined based on statistical data of existing lines or tests, in combination with the impacts of noise on humans and animals, also considering local standards and policies on environmental noise as well as the economic and technical conditions. The limits of audible noise vary from different countries in the range from 45 dB(A) to 58 dB(A).

The audible noise produced by transmission lines are often expressed with the A-weighted sound level. For ac overhead transmission lines, the audible noise on rainy days is 15 dB(A) to 20 dB(A) more than that on sunny days; therefore, the limits for audible noise may be mainly based on rainy conditions.

6.2.3.2 Methods of prediction

The prediction of audible noise is mostly deduced from the statistics, analysis, and regression of the long-term empirical data achieved by the corona cage simulation along the simulated and empirical line, via superimposing the noise generated by each phase conductor.

The main parameters of prediction formula generally contain the electric field on the surface of conductors, diameter of conductor, number of sub-conductors in a bundle, measurement distance, etc.

The formula for calculating the A-weighted sound level noise of single-phase conductors is given by:

$$AN = AN_0 + k_1 f_1(E_{\max}) + k_2 f_2(n) + k_3 f_3(d) + k_4 f_4(D) + k \quad (9)$$

where

$f_i()$	is the functional expression of each factor
E_{\max}	is the average maximum electric field produced on the surface of conductors (rms), in kV/cm
n	is the number of sub-conductors in a bundle
d	is the sub-conductor diameter, in cm
D	is the distance from the measurement point to the conductor, in m
AN_0	is the reference value, in dB(A)
k	is the correction factor

For a line with N_p phases, the total noise is given by:

$$SLA = 10 \log \sum_{i=1}^{N_p} 10^{\frac{AN_i}{10}} \quad (10)$$

where

SLA is the total noise of the line, in dB(A)

AN_i is the noise produced by the phase- i conductor, in dB(A)

Countries have proposed formulae for predicting audible noise from HV transmission lines based on their own long-term measured data. The representative predicting methods include the Electric Power Research Institute (EPRI) method, Ente Nazionale per L'Energia Elettrica (ENEL) method, Bonneville Power Administration (BPA) method, Hydro Quebec Institute of Research (IREQ) method, FGH, Germany method, and Electricite de France (EDF) method, as well as the empirical formulae developed by the Czech Republic, Belgium, Romania, and Japan. Among them, the BPA's method (Chartier and Stearns [B11]) is most widely used. In addition, China has developed a formula for calculating the audible noise produced by UHV ac transmission lines. See Annex B for details.

The formula for predicting audible noise from HV transmission lines as recommended by BPA is defined as follow:

$$SLA = 10 \log \sum_{i=1}^Z \log^{-1} \left[\frac{PWL(i) - 11.4 \log R_i - 5.8}{10} \right] \quad (11)$$

$$PWL(i) = -164.6 + 120 \log E_{\max} + 54 \log d_{eq} \quad (12)$$

where

$PWL(i)$ is the sound power level of the phase- i conductor

E_{\max} is the average maximum electric field on the surface of sub-conductors (rms), in kV/cm

d_{eq} is the equivalent diameter of conductor, in cm. $d_{eq} = d$ when $n \leq 2$, and $d_{eq} = 0.58n^{0.48}d$ for $n \geq 3$

d is the sub-conductor diameter, in cm

n is the number of sub-conductors in a bundle

Z is each individual phase

R_i is the distance from the measurement point to the phase- i conductor to be measured, in m

This formula is valid for common symmetrical bundle conductors with spacing between sub-conductors of 30 cm to 50 cm and electric field strength on the surface of conductors of 10 kV/cm to 25 kV/cm.

BPA suggests that the audible noise increases at an increment of about $Alt./300$ with the rise of altitude, in which, $Alt.$ refers to the altitude in m. The validity of this correction method was verified in early transmission line projects at altitudes up to 2000 m. Through measurements and demonstration of audible noise from transmission lines at four different altitudes, China Electric Power Research Institute (CEPRI) (Tang et al. [B35]) put forward that the application scope of the formula can be expanded to the altitude range of 3000 m.

6.2.4 Power-frequency electric field

6.2.4.1 Limits requirement

Generally, the power-frequency electric field limits for ac transmission lines are determined by considering three aspects: 1) to prevent transient electric shock causing discomfort, 2) prevent steady-state electric shock current larger than the let-go threshold, and 3) restrict harmful ecological effects due to long-term effects of electric fields.

In “ICNIRP Guidelines for Limiting Exposure to Time-varying Electric, Magnetic and Electromagnetic Fields (1 Hz–100 kHz)” issued by the International Commission for Non-Ionizing Radiation Protection (ICNIRP) in 2010 (ICNIRP [B31]), the reference level of exposure to 50 Hz and 60 Hz power-frequency electric field is specified: 5 kV/m and 4.17 kV/m, respectively, for the general public, and 10 kV/m and 8.33 kV/m for occupational workers.

Referring to IEEE Std C95.6™-2002, the limits for exposure to 50 Hz and 60 Hz electric fields is specified: respectively 20 kV/m for controlled environments and 5 kV/m for general public.

Subclause A.3 gives the design limits for electric fields on some lines. Although different countries or electric power companies have different requirements, there are still some common points: the maximum field strength is 10 kV/m to 15 kV/m under transmission lines (or in agricultural regions), 7 kV/m to 10 kV/m where lines cross roads, and less than 5 kV/m for public areas or areas where lines run close to residential buildings.

6.2.4.2 Calculation method

In calculations, it is usually assumed that transmission lines are infinitely long and parallel to the ground and that the ground is an ideal conductor, allowing the electric field of a space to be simplified as a two-dimensional field. Considering the maximum electric field produced on the ground, the height of conductors to ground is taken as the distance of the lowest point of the central conductor sag i to the ground. Bundle conductors, if used, can be substituted by equivalent single conductor.

The electric field produced by ac transmission lines can be calculated in the following steps:

- a) Calculate the equivalent charge on conductors Q with Maxwell’s equation, Equation (13), of voltage U and coefficient of potential λ :

$$[Q] = [\lambda]^{-1} [U] \quad (13)$$

where

Q is the equivalent charge on conductors

λ is the coefficient of potential

U is the voltage on conductor

The coefficient of potential λ is derived from the mirror image principle (by setting mirror-image charges on the mirror-image position of conductor on the ground to simulate the induced charges on the ground) and U is the voltage on conductor. As U is a time varying quantity, U and Q are divided into real and imaginary parts which are calculated respectively.

- b) Calculate the horizontal component E_x and vertical component E_y of the electric field generated by charge Q at any point in space based on the superposition principle.

- c) Calculate the maximum value of the resultant electric field at any point in space. As the resultant electric field at any point in space is a rotating elliptical field, the magnitude and direction of which vary constantly with time, its maximum value cannot be simply calculated with the equation $\sqrt{E_x^2 + E_y^2}$. The vector module of the resultant electric field can be expressed as a function of time, and then the maximum value can be calculated.

In addition, finite difference method, finite element method, or other numerical methods can also be used.

CIGRE 61 [B6], Chartier et al [B10], and EPRI [B14] [B15] give specific calculation methods.

6.2.4.3 Measures for limiting power-frequency electric field strength

The electric field induced on ground reduces with the increase of the height of conductors above ground; therefore, it can be reduced by increasing the height of conductors above ground.

For single-circuit overhead transmission lines with the same distance to ground, and on the condition that requirements for insulation clearance are satisfied, the maximum electric field strength induced on ground with the three-phase conductors in triangular configuration is lower and the scope of high-strength electric field is smaller than that with the three-phase conductors in horizontal configuration. For lines with the three-phase conductors in horizontal configuration, the electric field strength induced on ground will reduce slightly with the reduction of horizontal spacing between phase conductors.

For double-circuit lines with the same distance to ground, the maximum electric field strength on ground with the conductors in inverse phase sequence or other phase sequence is smaller than that with the conductors in same phase sequence.

6.2.5 Power-frequency magnetic field

6.2.5.1 Limits requirement

In “ICNIRP Guidelines for Limiting Exposure to Time-varying Electric, Magnetic and Electromagnetic Fields (1 Hz–100 kHz)” issued by ICNIRP in 2010, the limits for exposure to power-frequency magnetic field are specified, which is 1 mT for occupational workers and 0.2 mT for general public.

The limits for exposure of head and torso to power-frequency magnetic field as specified in IEEE Std C95.6-2002 are 2.71 mT for controlled environments and 0.904 mT for the general public.

6.2.5.2 Calculation method

Given the quasi-static nature of a power-frequency electromagnetic field, it can be considered for the magnetic field produced by lines that only current is generated. In this case, the magnetic field strength B surrounding the conductors can be obtained by applying Ampère’s law to the calculation of current-carrying conductors and superimposing the calculation results.

The mirror-image principle, if adopted, is based on the theory that the effect of the ground can be equivalent to that of an underground current of same magnitude and opposite direction, where the mirror-image depth δ can be roughly given by:

$$\delta = 1.31 \sqrt{\frac{\rho}{\pi f \mu}} \quad (14)$$

where

- ρ is ground resistivity, in $\Omega \times \text{m}$
- f is frequency, in Hz
- μ is permeability, in H/m
- μ_0 is the magnetic permeability of soil; normally equals $4\pi 10^{-7}$

The magnetic flux density of each phase conductor and its mirror-image conductor can be calculated with Equation (15), and then each component can be superimposed. Or the simplified formula for long-distance field (EPRI [B15]) can be applied.

$$B = \frac{\mu I}{2\pi \sqrt{h^2 + l^2}} \quad (15)$$

where

- B is the magnetic flux density, in T
- I is the line current, rms, in A
- h is the vertical distance from the conductor to the calculation point, in m
- l is the horizontal distance from the calculation point to the projection of the conductor on ground, in m

6.2.6 Corona loss

The annual average corona loss of a transmission line can be given by:

$$P_{ma} = \frac{1}{T_a} \sum_{i=1}^n p_i T_i \quad (16)$$

where

- $i = 1, 2, \dots, n$ refers to various types of weather conditions possibly occurring in a year, such as snow, rain, and rime
- T_i is the number of hours that each type of weather condition lasts

P_i is the corona loss of the line under each type of weather condition

T_a is the total number of hours in a year, which is 8760 h

It is difficult to accurately predict the corona loss as it is impacted by many factors, including the geometric dimensions of conductor, electric field strength on conductor surface, weather conditions, etc. The methods for calculating the corona loss commonly used around the world include the Ontario Hydro method, EdF method, EPRI method, IREQ method, BPA method, ENEL method, and some other empirical methods. For the specific calculation method, refer to CIGRE 61 [B6].

The empirical formula method developed by BPA (Chartier [B10]) accounts for effects of parameters of bundle conductors, rainfall rate, and altitude on corona loss. The corona loss P_i (in W/m) can be calculated using Equation (17) and Equation (18).

$$P_i = 10^{P_i(dB)/10} \quad (17)$$

$$P_i(dB) = 14.2 + 65 \log\left(\frac{E_{\max}}{18.8}\right) + 40 \log\left(\frac{d}{3.51}\right) + K_1 \times \log\left(\frac{n}{4}\right) + K_{2i} + \frac{Alt.}{300} \quad (18)$$

where

n is the number of sub-conductors

d is the sub-conductor diameter, in cm

E_{\max} is the average maximum electric field strength produced on the surface of the bundle conductor (rms), in kV/cm

K_1 is 13 when $n \leq 4$, and 19 when $n > 4$

K_{2i} is a factor varying with the rainfall rate,
when $RR \leq 3.6$ mm/h, $K_{2i} = 10 \log\left(\frac{RR}{1.676}\right)$,

and when $RR > 3.6$ mm/h, $K_{2i} = 3.3 + 3.5 \times \log\left(\frac{RR}{3.6}\right)$

$Alt.$ is the altitude, in m

The average corona loss $P(dB)$ in fair weather can be obtained by subtracting 17 dB from the calculated $P(dB)$ on a rainy day. The corona loss $P(dB)$ increases at an increment of $\frac{Alt.}{300}$ with the altitude.

6.3 Insulation coordination and air clearances

6.3.1 Introduction

The insulation coordination of transmission systems may comprehensively consider the costs of investment and losses due to faults to ensure the safety, cost-effectiveness, and high quality of the power supply.

6.3.2 Overvoltage and insulation coordination

Overvoltages occurring on an overhead transmission line mainly include temporary overvoltage, switching overvoltage, and lightning overvoltage. The insulation level of overhead transmission line can be determined based on the various voltages (operating voltage and overvoltage) possibly appearing in the grid and the characteristics of protection equipment.

Insulation coordination under the continuous operating voltage and temporary overvoltage may comply with the following requirements:

- a) The external insulation of a transmission line may withstand continuous operating voltage under the site's pollution severity. Insulators shall be capable of withstanding the continuous operating voltage throughout the design service life.
- b) The air clearances and insulators shall be capable of withstanding temporary overvoltages of certain amplitude and duration.

Insulation coordination under switching overvoltage may comply with the following requirements:

In determining the insulation levels required by switching overvoltages occurring on an overhead transmission line, the statistical approach or simplified statistical approach is used. For systems in Range I, the insulation strength can be determined as a random variable based on the maximum switching overvoltage. For Range II lines, the statistics method regarding the overvoltage amplitude and insulation strength as random variables is often used.¹⁰ See IEEE Std 1313.1TM-1996 [B28] for definition of of Range I and Range II.

For lines in Range II, switching overvoltages can be predicted according to the engineering conditions. The parameters may include the amplitude probability distribution of overvoltages at various points, statistical overvoltages, coefficient of variation, and time-to-crest of overvoltages.

For the effects of the time-to-crest of switching overvoltages, refer to C.5.

For lines in Range I, the time-to-crest and time-to-half-crest of the waveform of switching overvoltages are generally taken as 250 μs and 2500 μs , respectively. For lines in Range II, the time-to-crest of switching overvoltages is longer than 250 μs and can be determined depending on results of prediction made based on engineering conditions. In China, the time-to-crest of the switching impulse test waveform for UHV ac lines is generally taken as 1000 μs (IEEE Std 1862TM-2014).

The protection of transmission lines against lightning overvoltages may be implemented with the aim to achieve the expected lightning trip-out rate. The time-to-crest and time-to-half-crest of lightning impulse overvoltages are generally taken as 1.2 μs and 50 μs , respectively.

¹⁰ See IEEE Std 1313.1TM-1996. This guide only covers transmission systems above 110 kV in Range I. As the definition of the standard voltage varies in different countries; the maximum system voltages for classification of Range I and Range II may slightly differ among countries.

When live-line maintenance of transmission lines is necessary, the safe clearance for live work may be considered. When the maintenance personnel work on an energized power line, as no-load reclosing operations will not occur and the recloser has been taken out of service, the safe clearance for live work mainly depends on the overvoltage due to reclosing after single-phase earthing faults.

For EHV dimensions, flashover of live-line tools under normal ac line voltage stress of 100 kV/m has been observed, related to various combinations of extremely light tool surface equivalent salt deposit density (ESDD) and tool-to-conductor arcing in cold and warm weather.

6.3.3 Insulation coordination procedures

The insulation coordination procedure is basically a process of selecting a series of standard withstand voltages. For an overhead power line, the insulation coordination procedures generally include the following steps (BS EN 50341-1:2012 [B4] with modification):

- Determination of the representative overvoltages (U_{rp})
- Determination of the coordination withstand voltages (U_{cw})
- Determination of the required withstand voltages (U_{rw})
- Determination of the corresponding air clearances (d)

Table 2 shows the steps and the input parameters required for determining the insulation level of transmission lines.

Table 2—The steps and input parameters required for determining the insulation level of transmission lines

Results obtained	Actual steps	Input parameters required
Representative voltages and overvoltages, U_{rp}	Systematical analysis	Origin and classification of voltage stresses Overvoltage level Insulation characteristic
Coordination withstand voltage $U_{cw} = K_c U_{rp}$	Determine the insulation that meets the performance criteria.	Flashover voltage characteristic of single insulation The effects below constitute the coordination factor, K_c Statistical distribution Effects of insulation structure and waveform Factor of parallel insulations
Required withstand voltage $U_{rw} = K_s K_a U_{cw}$	Factor to account for the difference between the type test condition and actual operating condition	The altitude correction factor, K_c The safety factor, K_s K_s is constituted by the effects below: <ul style="list-style-type: none"> — Rain, fog, icing, and other meteorological conditions — Development of industries and local pollution level — Product difference and installation quality — Aging or damage of insulators — Other unknown factors
Minimum air clearance The minimum length of insulator string	Select the corresponding insulation strength $U_{50\%}$	The flashover characteristic test results of the insulation, considering the test conditions and the test conversion factor.

6.3.4 Air clearance

6.3.4.1 General requirements

The air clearances from live conductors to earthed supports under wind action on insulator strings shall be sufficient to withstand the continuous operating voltage, switching overvoltage and lightning overvoltage, and a certain margin may be reserved to account for natural conditions and installation error.

In the design of insulation coordination, the insulation strength of a single air clearance or insulator string on transmission lines under various voltages can be obtained through flashover voltage tests on simulated towers. Annex C shows the 50% flashover voltage test curves under standard power-frequency voltage, switching overvoltage, and lightning overvoltage for part of typical air clearances on supports. During design, existing test data may be referenced, with corrections being made to account for the environmental conditions, tower shape (mainly the tower width), waveform, and other factors.

Both the structure of supports and configuration of conductors on supports affect the flashover characteristics of the conductor-to-support clearance; therefore, in determining the flashover strength of air clearances on supports, tower width correction can be made with reference to C.6.

For typical air clearances with a size longer than 1 m and at an altitude up to 2000 m, the electrical strength can also be estimated using empirical formulae with reference to Appendix G of IEC 60071-2.

6.3.4.2 Air clearance under power-frequency voltage

The air clearance under the power-frequency voltage is generally determined assuming that the basic wind speed (average of 10-min wind speeds) occurs concurrently.

Based on the simplified statistical method, the power-frequency 50% flashover voltage $U_{50\%}$ for the air clearance between conductor and support under continuous operating voltage can be expressed as in Equation (19).

$$U_{50\%} \geq \frac{K_s K_c K_a \sqrt{2U_m}}{\sqrt{3}} \quad (19)$$

where

U_m is the maximum system operating voltage, in kV

K_a is the altitude correction factor

K_c is the coordination factor

K_s is the safety factor

Subclause C.2 shows the 50% power-frequency flashover voltage test curves of part of typical air clearances of supports.

6.3.4.3 Air clearance under switching overvoltage

Given the unlikelihood that switching overvoltage and basic wind speed appear concurrently, the wind speed concurrent with the switching overvoltage can be taken as a value smaller than the basic wind speed. It is usually determined based on operational experience. For example, it is generally taken as 50% of the basic wind speed in China, the medium wind speed (roughly 60% of the basic wind speed) in America, and the high wind speed with a three-year return period with the reduction of corresponding clearances considered in Europe (the specific value is to be determined by the respective countries at their own discretion).

The 50% switching impulse flashover voltage of the air clearance from conductor to support $U_{50\%}$ can be calculated by Equation (20).

$$U_{50\%} \geq K_s K_c K_a U_s \quad (20)$$

where

U_s is the phase-to-ground statistical switching overvoltage of the line

K_s is the safety factor

K_c is the coordination factor

K_a is the altitude correction factor

Subclause C.3 shows the 50% switching impulse flashover voltage test curves of part of typical air clearances.

6.3.4.4 Air clearance under lightning overvoltage

The air clearance under lightning overvoltage can be calculated with the lightning impulse withstand voltage and expected lightning trip-out rate. The concurrent wind speed for lightning overvoltage is generally taken as 0, or taken as a small value, for example, 10 m/s in China. Under lightning overvoltage, the 50% positive lightning impulse flashover voltage of air clearance may be smaller than the 50% lightning impulse flashover voltage of a clean insulator string.

Subclause C.4 shows the 50% lightning impulse flashover voltage test curves of part of typical air clearances. See 6.5 for lightning protection design and measures.

6.3.4.5 Safe clearance for live work

The safe clearance for live work depends on the voltage class, type of line, structure of support, as well as the manner of live work. The safe clearance for live work is determined to ensure the danger rate of the clearance, which can be calculated based on the test data of a full-scale tower and the overvoltage level of system, within the acceptable level. Currently, a danger rate less than 1.0×10^{-5} is deemed acceptable. Lacking test data, the calculation method given in IEEE Std 516™-2009 may be used as a reference. Furthermore, the range of workers' movement may be considered as well in determining the safe clearance for live work. The minimum clearance required for live work should also comply with local regulations, such as OSHA standards.

For UHV lines, the safe clearance for live work may not be included as a controlling factor for the insulation dimensions, in order to avoid an excessively large tower top geometry. The safe clearance for live work, plus the range of workers' movement, may not be greater than the clearance determined by switching overvoltage. Otherwise, special protection measures can be made in place for such live work.

6.3.5 Altitude correction of withstand voltages (or flashover voltages)

Test data of flashover voltages on external insulation may be given under standard atmospheric conditions at 0 m. As such, the flashover voltages may be corrected when the area of interest is at an altitude above 0 m. When the area of interest is at an altitude of 2000 m or below, the altitude correction factor K_a for the withstand voltages (or flashover voltages) of external insulation under various voltage stresses can be calculated by the formula given by Equation (21):

$$K_a = e^{mH/8150} \quad (21)$$

where

H is altitude, in m

m a factor taken as 1.0 for the short-duration power-frequency withstand overvoltage and as 1.0 for lightning impulse overvoltage for air clearances and clean insulators. For switching impulse overvoltage, the value of m can be determined from a and c curves in Figure 9 of IEC 60071-2.

For areas at an altitude above 2000 m, it is recommended that the altitude correction factor K_a be determined through tests. See C.7 for the flashover voltage test data of part of air clearances on supports obtained through tests in high-altitude areas in China.

6.4 External insulation design for polluted and icing conditions

6.4.1 External insulation design for polluted conditions

The insulator strings for transmission lines should be able to withstand the continuous operating voltage under the corresponding site pollution severity (SPS), as well as the specified switching and lightning overvoltage.

For the external insulation design for polluted conditions, the type and number of insulators can be determined based on SPS (equivalent salt deposit density [ESDD]/non-soluble deposit density [NSDD]), in combination with pollution and environmental conditions nearby, and a proper margin can be reserved for development.

The classification of SPS may be different in different countries. Where no such local requirements are available, reference may be made to IEC/TS 60815-1.

At present, two methods are commonly used to determine the number of insulators for HV transmission lines. The first method, the unified specific creepage distance (USCD) method, determines the USCD based on SPS in the area where the line runs, and then to determine the number of insulators. Simple and easy, this method is widely applied in engineering design and has been proven in practice.

The second method, contamination withstand method, obtains the pollution flashover withstand voltage of insulator strings under different SPS through tests and then determines the configuration of the insulator string, of which the pollution flashover withstand voltage is higher than the maximum operating voltage of the line. This method is preferred for UHV transmission lines and lines in heavily-polluted areas.

When the USCD method is used, the number of insulators is determined using Equation (22):

$$n \geq \frac{\lambda V_m}{\sqrt{3} K_e L_I} \quad (22)$$

where

- n is the number of insulators required for each string
- λ is USCD, in cm/kV
- V_m is the maximum system operating voltage, in kV
- L_I is the geometric creepage distance of a single suspension insulator, in cm
- K_e is the effectiveness factor for the creepage distance of insulators. It is mainly determined by the effectiveness of improvement of the withstand voltage under polluted conditions through the geometrical creepage distance of various insulators under test condition and operational condition. Insulators of U70BL and U160B (as defined in IEC 60305:1995 [B23]) are taken as basis for which K_e is taken as 1 (GB/T 50545-2010).

When the contamination withstand method is used, the number of insulators is determined using the formula in Equation (23):

$$N = \frac{V_m}{\sqrt{3}V_{50\%I}(1-n\sigma)} \quad (23)$$

where

N is the number of insulators required for a string

V_m is the maximum system operating voltage, in kV

$V_{50\%}$ is the pollution flashover voltage of a single insulator, in kV. It can be the value corrected on the basis of the pollution flashover voltage obtained through tests against the actual natural conditions and after fully considering such factors as the pollution composition, non-uniformity of pollution on top and bottom surfaces, and NSDD based on test values of pollution flashover voltage of the insulator and according to practical natural conditions.

σ is the standard deviation of pollution flashover voltage of insulator, generally 3% to 10%

n is the multiple of the standard deviation

Correction of ESDD: If ESDD is no more than 0.1 mg/cm², no correction is required. If ESDD is greater than 0.1 mg/cm², a coefficient K_c can be used for correction ($K_c = 1 - 1.13M^{2.57}$, where M is the equivalent concentration of Ca²⁺ in composite salt). If the corrected ESDD is smaller than 0.1 mg/cm², it may be taken as 0.1 mg/cm².

Correction of non-uniformity of pollution on top and bottom surfaces: The correction factor increases from 1.04 to 1.1 as the ESDD gradually increases.

Correction of NSDD: The correction factor decreases from 1.22 to 1.04 as the ESDD gradually increases.

6.4.2 External insulation design for icing conditions

For transmission lines in heavy icing areas, the number of insulators may be checked against the withstand voltage of the iced insulator string, and it can be calculated using Equation (24):

$$N = \frac{V_m}{\sqrt{3}H \times V_i} \quad (24)$$

where

N is the number of insulators required for a string

V_m is the maximum system operating voltage, in kV

H is the structure height of a single insulator, in m

V_i is the withstand voltage gradient of an iced insulator, kV per meter of dry arc distance; it can be determined through test

Currently, artificial simulation of pollution on iced insulators mainly includes simulation of pollution during icing and that before icing. The former is to simulate pollution by changing the water conductivity of ice and has been applied in many countries such as Canada, the United States, and Sweden; the latter is to simulate pollution by altering the solid layer on the surface. Both test methods are described in IEEE Std 1783™-2009 [B30]. For insulators in severely-polluted areas, the latter method or a combination of both methods is mostly used.

Icing test results vary by region. IEEE P1820/D9 [B26] provides a process to adapt standard icing test results for insulator selection based on the variable severity corresponding to local climate and environment.

The icing flashover voltage of V-type insulator string is higher than that of I-type string, since bridging insulators through icing will not occur easily. The number of insulators for V-type string can be determined based on the pollution flashover voltage. If I-type insulator strings are used, they may be configured using a model for flashover strength based on icing stress product (ISP) and the relevant 2% exceedance levels for ice accretion and conductivity considering the partial pick-up of pre-existing ESDD into the icicles that bridge the dry-arc distance in Figure 1.

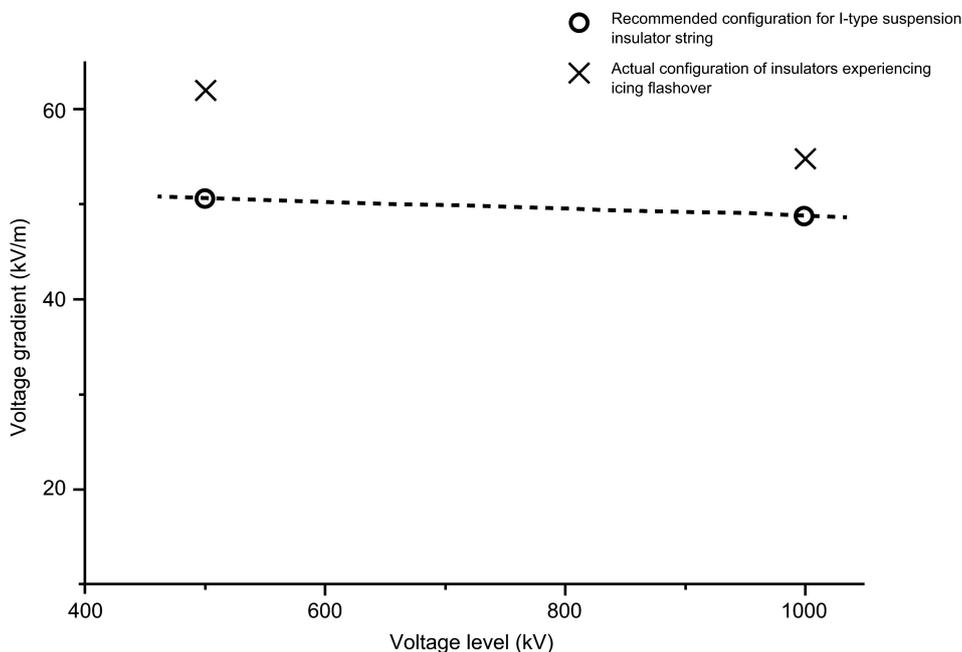


Figure 1—Actual configuration and recommended configuration for insulators used on sites experiencing icing flashover

6.4.3 Application criteria for composite insulators

The two methods stated in 6.4.1 may also be adopted for the external insulation design of composite insulators under polluted conditions. Silicone rubber composite insulators have excellent performance against pollution flashover. Even if the surface hydrophobicity of a composite insulator is lost, its pollution flashover voltage is higher than that of a porcelain insulator of the same structure height. When no pollution flashover test data is available for composite insulators, their structure height can be derived from the pollution flashover characteristic data of porcelain or glass cap-and-pin insulators and is generally accepted no less than three-quarters of the height of such cap-and-pin insulators.

In certain conditions specified in IEC 60815-3, the USCD of composite insulators may be adjusted downwards by up to one pollution class by agreement.

China Electric Power Research Institute (CEPRI) carried out power-frequency pollution tests on 9 m long composite insulators for 1000 kV transmission lines, and the results revealed that these insulators can ensure operational safety under the SPS class d and class e considering a weak hydrophobicity.

The length of composite insulators is generally determined based on their pollution flashover characteristics, and equivalent correction is made to the results of artificial pollution tests in line with the natural pollution conditions. Composite insulators for 230 kV (220 kV) and above transmission lines can be provided with grading rings at both ends, and their effective insulating length can withstand the switching and lightning overvoltages with the impact of altitude considered.

Similar to cap-and-pin insulators, the pollution flashover voltage of composite insulators varies linearly with the length. The length can be calculated with the pollution flashover withstand voltage using Equation (25):

$$L = \frac{V_m}{\sqrt{3}V'_{50\%} \times (1 - n\sigma)} \quad (25)$$

where

- L is the length of composite insulators, in m
- $V'_{50\%}$ is the corrected pollution flashover voltage per unit length of composite insulator, in kV
- σ is the standard deviation of pollution flashover voltage of insulator, taken as 7% generally
- n is the multiple of standard deviation

The corrected pollution flashover voltage per unit length of composite insulator ($V'_{50\%}$) can be calculated using Equation (26):

$$V'_{50\%} = V_{50\%} K_1 K_2 \quad (26)$$

where

- $V_{50\%}$ is the pollution flashover voltage per unit length of composite insulator, in kV/m. It is generally determined through test based on actual project conditions.
- K_1 is the correction factor of NSDD, the value of which is the same as that of cap-and-pin insulators
- K_2 is the correction factor of non-uniformity of pollution on top and bottom surfaces of insulator. It is generally taken as 1 for composite insulators.

6.4.4 Altitude correction method for pollution flashover voltage

The flashover voltage of polluted insulators will decrease non-linearly as the atmospheric pressure drops. The flashover voltage of polluted insulators in high-altitude areas varies with the rise of altitude or drop of atmospheric pressure, and it can be corrected using Equation (27) or simplified Equation (28).

$$U = U_0 \left(\frac{P}{P_0} \right)^n \quad (27)$$

$$U = (1 - k_1 H) U_0 \quad (28)$$

where

- U_0 is the pollution flashover voltage under normal pressure, P_0
- U is the pollution flashover voltage under the low pressure, P
- n is the descending index, which reflects the extent to which the atmospheric pressure affects the pollution flashover voltage
- H is altitude, in km
- k_1 is the descending slope. k_1 depends on such parameters as the shed type and materials of insulators. In general, k_1 can be taken as 6% to 8% for standard cap-and-pin insulators, 4% to 6% for outer-rib-type cap-and-pin insulators, and 6% for composite insulators.

6.5 Lightning protection and grounding

6.5.1 Lightning protection

6.5.1.1 Introduction

The design of lightning protection for transmission lines can be based on factors such as the importance and operation mode of the lines in the power grid, the operational experience of local existing lines, as well as the lightning activities, ground flash density, topology and landform, and the soil resistivity within the line right-of-way. Local conditions and economic rationality may also be suitable considerations for lightning protection.

In the design of lightning protection for transmission lines, the hazards of shielding failure strike and back flashover may be considered. Usually, for HV lines, the hazards are mainly from back flashover, while for EHV and UHV lines, the hazards from shielding failure strike are greater. For special line sections (e.g., transition from overhead line to cable line) in mountainous areas with strong thunderstorms, and some important lines, optimized lightning protection measures may be taken for supports at a high risk of lightning strike. Lightning trip-out rate is generally used as the control index for the risk evaluation of transmission lines. For the lightning calculation methods in this guide, refer to Annex D.

For lightning protection of transmission lines, installation of overhead ground wires and support-grounding devices are usually preferred. Other protection measures, such as the installation of arcing horns, line surge arresters, and coupling ground wires may be considered as well.

6.5.1.2 Overhead ground wires

The back-flashover rate can be decreased by reducing the shielding angle (IEEE Std 1243™-1997) between the ground wire and the conductor. The shielding angle on supports can be determined based on the operational experience of local existing lines or the calculated anticipated lightning trip-out rate. For lines equipped with ground

wires, the minimum spacing between the conductor and the ground wire at the mid-span may be controlled so as to prevent back flashover to conductors caused by lightning strikes to the ground wire at the mid-span.

Overhead ground wires of each support can be grounded or insulated. In the latter case, ground wires can be insulated reliably, and the insulators may be installed with discharge gap, the type and clearance of which can be determined based on the induced voltage on the ground wire during normal operation of lines and the follow-current extinction after operation of the gap.

The thermal stability of ground leads and grounding devices shall be checked over time. Observations should occur with the transmission line energized.

6.5.1.3 Arcing horns

For transmission lines equipped with auto-reclosing devices, insulators may be protected through the installation of arcing horns in areas with a high ground flash density, which may comply with the following requirements.

The breakdown voltage of arcing horns and the lightning flashover voltage of protected insulators can be coordinated so that the arcing horns operate reliably when lightning overvoltage occurs, without significantly reducing the capacity of lines to withstand shielding failure strike and back flashover. As for insulation coordination, the minimum spacing between electrodes of arcing horns (Z) is usually taken as $(85\% \pm 2.5\%)$ of the length of the insulator (string) connected in parallel with them (Z_0).

Arcing horns can be securely installed and able to resist arc and corrosion to a certain extent.

6.5.1.4 Line surge arresters

For supports or line sections at a high risk of lightning strike, if reducing the shielding angle of ground wire and support grounding resistance still fail to meet the requirements of lightning protection, line surge arresters may be installed. Generally, surge arresters with series gaps are used.

6.5.2 Grounding design

The supports equipped with ground wires should be grounded. The grounding resistance may meet the requirement of the anticipated lightning trip-out rate. If soil conditions are favorable, such that the natural grounding resistance of supports can meet the requirements for the back-flashover withstand level, the artificial grounding electrodes are not essential.

The support grounding devices consist of the grounding electrode and the down lead wire. Their types and dimensions can be determined by comprehensively considering the type of supports, soil resistivity, operational experience, etc., and may meet the requirements for limits of grounding resistance. For supports in areas with high soil resistivity, the resistance may be reduced by increasing the length and burial depth of electrodes, partially replacing soil, or using a resistance-reducing agent.

The electrodes for transmission lines running through farmland can be buried below the depth of tith, and those in residential areas and paddy fields can be arranged in a ring form.

The material and the cross section of grounding conductors and electrodes can be determined by accounting for corrosion caused by soil within the design service life and ensuring the grounding conductors and electrodes can pass the thermal stability check.

The power-frequency grounding resistance of electrodes in different shapes buried in uniform soil may be calculated with reference to IEEE Std 142 or E.1 of this guide. Furthermore, E.2 and E.3 also introduce the calculation methods for impulse grounding resistance. The soil resistivity used in the design of the grounding device for lightning protection may be taken as the maximum value ever occurring in the thunderstorm season, and can be corrected considering factors such as the burial depth, the layout, and the seasonal difference of soil resistivity.

7. Structural design criteria

7.1 Mechanical design of conductors, insulators, and fittings

7.1.1 Conductor tension

To protect conductors from mechanical breakage or fatigue damage, the conductor tension is generally limited from two aspects, i.e., the maximum allowable working tension and everyday stress (EDS).

The maximum allowable working tension of conductors or ground wires under the design load conditions can be calculated using the following formula (GB/T 50545-2010 and GB/T 50665-2011):

$$T_{\max} \leq \frac{RTS}{K_m} \quad (29)$$

where

T_{\max} is the maximum working tension of conductors or ground wires, in N

RTS is the rated tensile strength of conductors or ground wires, in N

K_m is the design safety factor of conductors or ground wires

The safety factor for conductor tension under the check condition of extreme (accidental) loads may be a little smaller than that under the normal design load condition. While for large-span lines crossing important rivers, or lines running through areas where traffic conditions are extremely inconvenient, the design safety factor may be increased as appropriate since repair of the lines will be very difficult once the lines are damaged.

The aeolian vibration effects of conductors intensify with the increase of tension. To protect conductors from fatigue damage due to continuous aeolian vibration, the EDS of conductors or ground wires may be limited. The upper limit on the EDS of conductors or ground wires may be considered in combination with corresponding anti-vibration measures.

CIGRE 273 reports that the vibration characteristics of conductors/ground wires are closely related to the tension parameter T/m (ratio of tension to mass per unit length of conductor/ground wire) and span parameter LD/m (ratio of the product of span and outer diameter to mass per unit length of conductor/ground wire). For limits on T/m and LD/m and corresponding anti-vibration measures, reference may be made to applicable provisions in CIGRE 273 [B8].

In general, reducing the design conductor tension will reduce the probability of mechanical damage, but, on the other hand, will also increase the conductor sag and tower height. Therefore, the safety factor of conductors can be determined within a reasonable and economic range based on local experience in engineering design. Experience

with limits on conductor tension under various conditions varies in different areas. Subclause F.1 gives the EDS panel recommendations for safe design tensions. Subclause F.2 gives empirical values of the safety factor of conductors, upper limits on the EDS of conductors/ground wires, and corresponding anti-vibration measures used in China. When spacer dampers are used for bundle conductors with four or more sub-conductors, other anti-vibration measures may be dispensed with if the span is no more than 500 m.

7.1.2 Plastic elongation of conductors/ground wires

The design of conductor sags may consider the plastic elongation and long-term creepage of conductors. The specific value can be determined based on data provided by the manufacturer or through tests. The designer may compensate the effects of plastic elongation and long-term creepage on sags with different methods, for example, the temperature decrement method, in which the conductor stress is increased and sags are reduced to compensate for the increment of sags resulting from creepage of conductors. In addition, the design may be based on the resultant sags after permanent elongation of conductors, thereby reserving a sufficient distance from conductor to ground. Another alternative is the pre-tensioning method: the conductors are pre-stretched with a force higher than the design stress before the erection of lines to eliminate plastic elongation during construction.

7.1.3 Mechanical requirements of insulators

The safety factor for the mechanical strength of insulators can be calculated using Equation (30) (GB/T 50545-2010 [B21] and GB/T 50665-2011 [B20]):

$$K_I = \frac{T_R}{T_d} \quad (30)$$

where

K_I is the safety factor of insulators

T_R is the rated mechanical failing load of insulator, in kN

T_d are the loads acting on insulators, in kN. Various load conditions may be considered, such as the maximum working load, normal load over years, check load, line breakage load, string breakage load, and so on.

The safety factor for the mechanical strength of insulators, K_I , can be determined depending on specific load conditions, and different regions have different rules. Subclause F.3 gives the values of factors used in China.

7.1.4 Design of fittings

The design of fittings of overhead lines may meet the requirements for mechanical strength. The safety factor for the mechanical strength of fittings can be taken with reference to that of insulators as specified in 7.1.3. Subclause F.4 gives the factor values used in China.

Spacer dampers can be used between conductors.

The first fitting connected with the cross-arm may be able to rotate flexibly, and is reasonably imposed with force, and its strength may be a level higher than that of other fittings within the same string.

On the condition that the insulator strings will not fall under the maximum wind deflection condition, the half of the included angle between the two arms of a suspended V-string may be slightly smaller than the maximum wind deflection angle of an I-string.

For lines in heavy icing areas, when double insulator strings are used, the two strings can be suspended at one point. The conductors and ground wires of such lines may be protected with pre-formed armor rods to mitigate or prevent damage of conductors and ground wires due to unbalanced tension, ice-shedding-induced line jumping and galloping. The spacers can be used to reduce the sub-span and increase the torsional strength. Pre-formed spacers can be used. The spacing between strings for multi-string insulators can be increased as appropriate to minimize the likelihood of collision between strings due to vibration of insulator strings when ice-shedding-induced line jumping occurs.

7.2 Type of support

Supports can be classified into:

- a) Self-supporting structure and guyed structure by the way of supporting
- b) Suspension structure, strain structure, terminal/dead-end structure, and anti-cascading structure by the way of performance
- c) Single-circuit, double-circuit, and multi-circuit structure according to the number of line circuits

7.3 Loads on lines

7.3.1 Classification of loads

Loads on lines can be classified as follows:

- a) Permanent loads: loads which are likely not to change or the change can be neglected during the design working life, such as the self-weight of conductors and ground wires, insulators and their fittings, as well as supports.
- b) Variable loads: loads whose change cannot be neglected during the design working life, such as wind and ice loads, tensions of conductors, ground wires, and guys; additional loads imposed during installation and maintenance; secondary loads resulting from structural deformation, and various dynamic loads from vibration.
- c) Accidental loads: loads which do not necessarily occur within the design working life, but are very high and last for a very short time once occurring, such as seismic loads.

7.3.2 Load cases

Generally, the design of supports may consider the following load cases: intact cases (weather loads), broken wire cases, construction and maintenance cases, as well as the legislated load cases in the region where the project will be located. For special supports, such as terminal supports and anti-cascading supports, special load cases may be considered according to engineering requirements. For double-circuit and multi-circuit supports, the possibility of wire installation or operation on one side may be considered according to actual project conditions.

7.3.3 Intact cases

The supports may satisfy the following weather loads during normal operation:

- a) Basic wind speed, with no ice, no unbalanced longitudinal loads from conductors and ground wires.
For the convenience of design, it is justified through calculation that the wind loads in the most unfavorable directions can be simplified as 0° , 45° (60°), and 90° .
- b) The design ice thickness, with concurrent wind speed and temperature, and without unbalanced longitudinal loads of conductors and ground wires.
The design ice thickness can be determined with reference to historical icing data or the ice map, and the values of concurrent wind speeds under the design ice thickness are usually diverse in different countries. Based on its rich experience designing in the icing areas, China usually takes a wind speed of 10 m/s for the design ice thickness of 15 mm or less, and 15 m/s for those of more than 15 mm.
- c) The load cases under the minimum temperature may also be considered when necessary.

7.3.4 Broken wire cases

Broken wire cases on supports may comply with the following load cases, or the legislated load cases in the region where the project will be located:

- a) For single-circuit supports: unbalanced longitudinal loads may be applied to any single conductor phase or at any one ground wire.
- b) For double-circuit supports within the same span: unbalanced longitudinal loads may be applied to any two conductor phases, or any one conductor phase and any one ground wire.
- c) For multi-circuit supports within the same span: unbalanced longitudinal loads may be applied to any three conductor phases, or any two conductor phases and any one ground wire.
- d) The values of unbalanced longitudinal loads from conductors and ground wires can be calculated in combination with following aspects: the typical geographical conditions along the line route, the ice thickness, and operational experience.

7.3.5 Construction and maintenance cases

The construction and maintenance cases may meet the following loads:

- a) The construction loads can be calculated based on the meteorological conditions of no icing, concurrent wind speed, and air temperature. The concurrent wind speed can be determined based on national electric safety codes, which vary greatly in different countries; for instance, wind speed is taken as 56 km/h in ASCE MOP 74 and 10 m/s in Chinese standards.
- b) Construction loads mainly refer to the actions of installing conductors, ground wires, insulators, and hardware on supports. While designers may consider different load effects for different installation methods, the following loads can be considered generally:
 - 1) For suspension support, loads caused by lifting and anchoring conductors, ground wires, and their fittings.
 - 2) For strain support, loads caused by anchoring and stringing/saging conductors and ground wires, temporary guyed wires, as well as additional loads imposed on supports during installation.

- 3) For all tower members which may be climbed and inclined with an angle no more than 30° to the horizontal, the weight of workman and instruments may be considered and may not be combined with other loads.
- 4) For construction and maintenance cases, the fall protection system shall meet all local regulations, such as OSHA standards, in the region where the project will be located.

7.3.6 Calculation of wind loads

Wind loads include those applied on the conductors, ground wires, insulator strings, and the support itself.

The calculation of wind load is specified in ASCE MOP 74. It should be noted that a 3 s gust wind speed is adopted in ASCE MOP 74, but 10 m/s is used in other countries. The conversion relationship of different wind time interval may be considered.

7.4 Design of structural members

7.4.1 General

The design of support structures mostly adopts the probability-based limit states design, including ultimate limit states and serviceability limit states.

The ultimate limit states design is expressed in Equation (31):

$$\gamma \times S \leq \psi \times F_y \quad (31)$$

where

- S is the effect of the characteristic value of loads
- γ is the load factor, depending on the type of loads and return period
- F_y is the minimum guaranteed yield stress of members
- ψ is the strength factor of members

The serviceability limit states shall meet the requirements of Equation (32):

$$S \leq C \quad (32)$$

where

- C are the specified limits for deformation, crack, vibration amplitude, acceleration, stress, etc., for structures or structural members to meet serviceability requirements

Generally, the design of structures, especially self-supporting structures, may be based on the first-order elastic analysis, and the second-order analysis will not be considered.

7.4.2 Limits for the slenderness ratio of members

The allowable maximum slenderness ratio for steel members has been specified in Table 3.¹¹

Table 3—Allowable maximum slenderness ratio for steel members

Item	Allowable maximum slenderness ratio for steel members
Compressed leg member	150
Compressed member	200
Redundant member	250
Tension member (prestressed members may not be subjected to limits of slenderness ratio)	400
NOTE—Alternatively, the allowable maximum slenderness ratio may be determined according to relevant codes in the project area.	

Excessive displacements of supports should not occur under normal working conditions. The calculated deflections of supports under long-term load combinations (no icing, wind speed of 5 m/s, and annual average temperature) may be as specified in Table 4.

Table 4—Calculated deflections of supports (excluding inclination of foundations and displacement of guying points)

Item	Calculated deflection limits
Top of guyed suspension tangent supports	$4h/1000$
Pole (tower) body below the guying point of guyed suspension tangent supports	$2h_1/1000$
Self-supporting suspension tangent supports	$3h/1000$
Self-supporting suspension angle supports	$5h/1000$
Self-supporting strain supports and terminal supports	$7h/1000$
NOTE 1—The variable h refers to the total height of the support which starts from the top surface of the foundation regarding the longest leg extension. The variable h_1 is the height from the attaching point of guyed wire to the ground.	
NOTE 2—The foundation pre-tilt requirements shall be proposed in the design as per characteristics of supports.	

Steel members of supports can be hot-dip galvanized for anti-corrosion or treated with other equivalent anti-corrosion measures. In areas exposed to more severe corrosion, other effective anti-corrosion measures can also be put in place for the guy anchors.

The thread of a fit bolt under shearing may not be included in the shear plane. Otherwise, their shearing strength may be checked by the net cross-sectional area of the thread portion.

¹¹ See ASCE/SEI 10-15, Design of Latticed Steel Transmission Structures, for additional information on structural design criteria.

7.4.3 Design of members

The design of members should consider strength requirements and stability requirements.

For the strength design of members, the net cross-sectional areas of members should be adopted; and for the stability design of members, the gross cross-sectional area should be used.

In the design of members, the effective length and slenderness ratio should consider the influence of eccentricity and restraint of end connections.

The design of members should be taken into consideration as specified in ASCE/SEI 10-15.

8. Design of foundations

8.1 General

The design of foundations may ensure the stability of subsoil and the strength of structures. The deformation of subsoil, displacement of structures, and width of concrete cracks (when required) may also be controlled within the allowable range by design.

The types of foundations can be selected comprehensively considering such factors as the topography, geology, and hydrology at the tower positions, as well as the force passed to foundations from towers.

For the design of foundations in mountainous areas, foundations with uneven height can be used in combination with different leg extensions of towers for environmental protection purposes.

When foundations are located partially or overall below the underground water table or in soft subsoils, a blinding layer may be placed, or other anti-disturbance measures can be taken. Calculation of foundations may consider the buoyancy force on the subsoils and foundations from ground water.

In foundation design, proper and effective protective measures can be taken against the corrosive effects of underground water or soil on foundations.

For foundations crossing rivers or in flood basins, relevant hydrogeological data may be collected, and when necessary, the scouring action of water and the collision pressure of floating debris may be considered, and proper protective measures can be taken.

For tower positions exposed to unfavorable geological conditions, such as expansive soil, collapsible loess, seasonally frozen ground or permafrost, and seismic liquefaction, proper treatment measures can be taken according to relevant regulations in the project area.

Parameters of subsoil, such as unit weight, cohesion, internal friction angle, bearing capacity, and underground water table, can be obtained by field geotechnical investigation and tests. If no field data are available, they can be determined with reference to relevant local specifications.

8.2 Design of foundations

8.2.1 Types of foundations

For latticed supports, the commonly-used foundations are pad and chimney foundation, drilled foundation, pile foundation, and rock foundation.

Pad and chimney foundations are buried in pre-excavated pits and then backfilled and compacted with soil.

Drilled foundations are formed by directly installing reinforcing bars and casting concrete into a hole, which is in the natural undisturbed soil and drilled by equipment or excavated manually, with bottom bell piles.

Pile foundations are formed by installing the reinforcing bars and casting concrete in the deep holes drilled (or punched) with special machines and tools. They are classified into single-pile foundations and group-pile foundations.

Rock foundations mainly include rock anchor foundations and rock embedded foundations. As for the former, the anchor bar is bonded to the rock through cementation of grout or fine-aggregate concrete in the rock holes; and the latter is a type of foundation where the reinforcing bar and concrete are directly cast into the rock pit drilled (or excavated) by mechanical means into the rock.

8.2.2 Design of pad and chimney foundations

8.2.2.1 Calculation of compression capacity

The compression capacity of subsoil can be determined through load tests or other in-situ tests, based on experience in engineering practices. If no data is available, the compression capacity can be calculated with relevant soil mechanics equations based on the foundation dimensions and parameters of subsoils. In calculating the compression loads of foundations, the effects of eccentric loading on foundation design may also be considered.

IEEE Std 691™ gives the method for the calculation of compression capacity of subsoils, in which the maximum load per unit area that can be placed on a soil at a given depth, called the *ultimate bearing capacity*, is the maximum load Q divided by the foundation area $B \times L$ at depth D . Q includes the structure loads, weight of the foundation, and weight of the backfill within the volume $B \times L \times D$.

8.2.2.2 Calculation of uplift capacity

As stipulated in IEEE Std 691, the failure modes of pad and chimney foundations may be different with the construction procedure, foundation depth, soil properties, and other factors. It also recommends three traditional design methods, namely earth cone method, shearing or friction method, and Meyerhof and Adams's method. The specific design method may be determined with reference to IEEE Std 691. In China, the earth cone method is the most common, widely used in UHV and other transmission line projects. In this method, the critical depth of uplift h_c , i.e., the calculated depth at which the soil is destroyed in overall pattern, is introduced for various soil. The calculation model is as shown in Figure 2.

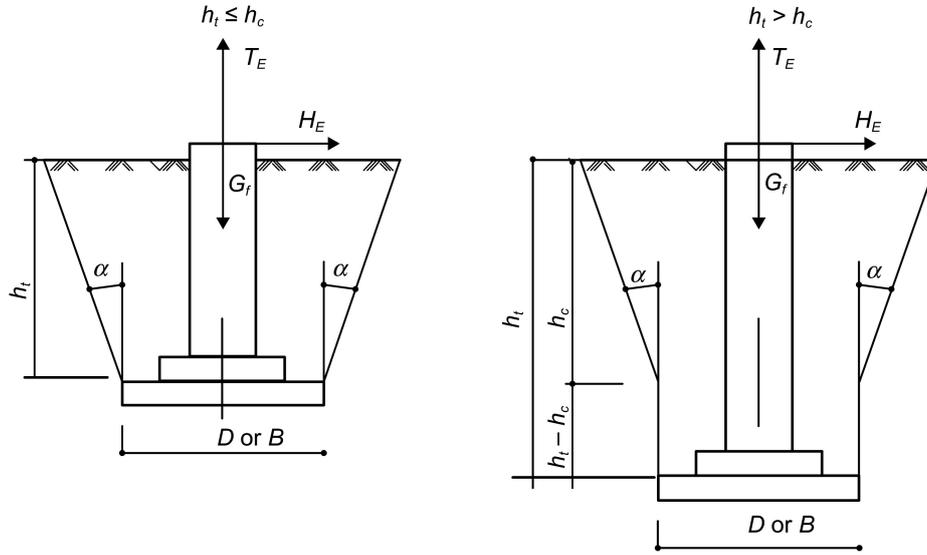


Figure 2—Uplift capacity calculation model in the earth cone method

The calculation formula is given in Equation (33).

$$T_E \leq \frac{1}{K} (\gamma_E \gamma_S \gamma_{\theta 1} (V_t - \Delta V_t - V_0) + G_f) \quad (33)$$

where

T_E is the characteristic value of uplift for foundations, in kN

K is the safety factor for foundation design

γ_E is the influence coefficient of horizontal load, which is determined from Table 5 based on the ratio of horizontal load H_E to uplift load T_E

Table 5—Influence factor of horizontal loads γ_E

Ratio of horizontal load H_E to uplift load T_E	Influence coefficient of horizontal load γ_E
0.15 to 0.40	1.0 to 0.9
0.40 to 0.70	0.9 to 0.8
0.70 to 1.00	0.8 to 0.75

γ_S is the effective unit weight of backfilled and undisturbed soil on the bottom of foundation, in kN/m³

$\gamma_{\theta 1}$ is the influence coefficient of upper surface slope angle of the pad, which is taken as 1.0 for $\theta \geq 45^\circ$ and 0.8 for $\theta < 45^\circ$

- V_t is the volume of soil and foundation within the depth of h_t , in m^3
- ΔV_t is the volume of common soil between adjacent foundations under uplifting, in m^3
- V_0 is the volume of foundation within the depth of h_t , in m^3
- G_f is the weight of foundation, in kN
- α is the uplift angle used for calculating uplift capacity in the earth cone method, which can be determined with reference to Table 6

Table 6—Unit weight of soil and uplift angle

Type of soil parameter	Clay and silty clay			Silty soil			Sandy soil			
	Hard/hard plastic	Plastic	Soft plastic	Dense	Moderately dense	Slightly dense	Gravel sand	Coarse and medium sand	Fine sand	Silt
Unit weight γ_s (kN/m ³)	17	16	15	17	16	15	19	17	16	15
Uplift angle α (°)	25	20	10	25	20	10 to 15	30	28	26	22

The critical depth h_c in the earth cone method is determined based on Table 7.

Table 7—Critical depth h_c in the earth cone method

Type of soil	Natural state of soil	Critical depth of uplift h_c	
		Circular pad (D)	Rectangular pad (B)
Sandy soil, silty soil	Dense to slightly dense	2.5	3.0
Clay	Hard to hard plastic	2.0	2.5
	Plastic	1.5	2.0
	Soft plastic	1.2	1.5

NOTE 1—For a rectangular pad, if the ratio of the longer side l to shorter side b is no more than 3, $D = 0.6(b + l)$.

NOTE 2—The natural states of soil may be used.

8.2.2.3 Local specifications

In addition to the uplift and compression requirements, the settlement of subsoils may also comply with relevant local specifications in the project area.

8.2.3 Design of drilled foundations

IEEE Std 691 gives three methods for the calculation of uplift capacity for bored concrete pile foundations, namely truncated cone model, traditional cylindrical shear model, and compression uplift foundation analysis and design (CUFAD). The specific design method may be determined with reference to IEEE Std 691.

In China, the shearing method is used for uplift capacity calculation of drilled foundations, with the calculation model as shown in Figure 3.

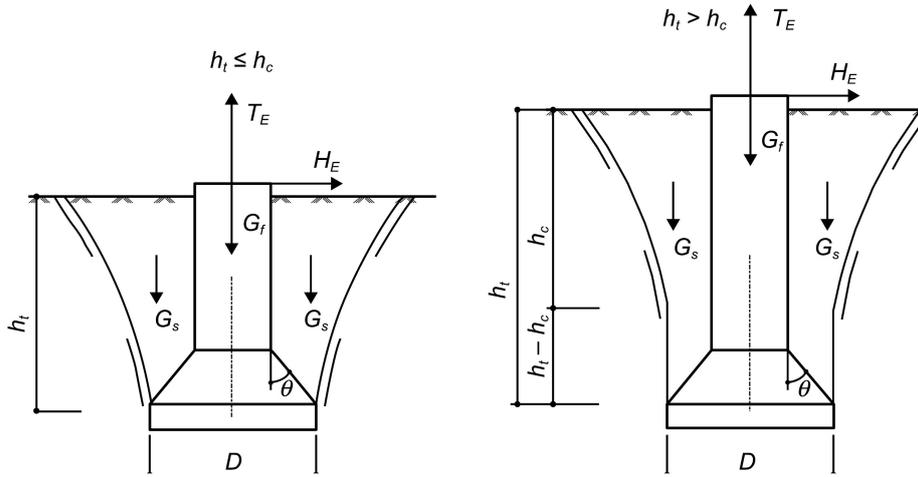


Figure 3—Uplift capacity calculation model of the shearing method

The calculation formula is given in Equation (34), Equation (35), and Equation (36).

$$T_E \leq \frac{1}{K} \gamma_E \gamma_\theta R_T \quad (34)$$

When $h_t \leq h_c$,

$$R_T = A_1 c h_t^2 + A_2 \gamma_s h_t^3 + \gamma_s (A_3 h_t^3 - V_0) + G_f \quad (35)$$

When $h_t > h_c$,

$$R_T = A_1 c h_c^2 + A_2 \gamma_s h_c^3 + \gamma_s (A_3 h_c^3 + \Delta V - V_0) + G_f \quad (36)$$

where

R_T is the standard value of uplift capacity of foundations, in kN

c is cohesion of soil determined based on the saturated undrained shear strength or equivalent saturated undrained shear strength, in kPa

A_1 is a dimensionless calculation factor dependent on the pattern of sliding surface of soil with uplift resistance; it can be calculated using Equation (37)

A_2 is a dimensionless calculation factor dependent on the angle of internal friction φ ; it can be calculated using Equation (38)

A_3 is a dimensionless calculation factor dependent on the depth/diameter ratio $\lambda = \frac{h_i}{D}$ (with $\lambda \geq 1$) of the foundation; it can be calculated using Equation (39)

$$A_1 = 2\pi\zeta^2 K_1 (1 + \sin \varphi) e^{2\left(\frac{\pi}{4} - \frac{\varphi}{2}\right)\tan \varphi} \quad (37)$$

$$A_2 = \frac{2\pi \sin \varphi}{1 + 4 \tan^2 \varphi} \zeta^3 \left\{ K_2 - K_1 \cos\left(\frac{\pi}{4} + \frac{\varphi}{2}\right) e^{2\left(\frac{\pi}{4} - \frac{\varphi}{2}\right)\tan \varphi} \left[2 \tan \varphi \tan\left(\frac{\pi}{4} + \frac{\varphi}{2}\right) - 1 \right] \right\} \quad (38)$$

$$A_3 = \pi \left(\frac{1}{4\lambda^2} + \frac{1}{\lambda} \zeta \cos \alpha + \zeta^2 \cos^2 \alpha \right) - \frac{1}{4} \pi \zeta^2 \left(\frac{1}{\lambda} + 2\zeta \cos \alpha \right) \left(\frac{\pi}{2} - 2\alpha + \varphi - \sin 2\alpha + \cos \varphi \right) - \frac{1}{3} \pi \zeta^3 \left\{ \sin \alpha (2 + \cos^2 \alpha) - \cos\left(\frac{\pi}{4} - \frac{\varphi}{2}\right) \left[2 + \sin^2\left(\frac{\pi}{4} - \frac{\varphi}{2}\right) \right] \right\} \quad (39)$$

where

$$K_1 = -\frac{1}{1 + 4 \tan^2 \varphi} \left\{ \left(\frac{1}{2\lambda\zeta} + \cos \alpha \right) \left\{ e^{-2\left(\frac{\pi}{2} - \alpha\right)\tan \varphi} (\sin \alpha + 2 \tan \varphi \cos \alpha) \right. \right. \\ \left. \left. - e^{-2\left(\frac{\pi}{4} - \frac{\varphi}{2}\right)\tan \varphi} \left[\cos\left(\frac{\pi}{4} - \frac{\varphi}{2}\right) + 2 \tan \varphi \sin\left(\frac{\pi}{4} - \frac{\varphi}{2}\right) \right] \right\} \right\} \\ + \frac{1}{4 \tan \varphi} \left[e^{-2\left(\frac{\pi}{2} - \alpha\right)\tan \varphi} - e^{-2\left(\frac{\pi}{4} - \frac{\varphi}{2}\right)\tan \varphi} \right] \\ + \frac{1}{4(1 + \tan^2 \varphi)} \left[e^{-2\left(\frac{\pi}{2} - \alpha\right)\tan \varphi} (\tan \varphi \cos 2\alpha + \sin 2\alpha) + e^{-2\left(\frac{\pi}{4} - \frac{\varphi}{2}\right)\tan \varphi} (\tan \varphi \sin \varphi - \cos \varphi) \right]$$

$$K_2 = \left(\frac{1}{2\lambda\zeta} + \cos\alpha \right) \left[\left(\frac{3\pi}{8} - \frac{3\alpha}{2} + \frac{3\varphi}{4} \right) \sin\varphi - \frac{1}{2} \sin(2\alpha - \varphi) \tan\varphi + \frac{1}{2} \tan\varphi - \frac{1}{4} \cos(2\alpha - \varphi) \right] \\ + 2 \tan\varphi \left[\frac{1}{12} \sin(3\alpha - \varphi) + \frac{1}{2} \sin(\alpha - \varphi) + \frac{1}{4} \sin(\alpha + \varphi) + \frac{1}{12} \cos\left(\frac{3\pi}{4} - \frac{\varphi}{2}\right) \right. \\ \left. - \frac{1}{2} \cos\left(\frac{\pi}{4} + \frac{\varphi}{2}\right) - \frac{1}{4} \cos\left(\frac{\pi}{4} - \frac{3\varphi}{2}\right) \right] + \frac{1}{2} \cos(\alpha - \varphi) - \frac{1}{4} \cos(\alpha + \varphi) \\ + \frac{1}{12} \cos(3\alpha - \varphi) - \frac{1}{2} \sin\left(\frac{\pi}{4} + \frac{\varphi}{2}\right) + \frac{1}{4} \sin\left(\frac{\pi}{4} - \frac{3\varphi}{2}\right) + \frac{1}{12} \sin\left(\frac{3\pi}{4} - \frac{\varphi}{2}\right)$$

$$\zeta = \frac{1}{\cos\left(\frac{\pi}{4} - \frac{\varphi}{2}\right) - \sin\alpha}$$

The critical depth h_c in shearing method can be determined based on Table 8.

Table 8—Critical depth h_c in shearing method

Type of soil	State of soil	Critical depth h_c in shear method
Gravel, coarse, medium sand	Dense to slightly dense	4.0 D to 3.0 D
Fine sand, silt, silty soil	Dense to slightly dense	3.0 D to 2.5 D
Clay	Hard to plastic	3.5 D to 2.5 D
	Plastic to soft plastic	2.5 D to 1.5 D

8.2.4 Design of pile foundations

Pile foundations may be used at positions featuring a shallow groundwater table, soft subsoil, or river crossings. Manually excavated pile foundations may be used in mountainous areas inaccessible to machinery.

The design diameter of pile foundations can be determined in combination with construction machinery locally available and comply with relevant local specifications in the project area.

The geological parameters used in calculation of pile foundations—such as unit weight, bearing capacity of subsoil, shaft side resistance, and coefficient of subsoil—can be obtained through field tests and comply with relevant local specifications in the project area.

The specific design methods for pile foundations of various types given in IEEE Std 691 may be used for reference.

8.2.5 Design of rock foundations

When using rock foundations, the stability of rock, thickness of overburden, mechanical properties of rock, degree of rock weathering, etc., of each foundation may be checked. The methods described below may be used as reference for the design of rock foundations.

The following four aspects may be included in the design of rock anchor foundations:

- 1) The strength of a single anchor bar in tension can be calculated using Equation (40):

$$T \leq \frac{1}{K} \times f_y \times A_n \quad (40)$$

where

T is the characteristic value of uplift force on a single anchor bar, in kN

f_y is the minimum guaranteed yield stress of anchor bars, in kPa

A_n is the net cross-sectional area of a single anchor bar, in m²

- 2) The bearing capacity of the bonding between a single anchor bar and grout should meet the requirement of Equation (41):

$$T \leq \frac{1}{K} \times \pi \times d \times l_0 \times \tau_a \quad (41)$$

where

d is the diameter of an anchor bar, in m

l_0 is the effective embedment length of an anchor bar, dependent on the diameter and the degree of rock weathering, in m

τ_a is the average bonding strength between anchor bar and grout, in kPa

- 3) The bearing capacity of the bonding between a single anchor shaft and rock should meet the requirement of Equation (42):

$$T \leq \frac{1}{K} \times \pi \times D \times h_0 \times \tau_b \quad (42)$$

where

D is the diameter of the anchor shaft, in m

h_0 is the embedment length of the anchor shaft, depending on the degree of rock weathering and diameter of the anchor shaft, in m

τ_b is the average bonding strength between grout of shaft and rock, in kPa

- 4) Shearing capacity calculation of rock

It is assumed that the shearing failure of rock is in a shape of an inverted truncated cone, the uplift force is resisted by the sum of vertical components of the shearing strength of the rock τ_s evenly distributed on the cone surface.

For a single anchor shaft, the requirement of Equation (43) may be satisfied:

$$T \leq \frac{1}{K} \times \pi \times h_0 \times \tau_s \times (D + h_0) \quad (43)$$

where

τ_s is the equivalent shearing strength of the rock, in kPa

In cases where a foundation comprises multiple anchor shafts, the effects of spacing between anchor bars on the shearing capacity of the rock may be considered.

The uplift capacity of a rock-embedded foundation may meet the requirement of Equation (44):

$$T_E \leq \frac{1}{K} \left[\pi h_0 \tau_s (D + h_0) + G_f \right] \quad (44)$$

8.3 Design of connections

8.3.1 Design of stubs and anchor bolts

Stubs or anchor bolts can be used in the connections of tower and foundations.

The calculation of stubs may consider the combination of axial force and shear force.

The calculation of anchor bolts should consider uplift and shear loads.

8.3.2 Design of tower base plate

The strength of the base plate of a non-stiffened square base can be calculated using the following formulas (Figure 4).

When subject to compression,

Thickness of the base plate:

$$Q = \frac{N}{A} \quad (45)$$

$$t \geq \sqrt{\frac{3Q \times C^2}{f}} \quad (46)$$

where

Q is the uniform reaction of base plate, in N/mm²

- N are compressive loads on the foundation, in N
- A is the area of the base plate ($B \times B$), in mm^2
- C is the distance from the edge of the main angle steel to the edge of base plate, in mm
- t is the thickness of the base plate, in mm

Strength of I-I section:

$$W_1 = \frac{1}{6} B \times t^2 \quad (47)$$

$$M_1 = Q \times B \times \frac{C^2}{2} \quad (48)$$

$$\sigma_1 = \frac{M_1}{W_1} \leq f \quad (49)$$

where

- W_1 is the bending modulus of I-I section, in mm^3
- M_1 is the bending moment of I-I section, in $\text{N} \times \text{mm}$
- B is the width of base plate, in mm

When subject to tension,

Tensile force on anchor bolt:

$$T_1 = \frac{T}{4} \quad (50)$$

where

- T are the uplift loads on the foundation, in N
- T_1 are the uplift loads borne by an anchor bolt, in N

Strength of the II-II section:

$$W_2 = \frac{1}{6} D \times t^2 \quad (51)$$

$$M_2 = T_1 \times Y \quad (52)$$

$$\sigma_2 = \frac{M_2}{W_2} \leq f \quad (53)$$

where

W_2 is the bending modulus of the II-II section of an anchor bolt, in mm^3

M_2 is the bending moment of the II-II section of an anchor bolt, in $\text{N} \times \text{mm}$

D is the effective width of the II-II section of an anchor bolt, in mm

Y is the distance from the center of an anchor bolt to the edge of the main angle steel, in mm

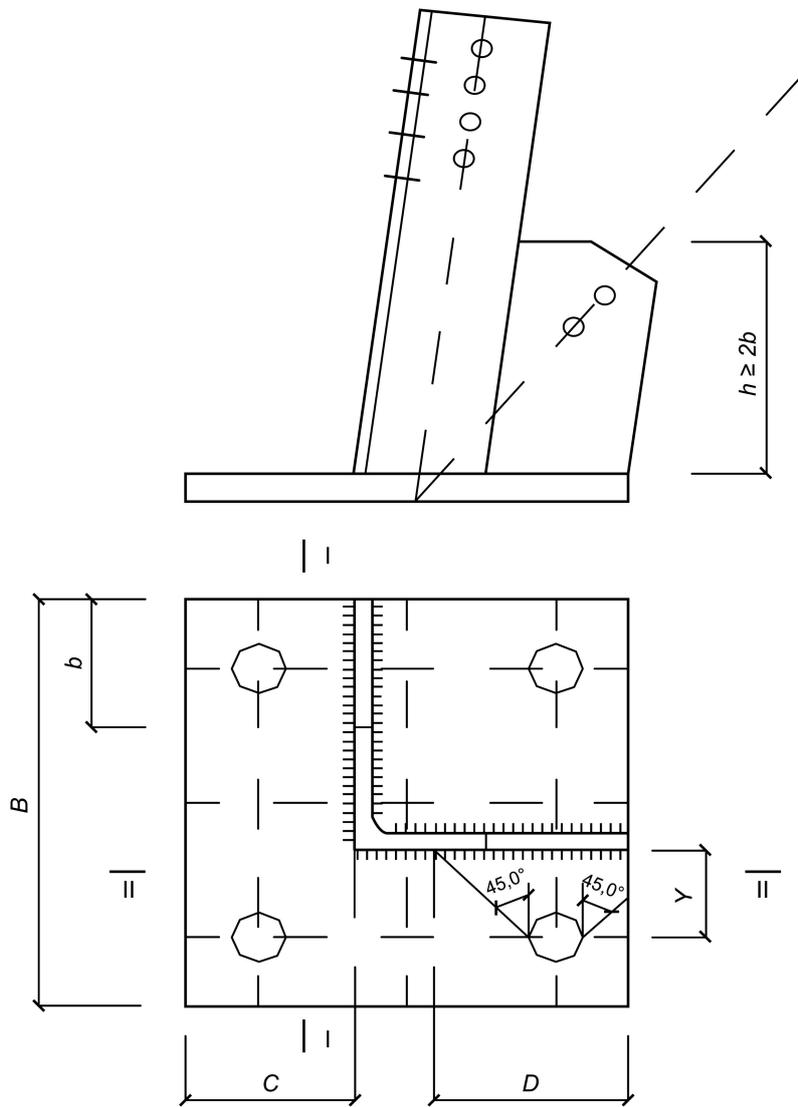


Figure 4—Non-stiffened tower base plate

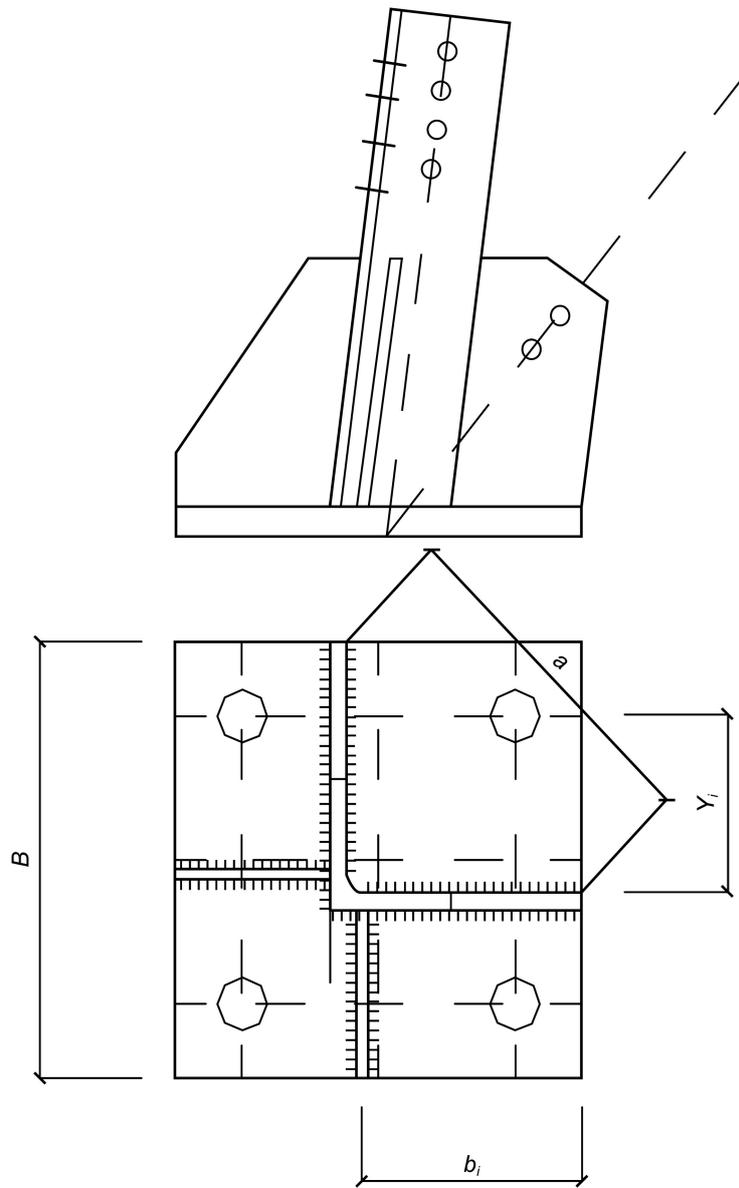


Figure 5—Stiffened tower base plate

The strength of the base plate of a stiffened square base assembly can be calculated using the following formulas (Figure 5).

When subject to compression,

Bending moment of the base plate:

$$M = 0.06Q \times a^2 \quad (54)$$

where

a is the length of the free edge of the base plate segment under calculation, in mm

Thickness of base plate:

$$t \geq \sqrt{\frac{5M}{f}} \quad (55)$$

Thickness of base plate when subject to tension:

$$t = \frac{1}{1.5} \sqrt{\frac{3T}{f \times B^2} \times (Y_i \times b_i)_{\max}} \quad (56)$$

If $Y_i < 0.5b_i$, $Y_i = 0.5b_i$

where

T is the tensile load acting on the base plate, in N

B is the width of tower foot plate, in mm

Y_i is the distance from the center of the anchor bolt in the i^{th} segment to the main angle steel

Annex A

(informative)

Reference design limits for electromagnetic environment

A.1 Design limits on radio interference

Table A.1 gives the design limits for radio interference for ac transmission lines in some countries (Wu and Wan [B37]).

Table A.1—Design limits for radio interference in some countries or regions

Country	Line voltage (kV)	Frequency (MHz)	Distance (m)	Permissible radio interference (dB)	Remarks
Canada	70 to 200 200 to 300 300 to 400 400 to 600 600 to 800	0.5	15	49 53 56 60 63	0.15 to 30 MHz maximum radio noise field in fair weather
China	110 220 to 330 500 750 to 1000	0.5	20	46 53 55 58	The specified value for 80% of a year and with a confidence of 80%. The radio interference limits at 1 MHz is about 5 dB less than that at 0.5 MHz.
Japan	275 to 500	1	10	60	On rainy days
Switzerland	< 100 > 150	0.5	20	34 48	The average of radio interference values in fair weather, which is permitted to be exceeded in 10% of the time.
Italy	420	0.5	30 70	35	In densely populated areas In sparsely populated areas
Brazil	1000	1	Edge of line right-of- way	42	50% of the time in fair weather

A.2 Design limits on audible noise

The design limits on audible noise from transmission lines vary from country to country. They are also implicitly specified in many local laws.

The operational experience in the United States shows that at the edge of the corridor there is basically no complaint about the audible noise level below 53 dB(A) at 30 m from the centerline of the line. When the noise level reaches 53 dB(A) to 59 dB(A), people living near the line will propose some complaints; when the noise level exceeds 59 dB(A), there is a large increase in the number of complaints (EPRI [B14]).

The *Standard of Environmental Noises for Urban Areas* of China is formulated with a view to ensuring the life quality of urban residents. It applies to urban areas, and can be used as reference for rural areas. The limits on environmental noise in the five categories of areas in cities specified in the standard are given in Table A.2. The audible noise from wet conductors of 500 kV and 750 kV lines are limited to 55 dB(A) in China, equal to the limit on audible noise at night in the category-3 area (industrial area).

Table A.2—Criteria for environmental noise in the five categories of areas in cities, in dB(A)

Category ^a	Day	Night
0	50	40
1	55	45
2	60	50
3	65	55
4	70	55

^aCategory 0 refers to areas such as sanatoria, luxury villas, and high-standard hotels where quietness is specially required.
Category 1 refers to areas where residential buildings and cultural and educational offices are located. Standards for this category of area can be used as reference for rural areas.
Category 2 refers to mixed residential, business, and industry areas.
Category 3 refers to industrial areas.
Category 4 refers to areas on both sides of trunk roads in cities and those on both sides of inland river channels passing through urban areas.

Table A.3 shows the criteria for environmental noise in Japan, which, similar to the environmental noise criteria of China, also vary with the time and category of area.

Table A.3—Criteria for environmental noise in Japan, in dB(A)

Category ^a	Day	Dawn and dusk	Night
AA	Less than 45	Less than 40	Less than 35
A	Less than 50	Less than 45	Less than 40
B	Less than 60	Less than 55	Less than 50

^aAA—areas where quietness is specially required, such as sanatoria.
A—areas where quietness is generally required, such as living environment.
B—common areas mixed with residential buildings, business, and some industries.

Table A.4 gives the measuring positions and design limits of audible noise from ac transmission lines in some countries or regions (Wu and Wan [B37]).

Table A.4—Design limits for audible noise from some lines in some countries or regions

Country		Rated voltage (kV)	Measuring position	Design limits for audible noise, in dB(A)
USA	New York	765	Bedroom of house near the line	35
			125 feet from the line center	56 (L ₅) 53 (L ₅₀)
	Oregon		Edge of line right-of-way	53 ± 2 (L ₅₀)
Japan		1000	Beneath the line	50 (L ₅₀ for rainy days)
Italy		1000	15 m outside the projection of side-phase conductor	56 to 58 (wet conductor after rainfall) 58 to 60 (L ₅ in heavy rain)
Brazil		1000	Edge of line right-of-way	
South Korea		765	15 m outside the side-phase conductor	50 (L ₅₀ in rainy days)
China		1000	20 m outside the projection of side-phase conductor	55 (wet conductor)
NOTE—In the case of natural rainfall, the audible noise level in heavy rain is equivalent to L ₅ ; the audible noise level from wet conductors is equivalent to L ₅₀ for natural rainfall and to the highest noise level that can be reached in heavy fog.				

A.3 Design limits for electric field strength

According to the survey conducted by CIGRE Working Group 36.01 in 1986, among the member countries of CIGRE, dozens of countries had established codes or design guidelines on electrostatic induction in HV transmission projects. Table A.5 gives the design limits for the electric field strength in the proximity of transmission lines in some countries (Wu and Wan [B37]).

Table A.5—Design limits for the electric field strength in the proximity of transmission lines in some countries

Country		Limit on electric field strength (kV/m)	Position	Criteria ^a
Czech		15		
		10	Crossings over Class 1 or 2 roads	
		1	Edge of line right-of-way	
Japan		3	Locations where people walk with an umbrella	A
Denmark		10	Farmlands	
		5	Locations with frequent traffic activities	
Poland		10		A, C
		1	Hospitals, residences, and schools	A, C
Former Soviet Union		20	Inaccessible areas	A, C
		15	Non-public areas	A, C
		10	Crossings over roads	A, C
		5	Public areas	A, C
		1	Building areas	A, C
		0.5	Nearby residential buildings	A, C
USA	Minnesota	8		
	Montana	7	Crossings over roads	B
		1	Residential area at the edge of line right-of-way	C
	New Jersey	3	Edge of line right-of-way	A, C
	New York	11.8		
		11	Crossings over private roads	
		7	Crossings over roads	
		1.6	Edge of line right-of-way	
	North Dakota	8		
Oregon	9	Areas readily accessible to people		
Florida	2	Edge of line right-of-way		
China		4	Nearby residence	
		7	Residential area and roads	
		10	Center of spans in non-residential areas	

^aA—To prevent transient electric shock causing discomfort

B—To prevent steady-state electric shock current larger than the let-go current

C—To limit harmful ecological effects due to long-term effects of electric field

Annex B

(informative)

Formula for predicting audible noise from ultra-high-voltage ac transmission lines in China

China Electric Power Research Institute (CEPRI) proposed the formula for predicting the audible noise from ultra-high-voltage (UHV) ac transmission lines and compared the results calculated with the formula with the actually measured values, which shows that the formula is pretty accurate for UHV ac lines. The formula from Wan et al. [B36]) is shown in Equation (B.1):

$$AN = -123.0 + 96.2 \log E_{\max} + 19.1 \log n + 42.7 \log d \quad (\text{B.1})$$

where

- AN is the A-weighted sound level noise of single-phase conductors, in dB(A)
- E_{\max} ranges from 12 kV/cm to 20 kV/cm
- n is the number of sub-conductors in a bundle, ranging from 6 to 12
- d is the sub-conductor diameter, in cm, ranging from 2.4 cm to 4.0 cm

Annex C

(informative)

Flashover voltage test results for air clearances of transmission line structures

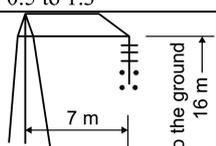
C.1 Introduction

The flashover voltage test results for part of typical air clearances is given in this annex. All test results hereinafter were obtained from simulated towers or gantries and have been calibrated to the standard atmospheric conditions. If not specified, all tests were performed outdoors (Chen et al. [B12]; State Grid Corporation of China [B34]; Xi'an Jiaotong University and Tsinghua University [B38]).

C.2 The 50 percent power-frequency flashover voltage test results for air clearances of transmission line structures

The 50% power-frequency flashover voltage characteristic for air clearances of 330 kV lines and substations are given in Figure 10.6.1 in EPRI [B14], which is derived from Aleksandrov et al. [B1].

Table C.1—The 50 percent power-frequency flashover voltage for air clearances of 500 kV single-circuit lines

Voltage type	Power-frequency ac voltage	
Data	Data 1 (EPRI [B14])	Data 2 (Baoding Transformer Works [B2])
$u_{50\%}$ (kV)	Figure C.2	4431 + 80 (1.0 m < l < 2.5 m)
$\sigma_s/u_{50\%}$ (%)	2	0.5 to 1.3
Shape of tower head	—	

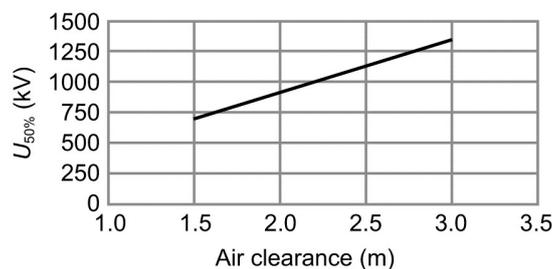


Figure C.1—The 50 percent power-frequency flashover voltage characteristic for air clearances of 750 kV double-circuit lines (GB/T 50545-2010 [B21])

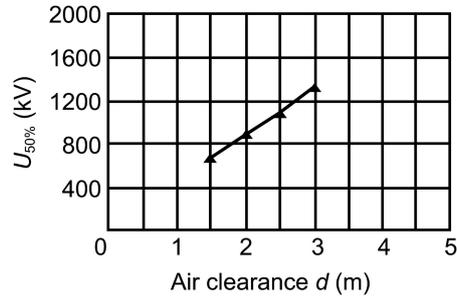


Figure C.2—The 50 percent power frequency flashover voltage characteristic for air clearances of 750 kV single-circuit lines (I-type strings used at side phases, 6-bundle conductors) (GB/T 50064-2014 [B19])

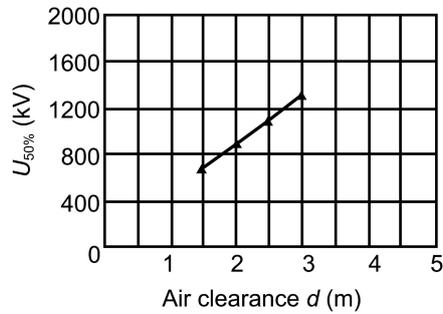


Figure C.3—The 50 percent power-frequency flashover voltage characteristic for air clearances of 750 kV single-circuit lines (cup type tower with 6-bundle conductors and V-type string at middle phase) (GB/T 50064-2014 [B19])

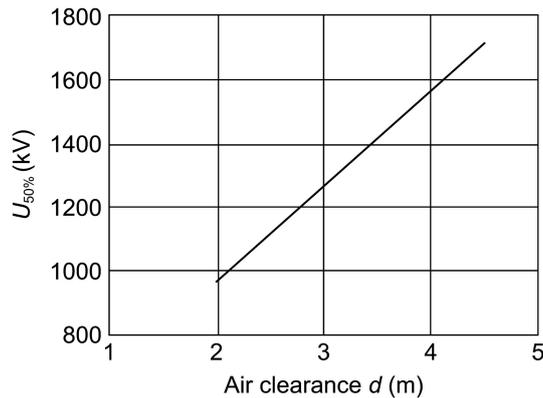


Figure C.4—The 50 percent power-frequency flashover voltage characteristic for air clearances of 750 kV lines

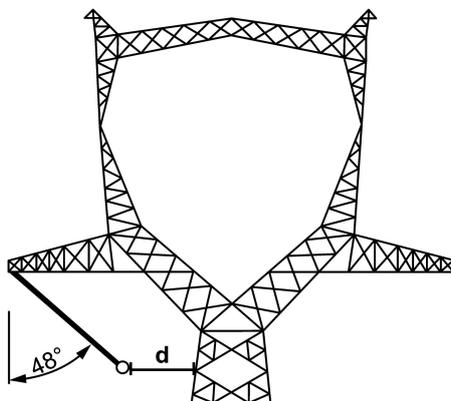


Figure C.5—The arrangement of power-frequency flashover voltage test for side-phase air clearances of 1000 kV cat-head type towers (GB/T 24842-2009 [B18])

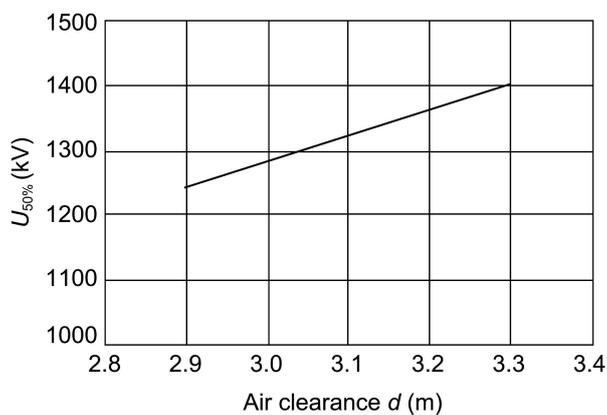


Figure C.6—The 50 percent power-frequency flashover voltage characteristic for air clearance from side-phase conductor to tower body for 1000 kV cat-head type towers (GB/T 24842-2009 [B18])

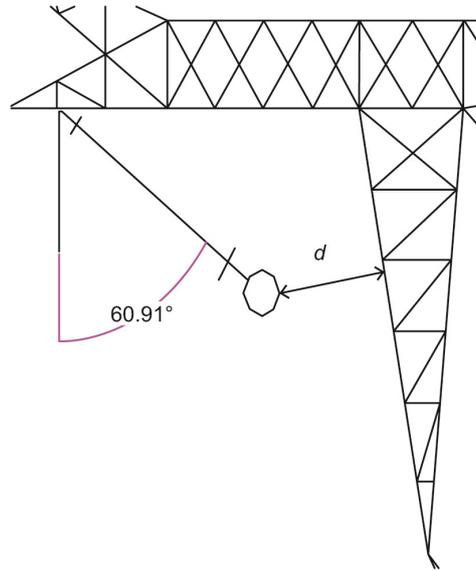


Figure C.7—The arrangement of power-frequency flashover voltage test for side-phase air clearances of 1000 kV cup type towers (GB/T 24842-2009 [B18])

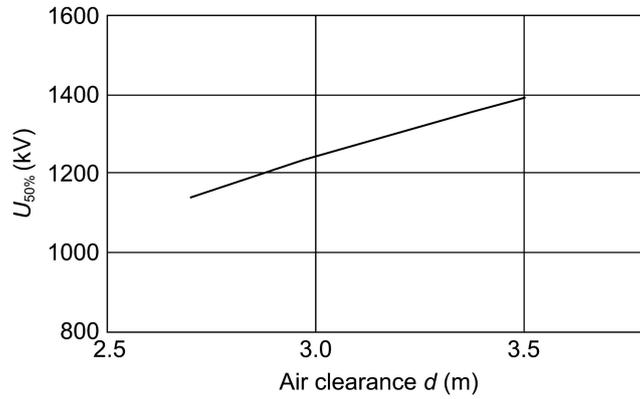


Figure C.8—The 50 percent power-frequency flashover voltage characteristic for air clearance from side-phase conductor to tower body for 1000 kV cup type towers (GB/T 24842-2009 [B18])

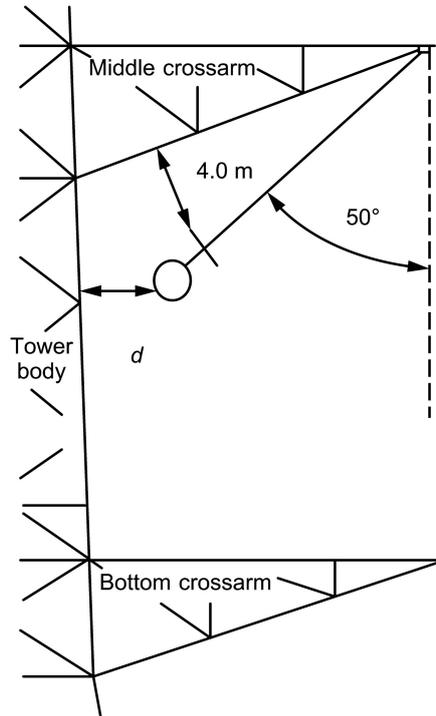


Figure C.9—The arrangement of power-frequency flashover voltage test for air clearances of 1000 kV double-circuit lines (GB/T 24842-2009 [B18])

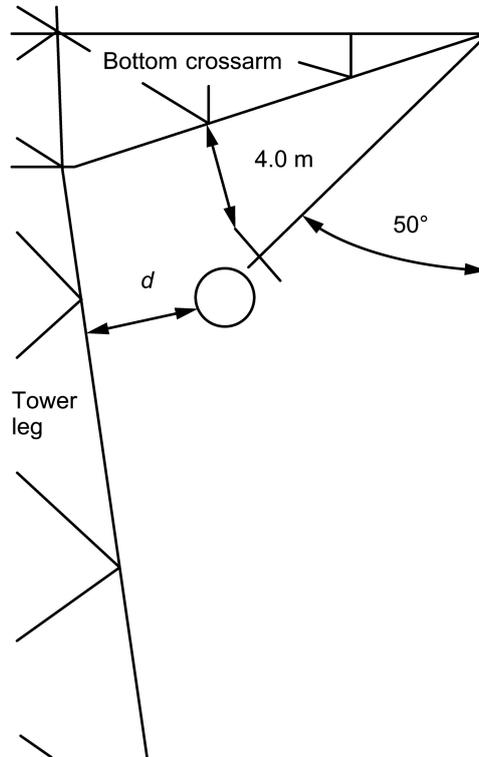


Figure C.10—The arrangement of the power-frequency flashover voltage test for air clearances of bottom-phase with I-type string of 1000 kV double-circuit lines (GB/T 24842-2009 [B18])

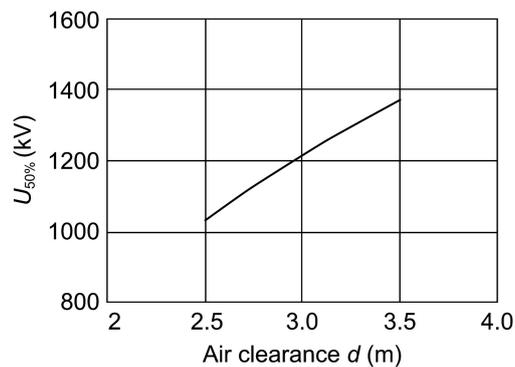
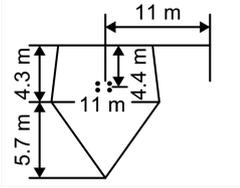
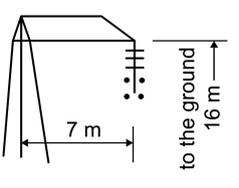
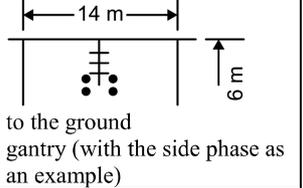
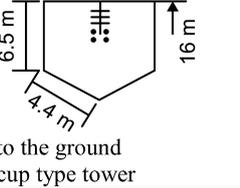


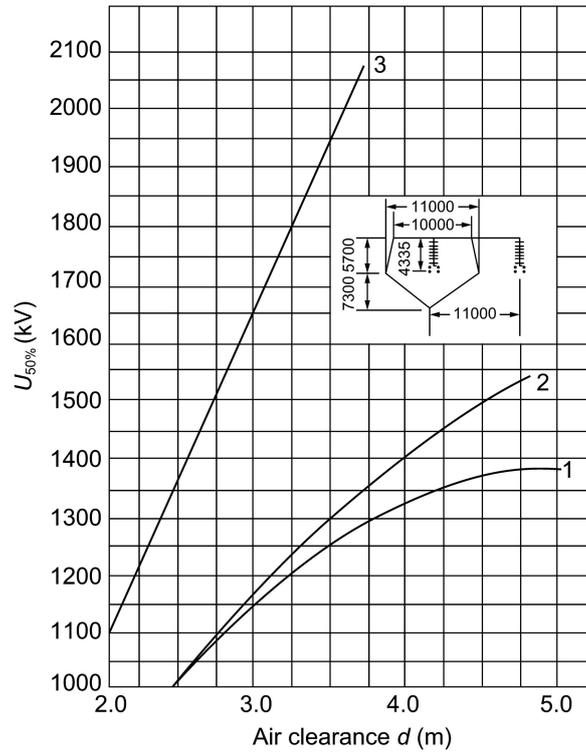
Figure C.11—The power-frequency flashover voltage characteristic of air clearance from bottom-phase conductor (with I-type string) to tower body of 1000 kV double-circuit lines (GB/T 24842-2009 [B18])

C.3 The 50 percent switching impulse flashover voltage test results for air clearances of transmission line structures

Except for 330 kV and 1000 kV voltage classes and unless otherwise specified, the switching impulses used for tests are of a positive-polarity 250/2500 μ s waveform.

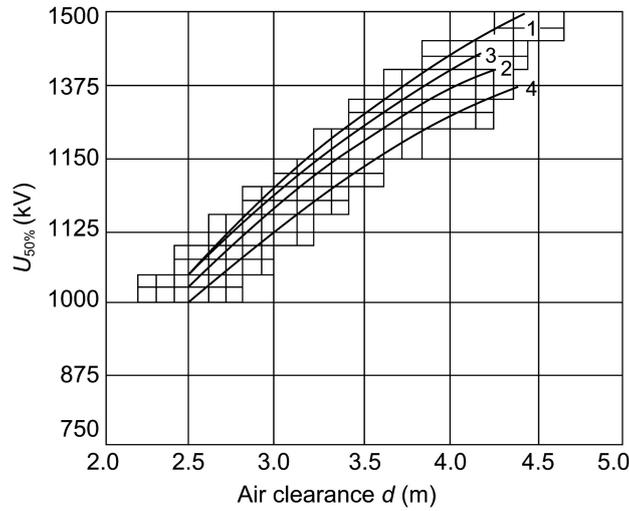
Table C.2—The 50 percent switching impulse flashover voltage for air clearances of 500 kV single-circuit lines (GB/T 50064-2014 [B19])

Voltage type	Switching impulse			
	Data 1 (China Electric Power Research Institute [B5])	Data 2 (Baoding Transformer Works [B2])	Data 3 (Baoding Transformer Works [B3])	Data 4 (Baoding Transformer Works [B3])
Data	Data 1 (China Electric Power Research Institute [B5])	Data 2 (Baoding Transformer Works [B2])	Data 3 (Baoding Transformer Works [B3])	Data 4 (Baoding Transformer Works [B3])
$u_{50\%}$ (kV)	Curves 1 and 2 in Figure C.12	Curves 1 and 2 in Figure C.12	Curves 2 and 3 in Figure C.13	Curve 4 in Figure C.13
$\sigma_s/u_{50\%}$ (%)	2.75 to 5.4	3.0 to 5.4	Middle phase: 3.58 to 4.98 Side phase: 5.0 to 5.13	3.0 to 4.77
Shape of tower head			 to the ground gantry (with the side phase as an example)	 to the ground cup type tower



1—switching impulse on middle-phase; 2—switching impulse on side phase; 3—lightning impulse $\left(\frac{1.5\mu s}{40\mu s}\right)$

Figure C.12—The 50 percent switching impulse and lightning impulse flashover voltages for tower-head air clearances of cup type towers (ZB3) of 500 kV transmission lines (GB/T 50064-2014 [B19])



1—air clearance from side-phase conductor to structure post; 2—middle-phase air clearances of gantry tower; 3—side-phase air clearances of gantry tower; 4—air clearances of cup type tower

Figure C.13—The 50 percent switching impulse flashover voltages for tower-head air clearances of 500 kV gantry towers and cup type towers (GB/T 50064-2014 [B19])

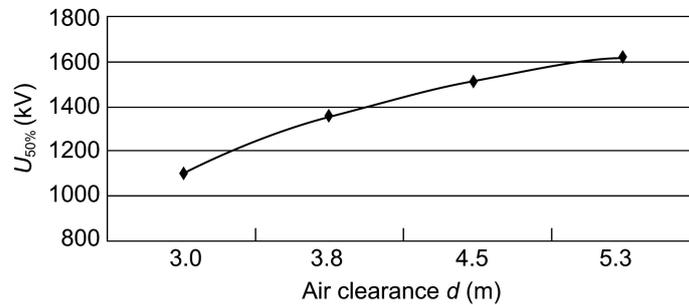


Figure C.14—The 50 percent switching impulse flashover voltages for air clearance from middle-phase conductor (with V-type string) to tower window for 500 kV cup type towers (ZVB452) (GB/T 50064-2014 [B19])

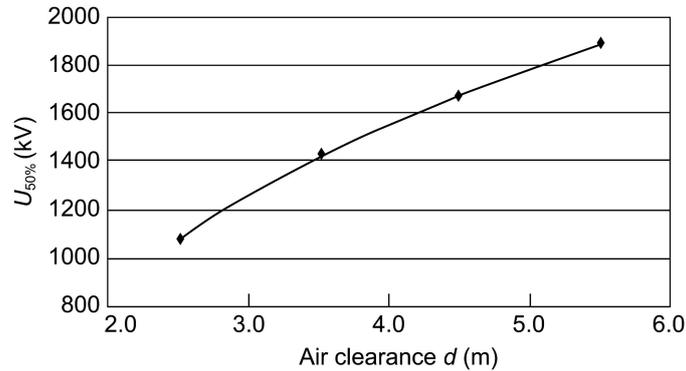


Figure C.15—The 50 percent switching impulse flashover voltage for air clearance from conductor to lower crossarm of 500 kV double-circuit lines (GB/T 50064-2014 [B19])

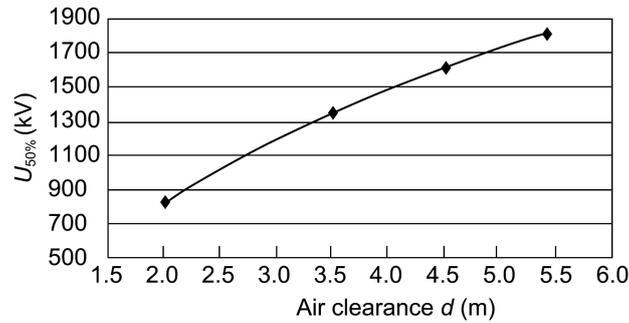


Figure C.16—The 50 percent switching impulse flashover voltage for air clearance from the bottom-phase conductor to tower leg of 500 kV double-circuit lines (GB/T 50064-2014 [B19])

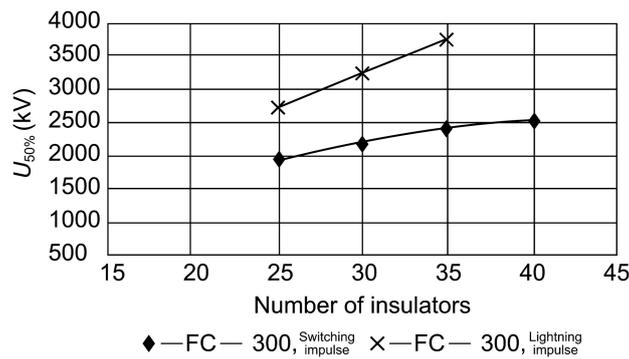


Figure C.17—The 50 percent impulse flashover voltage for 750 kV lines with 6-bundle conductors and FC-300 I-type strings (GB/T 50064-2014 [B19])

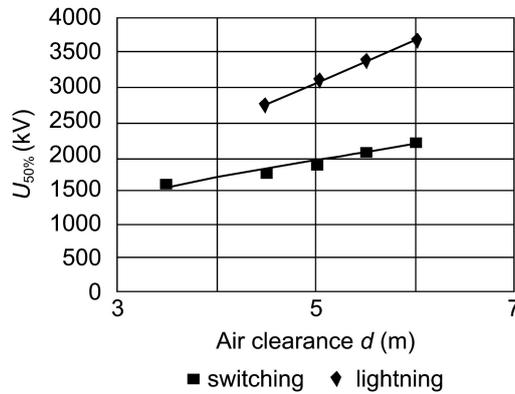


Figure C.18—The 50 percent switching impulse and lightning impulse flashover voltage characteristics for side-phase air clearances of 750 kV single-circuit lines (I-type strings used at side phases and 6-bundle conductors) (GB/T 50064-2014 [B19])

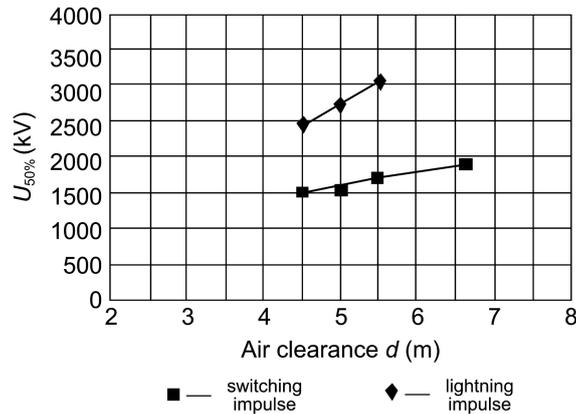
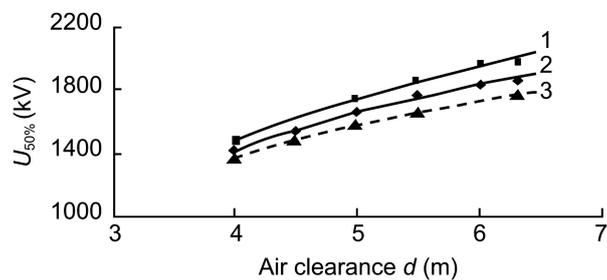


Figure C.19—The 50 percent switching impulse and lightning impulse flashover voltage characteristics for middle-phase air clearances of 750 kV single-circuit lines (cup type tower with 6-bundle conductors and V-type string at middle phase) (GB/T 50064-2014 [B19])



1-time-to-crest of 800 μ s at middle phase; 2-time-to-crest of 250 μ s at middle phase; 3-time-to-crest of 250 μ s at bottom phase

Figure C.20—The 50 percent switching impulse flashover voltage for air clearances of 750 kV double-circuit lines (GB/T 50064-2014 [B19])

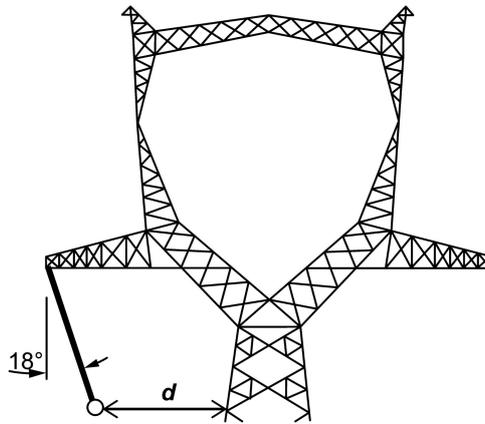


Figure C.21—The arrangement of switching impulse flashover voltage test for side-phase air clearances of 1000 kV cat-head type towers (GB/T 24842-2009 [B18])

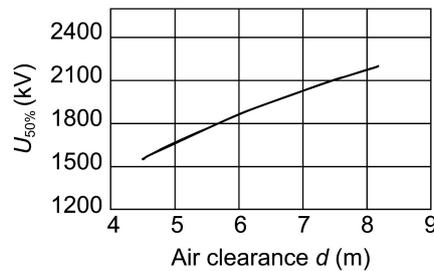


Figure C.22—The 50 percent switching impulse flashover voltage characteristic for air clearances from conductor to tower body of 1000 kV lines (with a time-to-crest of 250 μ s) (GB/T 24842-2009 [B18])

When the air clearance from the side-phase conductor (with I-type string) to tower leg with windage yaw considered is 5.6 m, and the switching impulse test results with different test time-to-crest are as shown in Table C.3.

Table C.3—Switching impulse flashover voltages of side-phase air clearances of 1000 kV cat-head type towers with different test time-to-crest (GB/T 24842-2009 [B18])

Time-to-crest (μ s)	250	500	1000	5000
$U_{50\%}$ (kV)	1789	1880	1915	2125

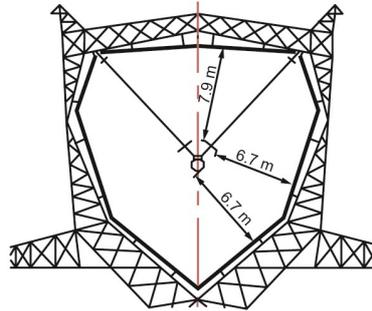


Figure C.23—The arrangement of switching impulse flashover voltage test for middle-phase air clearances of 1000 kV cat-head type towers (GB/T 24842-2009 [B18])

Figure C.23 shows the arrangement of switching impulse flashover voltage test for middle-phase air clearances, and Table C.4 lists the switching impulse flashover voltage test results of air clearances from conductor to tower window with different test time-to-crest.

Table C.4—The switching impulse flashover voltage of air clearances from middle-phase conductor to tower for 1000 kV full-scale towers (GB/T 24842-2009 [B18])

Time-to-crest (μs)	250	1000	5000
U_{50} (kV)	1801	2015	2149

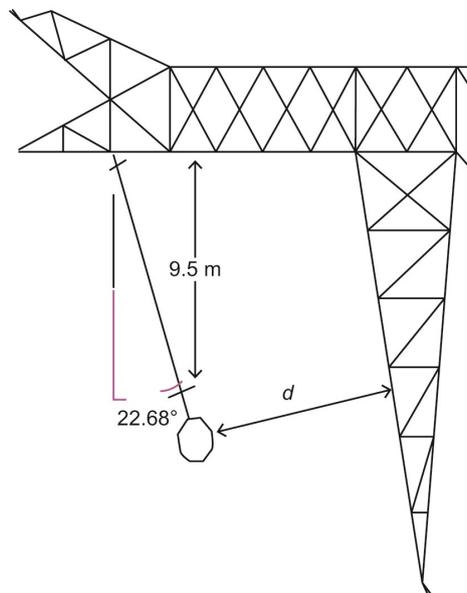


Figure C.24—The arrangement of switching impulse flashover voltage test for side-phase air clearances of 1000 kV cup type towers (GB/T 24842-2009 [B18])

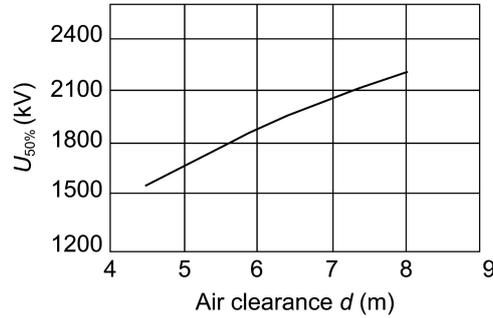


Figure C.25—The 50 percent switching impulse flashover voltage characteristic for air clearances from conductor to tower body of 1000 kV lines (with a time-to-crest of 250 μ s) (GB/T 24842-2009 [B18])

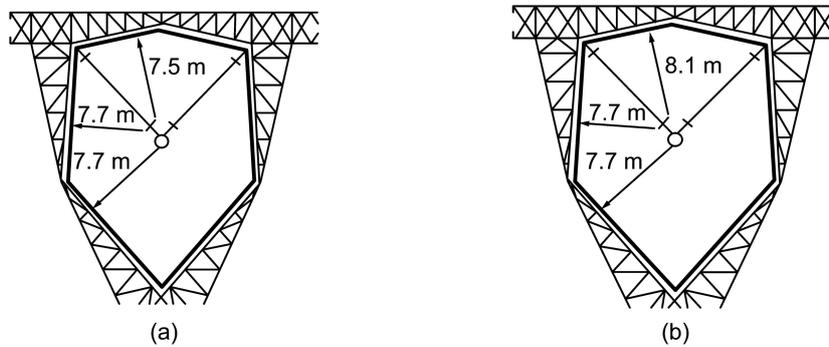


Figure C.26—The arrangement of switching impulse flashover voltage test for middle-phase air clearances of 1000 kV cup type towers (GB/T 24842-2009 [B18])

Table C.5—The switching impulse flashover voltage for air clearance from the middle-phase conductor to tower window in the arrangement shown in Figure C.26(a) (GB/T 24842-2009 [B18])

Time-to-crest (μ s)	250	1000	5000
U_{50} (kV)	1862	2035	2217

Table C.6—The switching impulse flashover voltage for air clearance from the middle-phase conductor to tower window in the arrangement shown in Figure C.26(b) (GB/T 24842-2009 [B18])

Time-to-crest (μ s)	250	1000	5000
U_{50} (kV)	1909	2064	2248

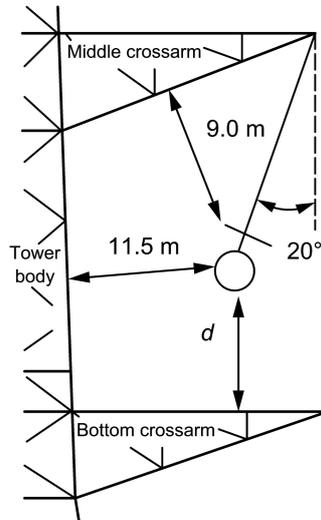


Figure C.27—The arrangement of switching impulse flashover voltage test at long time-to-crest for middle-phase air clearances (with I-type string) of 1000 kV double-circuit lines (GB/T 24842-2009 [B18])

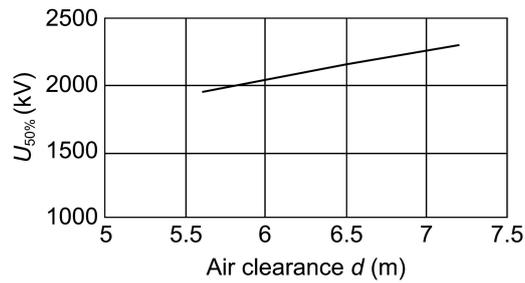


Figure C.28—The 50 percent switching impulse (1000 μ s) flashover voltage characteristic for air clearances from conductor to bottom crossarm of 1000 kV double-circuit lines (a distance of 9.0 m between conductor and middle crossarm) (GB/T 24842-2009 [B18])

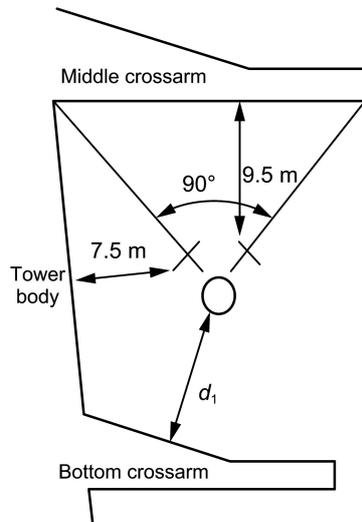


Figure C.29—The arrangement of switching impulse flashover voltage test for air clearances from middle-phase conductor (with V-type string) to bottom crossarm of 1000 kV double-circuit lines (GB/T 24842-2009 [B18])

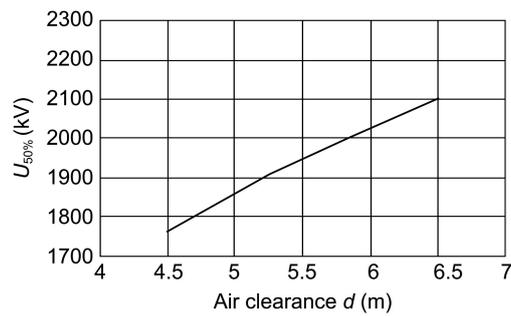


Figure C.30—The 50 percent switching impulse (1000 μ s) flashover voltage characteristic of air clearances from conductor to bottom crossarm of 1000 kV double-circuit lines (GB/T 24842-2009 [B18])

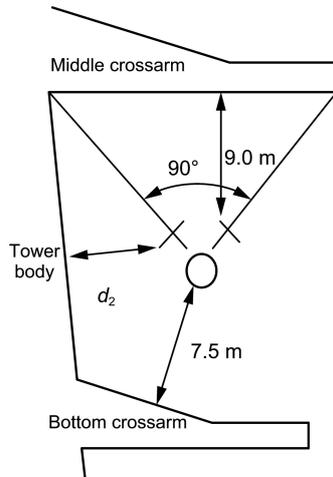


Figure C.31—The arrangement of switching impulse flashover test for air clearances from middle-phase conductor (with V-type string) to tower body of 1000 kV double-circuit lines (GB/T 24842-2009 [B18])

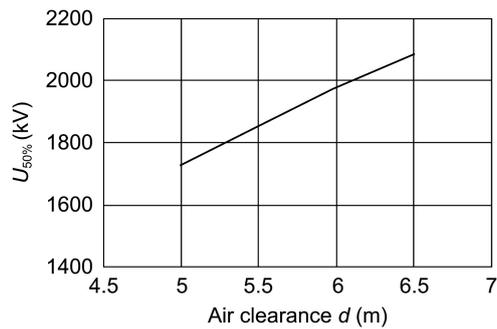


Figure C.32—The 50 percent switching impulse (1000 μ s) flashover voltage characteristic for air clearances from conductor to tower body of 1000 kV double-circuit lines (GB/T 24842-2009 [B18])

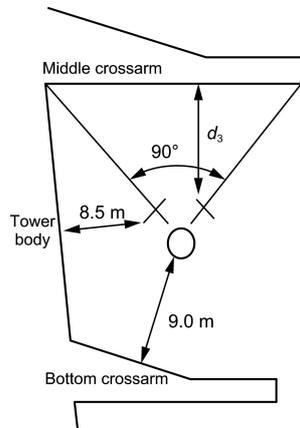


Figure C.33—The arrangement of switching impulse flashover voltage test for air clearances from middle-phase conductor (with V-type string) to middle crossarm of 1000 kV double-circuit lines (GB/T 24842-2009 [B18])

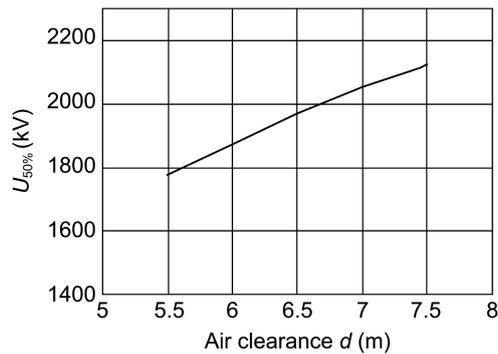


Figure C.34—The 50 percent switching impulse (1000 μ s) flashover voltage characteristic for air clearances from conductor to middle crossarm of 1000 kV double-circuit lines (GB/T 24842-2009 [B18])

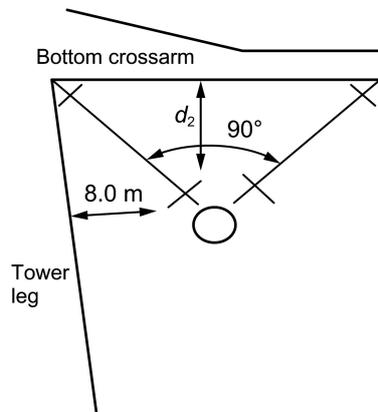


Figure C.35—The arrangement of switching impulse flashover voltage test for air clearances from bottom-phase conductor (with V-type string) to crossarm of 1000 kV double-circuit lines (GB/T 24842-2009 [B18])

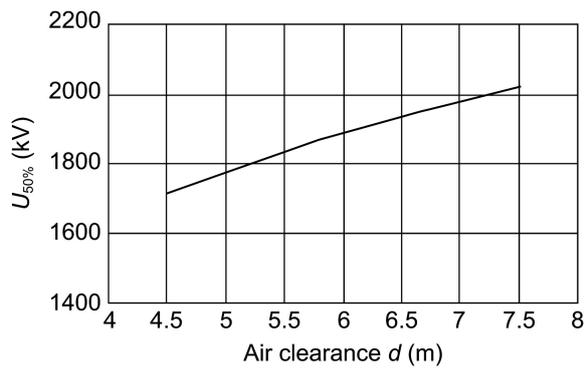


Figure C.36—The 50 percent switching impulse (1000 μ s) flashover voltage characteristic for air clearances from conductor to crossarm of 1000 kV double-circuit lines (GB/T 24842-2009 [B18])

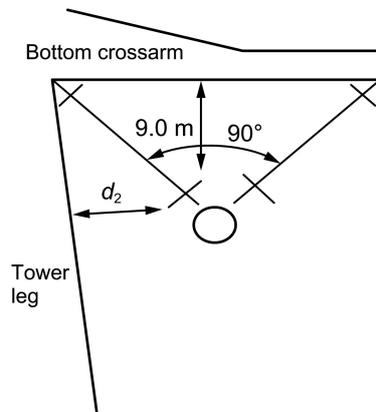


Figure C.37—The arrangement of switching impulse flashover voltage test for air clearances from bottom-phase conductor (with V-type string) to tower body of 1000 kV double-circuit lines (GB/T 24842-2009 [B18])

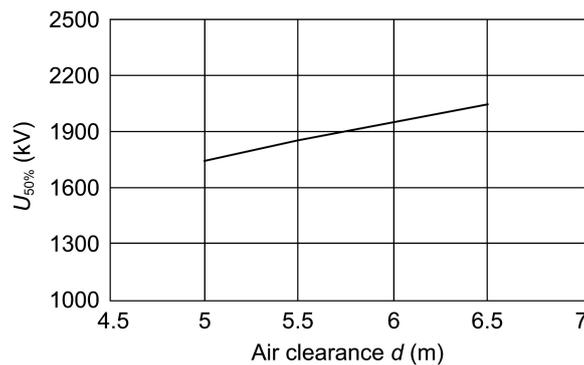
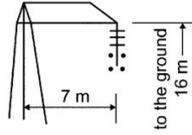
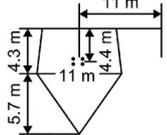


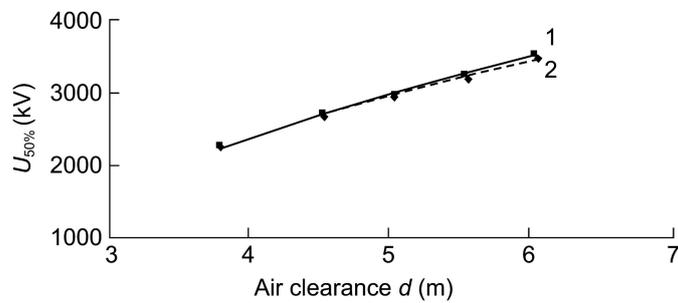
Figure C.38—The 50 percent switching impulse (1000 μ s) flashover voltage characteristic for air clearances from conductor to tower body of 1000 kV double-circuit lines (GB/T 24842-2009 [B18])

C.4 The 50 percent lightning impulse flashover voltage test results for air clearances of transmission line structures

Unless otherwise specified, the lightning impulses used for tests are of a positive-polarity 1.2/50 μ s waveform.

Table C.7—Flashover voltages of air clearances of supports

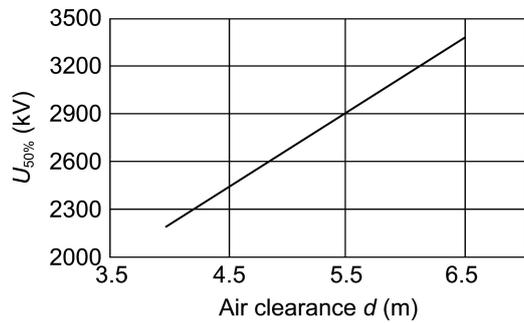
Voltage type	Lightning impulse		
Data	Data 1 (Kawai, Yasui, and Kishizima [B32])	Data 2 (Baoding Transformer Works [B2])	Data 3 (China Electric Power Research Institute [B5])
$u_{50\%}$ (kV)	$531.25 l + 31$ ($2.5 \text{ m} < l < 5.5 \text{ m}$)	$555 l$ ($3.0 \text{ m} < l < 4.5 \text{ m}$)	Curve 3 in Figure C.12
$\sigma_s/u_{50\%}$ (%)	—	1.22 to 1.76	—
Shape of tower head			



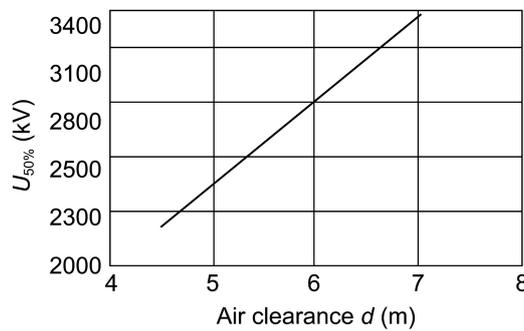
1—middle phase; 2—bottom phase

Figure C.39—The 50 percent lightning impulse flashover voltage for air clearances of 750 kV double-circuit lines (GB/T 50064-2014 [B19])

For 1000 kV single-circuit lines, considering windage yaw of about 10° , the 50% lightning impulse flashover voltage characteristic for side-phase air clearances of cat-head type towers is as shown in Figure C.40(a), and that of cup type towers is as shown in Figure C.40(b).



(a) 1000 kV cat-head type tower



(b) 1000 kV cup type tower

Figure C.40—The 50 percent lightning impulse flashover voltage characteristic for air clearances from side-phase conductor to tower body of 1000 kV single-circuit lines (GB/T 24842-2009 [B18])

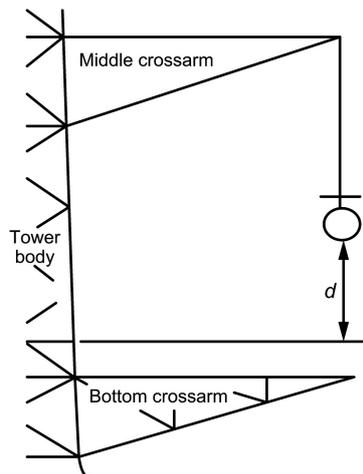


Figure C.41—The arrangement of lightning impulse flashover voltage test for air clearances from middle-phase conductor (with I-type string) to bottom crossarm of 1000 kV double-circuit lines (GB/T 24842-2009 [B18])

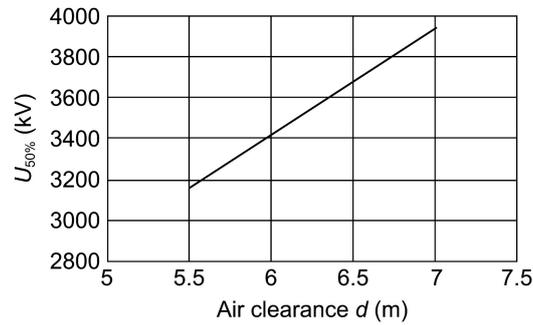


Figure C.42—The 50 percent lightning impulse flashover voltage characteristic for air clearances from conductor to lower crossarm of 1000 kV double-circuit lines (GB/T 24842-2009 [B18])

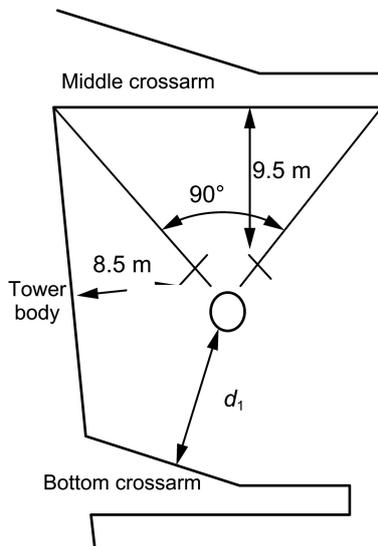


Figure C.43—The arrangement of lightning impulse flashover voltage test for air clearances from middle-phase conductor (with V-type string) to bottom crossarm of 1000 kV double-circuit lines (GB/T 24842-2009 [B18])

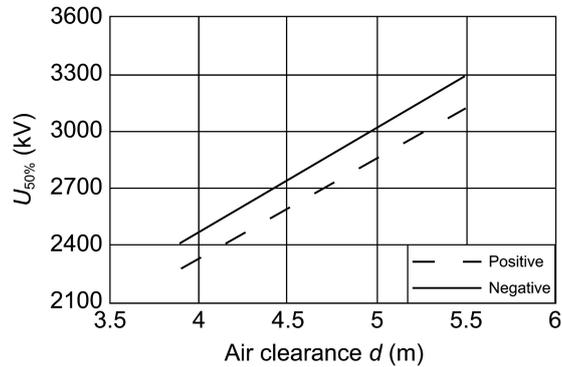


Figure C.44—The 50 percent positive and negative lightning impulse flashover voltage characteristic for air clearances from conductor to lower crossarm of 1000 kV double-circuit lines (GB/T 24842-2009 [B18])

C.5 Effects of switching overvoltage time-to-crest on flashover voltage

The waveforms of switching overvoltages play an important role in determining the flashover strength of air clearances. For air clearances of a given shape, the switching impulse applied has a special time-to-crest, and the switching impulse flashover strength with this time-to-crest is the lowest. This is the widely known U-curve of the flashover voltage as a function of the time-to-crest.

In its studies on 750 kV transmission lines, China conducted switching impulse flashover voltage tests with different test time-to-crest, respectively 100 μs , 250 μs , 435 μs , 720 μs , and 5000 μs , with an air clearance of 5 m from conductor to tower leg, and obtained the curve of the 50% switching impulse flashover voltage as a function of the time-to-crest, as shown in Figure C.45 (GB/T 50545-2010 [B21]).

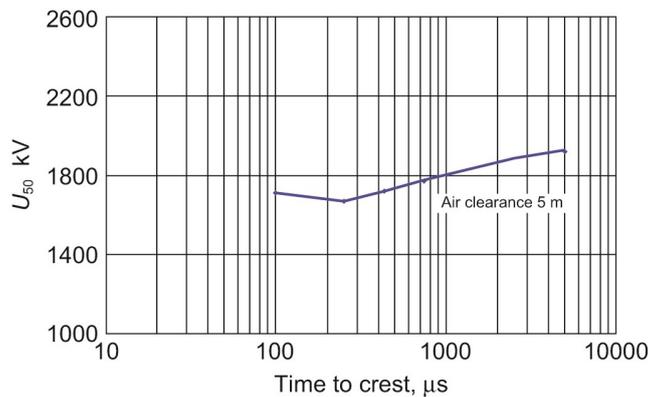


Figure C.45—Curve of the 50 percent switching impulse flashover voltage as a function of the time-to-crest for the air clearance from conductor to tower leg

C.6 Tower width correction approaches for air clearances of transmission line structures

C.6.1 Introduction

The tower width correction for air clearances of transmission line supports can be made with the empirical formula approach described in C.6.2 or the correction factor approach described in C.6.3. The result calculated with the latter approach is about 2% greater than that with the former approach. The empirical formula approach is recommended for power-frequency voltages, and the correction factor approach is recommended for switching impulse flashover voltages. Furthermore, the test reference data from China is given in C.6.4 (GB/T 50545-2010 [B21]).

C.6.2 Empirical formula approach

The tests conducted in the former Soviet Union illustrate that the relationship between the flashover voltage and tower width (W) at the position of corresponding conductor can be corrected with the following empirical formula:

$$V_{50\%}(W) = V_{50\%}(1) \cdot (1.03 - 0.03W) \quad (\text{C.1})$$

where flashover voltage with a tower width of 1 m, $0.02 \text{ m} \leq W \leq 5 \text{ m}$.

C.6.3 Correction factor approach (EPRI [B14])

The curve of the tower-width voltage correction factor obtained through tests as shown in Figure C.49 in EPRI [B14] shows the switching impulse critical flashover (CFO) under the standard condition ($W/D = 0.2$), and the CFO under other tower width conditions can be obtained by multiplying the CFO under the standard condition by this tower-width voltage correction factor.

The required air clearance under other tower width conditions can be obtained by multiplying the required air clearance under the standard condition by the tower width correction factor for air clearance shown in Figure 11.11.3 in EPRI [B14].

C.6.4 Test results of effects of tower width variation on the flashover voltage (China)

Wuhan High Voltage Research Institute of the State Grid Corporation of China (SGCC) conducted tests on 750 kV double-circuit lines. Switching impulse with long time-to-crest ($720 \mu\text{s}$) is applied when the tower width is 2 m and 5 m and the minimum air clearance d from conductor to tower leg is adjusted to 4 m, 4.5 m, 5 m, and 5.5 m, respectively, and the 50% flashover voltages obtained are as shown in Figure C.47 in GB/T 50545-2010 [B21].

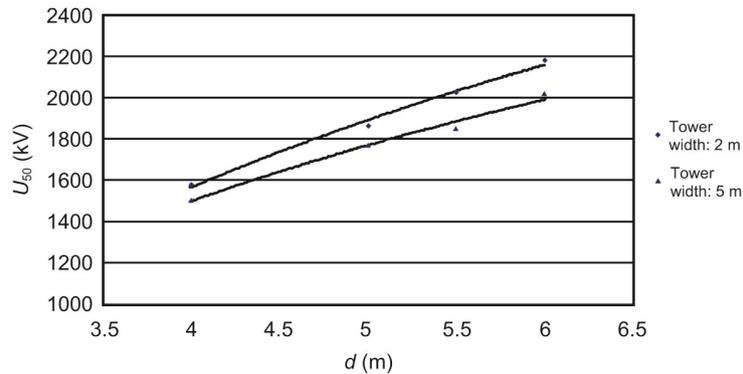


Figure C.46—Effects of tower leg width on switching impulse flashover voltage (with a time-to-crest of 720 μ s)

It can be seen from the test results that the 50% switching impulse flashover voltage with a tower width of 5 m is about 6% less than that with a tower width of 2 m, on average.

C.7 Flashover voltage data of air clearances on transmission line towers in high-altitude areas

C.7.1 Flashover voltage data of tower head air clearances of 500 kV transmission lines at an altitude of 4300 m

CEPRI conducted switching impulse and lightning impulse flashover voltage characteristic tests on side-phase air clearances of 500 kV ac transmission line towers at an altitude of 4300 m and obtained the curve of the 50% flashover voltage as a function of air clearance. The lightning impulses used for tests have a waveform of 1.2/50 μ s, and switching impulses used for tests have a waveform of 250/2500 μ s. The curves of switching impulse flashover voltage and lightning impulse flashover voltage are respectively shown in Figure C.47 and Figure C.48. In addition, the flashover voltage characteristic curve obtained with the exact same test object under reference meteorological conditions is also shown in the figures.

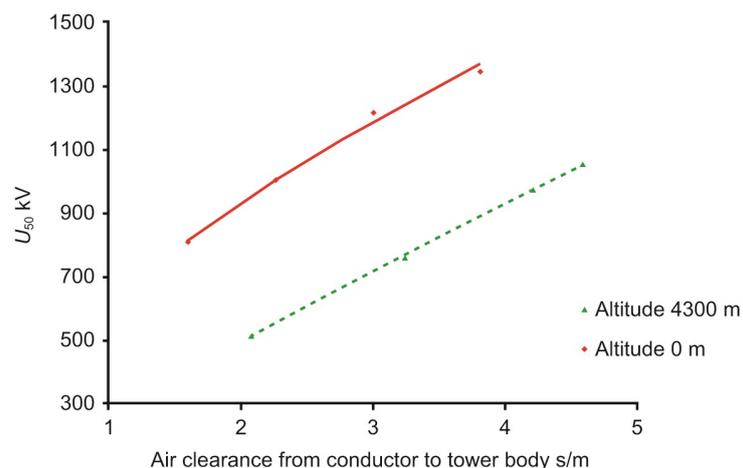


Figure C.47—The 50 percent switching impulse flashover voltage characteristic for air clearances from side-phase conductor to tower body of 500 kV transmission lines

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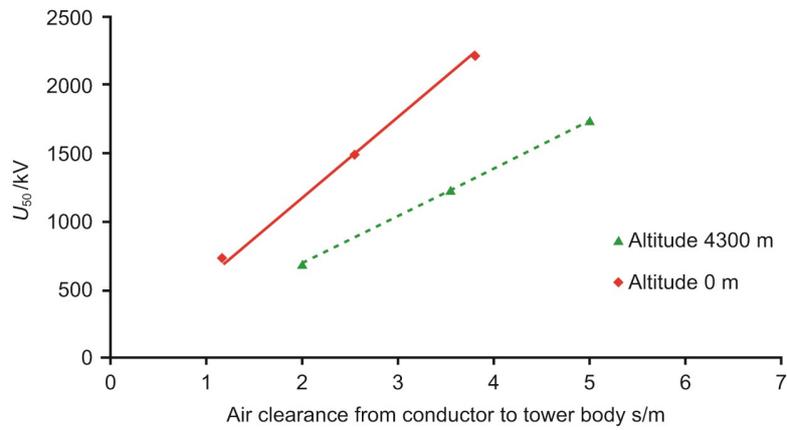


Figure C.48—The 50 percent lightning impulse flashover voltage characteristic for air clearances from side-phase conductor to tower body of 500 kV transmission lines

Annex D

(informative)

Calculation of transmission line lightning protection

D.1 Number of lightning strikes on line

The number of lightning strikes per hundreds of kilometers of a line every year, N_L , can be calculated using Equation (D.1), and the relation between the lightning strikes per square kilometer of the ground every year, N_g , and the annual average number of thunderstorm days, T_d , can be given by Equation (D.2) as recommended in CIGRE 63 [B7]:

$$N_L = 0.1N_g(28h_r^{0.6} + b) \quad (\text{D.1})$$

$$N_g = 0.023T_d^{1.3} \quad (\text{D.2})$$

where

N_L is lightning strikes on line, in number/(100 km-year)

N_g is cloud-to-ground lightning density, in number/(km²-year)

b is distance between two ground wires, in m

h_r is structure height, in m

D.2 Waveform of lightning currents

In the lightning protection calculation of an overhead transmission line, the dual-bevel lightning current waves of 2.6/50 μs can be used.

D.3 Equivalent impedance of the lightning current channel

The equivalent impedance of the lightning channel Z_0 may be calculated respectively for different lightning current amplitudes. See Russian United Power Network [B33] for the change pattern of Z_0 with the amplitude of lightning current.

D.4 Calculation method of lightning shielding failure

The operational experience, field measurement, and simulated tests of lines indicate that the probability of lightning shielding failure depends on the arrangement of conductors and ground wires, shielding angle, structure height, as well as the topography, landform, and geological conditions in the areas where the line passes through. The methods used for estimating the lightning performance of transmission lines are mainly electro-magnetic model (EGM) and leader progression model (LPM). The EGM method is introduced in this guide. The basic principle of the EGM

method is as follows: The point of striking is uncertain before the head of the discharge channel of the leader initiated from cloud to ground reaches the position with a distance of the critical breakdown distance (striking distance for short) from the object to be struck. But when it reaches the corresponding striking distance from an object, it will discharge to the object.

Figure D.1 is the transverse section of lines, where the EGM of direct lightning strikes on conductors of a dual-ground-wire line is displayed. S represents ground wire, C is conductor, AA' is the center line of support, and θ is the shielding angle of ground wires to conductors. If the lightning leader head falls on arc AB, the lightning strikes on the ground wire, thereby protecting the conductor from lightning strike. Therefore, the arc AB is referred to as the *protection arc*. If the leader head falls on arc BD, the lightning strikes on conductors. Therefore, the arc BD is referred to as the *exposure arc*. If the leader head falls on plane DE, the lightning strikes on the ground. Therefore, the plane DE is referred to as the *lightning capture surface*. As the lightning current amplitude increases, the exposure arc, BD, diminishes. When the lightning current amplitude increases up to I_{\max} (the maximum current for lightning shielding failure), the arc BD vanishes, which means that no shielding failure will occur. ψ in the figure represents the lightning leader angle of incidence.

In case of lightning shielding failure, only when the lightning current exceeds the lightning withstand level for shielding failure I_{\min} will the insulation flashover occur.

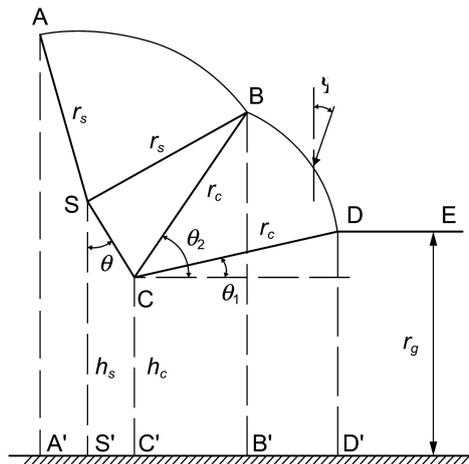


Figure D.1—EGM of direct lightning strikes to line conductors

In calculation of lightning shielding failure, the striking distance to conductors, ground wires, and ground can be calculated with Equation (D.3) through Equation (D.5) (He, Zeng, and Zhang [B22]):

$$r_s = 10I^{0.65} \quad (D.3)$$

$$r_c = 1.63(5.015I^{0.578} - 0.001U_{ph})^{1.125} \quad (D.4)$$

$$r_g = \begin{cases} [3.6 + 1.7 \ln(43 - h_{c.av})]I^{0.65} & h_{c.av} < 40 \text{ m} \\ 5.5I^{0.65} & h_{c.av} \geq 40 \text{ m} \end{cases} \quad (D.5)$$

where

r_s is the striking distance to ground wire, in m

I is the lightning current amplitude, in kA

r_c is the striking distance to conductor, in m

U_{ph} is the operating voltage on conductor, in kV

r_g is the striking distance to the ground, in m

$h_{c.av}$ is the average height of conductor above ground, in m

The probability distribution density function of lightning leader angle of incidence $P_g(\psi)$ for high supports is given by:

$$P_g(\psi) = 0.75 \cos^3 \psi \quad (\text{D.6})$$

where

ψ is the lightning leader angle of incidence ($^\circ$).

In the case of negative lightning, the lightning withstand level for shielding failure I_{\min} is given by:

$$I_{\min} = \left(U_{50\%} + \frac{2Z_0}{2Z_0 + Z_c} U_{ph} \right) \frac{2Z_0}{Z_0 Z_c} \quad (\text{D.7})$$

where

I_{\min} is the lightning withstand level for shielding failure, in kA

$U_{50\%}$ is the absolute value of the 50% negative flashover voltage of insulator, in kV

Z_0 is the impedance of lightning current channel, in Ω

Z_c is the impedance of conductor, in Ω

D.5 Calculation method of back flashover

The numerical method is generally used for calculation of back flashover of transmission lines. The intersection method or leader progression model (LPM) method can be used in judging whether insulation flashover occurs on a line. In the calculation, the effects of power-frequency voltage on conductors and the induced voltage on conductors when lightning strikes on the top of supports should be considered. Supports can be simulated with sectionalized wave impedance.

The impedance of conductor accounting for the corona effects under lightning impulse can be calculated with Equation (D.8).

$$Z_c = 60 \sqrt{\ln\left(\frac{2h}{R_c}\right) \ln\left(\frac{2h}{r}\right)} \quad (\text{D.8})$$

where

- Z_c is the impedance of conductor accounting for corona effects, in Ω
- R_c is the radius of conductor corona, in m
- r is the radius of the conductor, in m
- h is the height of conductor, in m

The induced voltage component can be calculated using Equation (D.9) or Equation (D.10).

$$u_i = \frac{60ah_{c,t}}{k_\beta \times c} \left[\ln \frac{h_T + d_R + k_\beta \times ct}{(1 + k_\beta)(h_T + d_R)} \right] \left(1 - \frac{h_{t,av}}{h_{c,av}} k_0 \right) \quad (\text{D.9})$$

$$u_i = 2.2i^{0.4} h_{c,av} \left(1 - \frac{h_{t,av}}{h_{c,av}} k_0 \right) \quad (\text{D.10})$$

$$k_\beta = \sqrt{i / (500 + i)} \quad (\text{D.11})$$

$$d_R = 5i^{0.65} \quad (\text{D.12})$$

where

- u_i is the induced voltage component at the time of back flashover, in kV
- i is the instantaneous lightning current, in kA
- a is the steepness of lightning current, in kA/ μ s
- c is the speed of light, $c = 3.0 \times 10^8$ m/s
- t is time, in s
- k_β is the ratio of the main discharge speed to the speed of light, c
- h_T is the structure height, in m
- $h_{c,t}$ is the height of the conductor attached on tower, in m
- $h_{c,av}$ is the average height of conductor above ground, in m
- $h_{t,av}$ is the average height of ground wire above ground, in m

d_R is the length of the upward leader in case of a lightning strike on tower, in m
 k_0 is the coupling factor between ground wire and conductor

D.6 Calculation of lightning trip-out rate

The lightning trip-out rate can be calculated using Equation (D.13):

$$N = N_L \eta (gP_1 + P_{sf}) \quad (\text{D.13})$$

$$\eta = (4.5E^{0.75} - 14) \times 10^{-2} \quad (\text{D.14})$$

where

- N is the lightning trip-out rate of transmission line, number/(100 km·a)
- η is the arc-establishing rate. According to laboratory test results and transmission line operational experience, the relationship between the arc-establishing rate and average operating voltage gradient can be expressed with Equation (D.14)
- g is the rate of lightning strikes on poles, depending on the number of lightning wires and topography. It is normally expressed with the data given in Table D.1
- P_1 is the probability of lightning currents exceeding the withstand level for lightning strikes on tower top I_1 , i.e., $P(I_0 \geq I_1)$. The value of I_1 varies with the instantaneous system operating voltage at the instant of lightning strike.
- P_{sf} is the shielding failure flashover rate, which can be calculated with the interval combination statistics method considering the instantaneous system operating voltage at the time of lightning strike (evenly distributed in a power-frequency cycle)
- E is the average operating voltage (rms) gradient of insulator string, in kV/m

For a system whose neutral point is grounded, $E = \frac{U_n}{\sqrt{3}l_i}$

where

- l_i is the strike distance of insulator string, in m

Table D.1—Rate of lightning strikes on poles

Number of lightning wires	1	2
Plain areas	1/4	1/6
Hilly areas	1/3	1/4

Annex E

(informative)

Calculation of support grounding resistance

E.1 Calculation of power-frequency grounding resistance

The power-frequency grounding resistance of common horizontal grounding devices of supports can be roughly calculated using Equation (E.1):

$$R = \frac{\rho}{2\pi L} \left(\ln \frac{L^2}{hD} + A_t \right) \quad (\text{E.1})$$

where

- R is grounding resistance of the electrode, in Ω
- ρ is soil resistivity, in $\Omega\text{-m}$
- L is total length of the horizontal electrode, in m
- h is buried depth of the horizontal electrode, in m
- D is diameter or equivalent diameter of the horizontal electrode, in m
- A_t is shape factor of the horizontal electrode. Refer to Table E.1.

Table E.1—Grounding device, L , and shape factor of horizontal electrode, A_t

Type of grounding device	Parameter
Tower grounding device	$A_t = 1.76$ $A_t = 1.76$ $L = 4(l_1 + l_2)$ $L = 4(l_1 + l_2)$

E.2 Calculation of impulse grounding resistance of simple electrodes

The impulse grounding resistance of an independent electrode or tower earthing device can be calculated using Equation (E.2).

$$R_i = \alpha R \quad (\text{E.2})$$

where

- R_i is the impulse grounding resistance of an independent electrode or tower earthing device, in Ω
- R is the power-frequency grounding resistance of an independent electrode or tower earthing device, in Ω
- α is the impulse factor of an independent electrode or support grounding device, which can be calculated using Equation (E.3) through Equation (E.7).

Tower earthing device:

$$\alpha = 0.74\rho^{-0.4}(7.0 + \sqrt{L})[1.56 - \exp(-3.0I_i^{-0.4})] \quad (\text{E.3})$$

where

- I_i is impulse current flowing through the tower earthing device or independent electrode, in kA

The impulse factor for the grounding resistance of an independent electrode can be calculated using the following formulae, respectively.

Vertical electrode:

$$a = 2.75\rho^{-0.4}(1.8 + \sqrt{L})[0.75 - \exp(-1.50I_i^{-0.2})] \quad (\text{E.4})$$

Horizontal electrode with impulse current injected at one end:

$$a = 1.62\rho^{-0.4}(5.0 + \sqrt{L})[0.79 - \exp(-2.3I_i^{-0.2})] \quad (\text{E.5})$$

Horizontal electrode with impulse current injected in the middle:

$$a = 1.16\rho^{-0.4}(7.1 + \sqrt{L})[0.78 - \exp(-2.3I_i^{-0.2})] \quad (\text{E.6})$$

For $\rho \leq 300 \Omega\text{-m}$, the effects of a tower as a natural electrode can be accounted for, and its impulse factor can be calculated using the following formula:

$$a = \frac{1}{1.35 + \alpha_1 I_i^{1.5}} \quad (\text{E.7})$$

where

- α_1 is 0.053 for tower foundation (with one tower footing) and 0.038 for prefabricated reinforced concrete foundation (with one tower footing) and guy anchor (with rod)

E.3 Calculation of impulse grounding resistance of multiple electrodes

When a grounding device is composed of multiple horizontal or vertical electrodes, they may be separated with a certain spacing to minimize mutual shielding between adjacent electrodes.

For an earthing device composed of n long horizontal radiate electrodes of equal length, the impulse grounding resistance can be calculated using the following formula (GB/T 50065-2011 [B20]):

$$R_i = \frac{R_{hi}}{n} \times \frac{1}{\eta_i} \quad (\text{E.8})$$

where

R_{hi} is the impulse grounding resistance of each horizontal radiate electrode, in Ω

η_i is the impulse utilization factor with the mutual effects between electrodes considered. The value of η_i can be determined with reference to Table E.2.

For an earthing device composed of n vertical electrodes connected with horizontal electrodes, the impulse grounding resistance can be calculated using Equation (E.9) (GB/T 50065-2011 [B20]):

$$R_i = \frac{\frac{R_{vi}}{n} \times R'_{hi}}{\frac{R_{vi}}{n} + R'_{hi}} \times \frac{1}{\eta_i} \quad (\text{E.9})$$

where

R_{vi} is the impulse grounding resistance of each vertical electrode, in Ω

R'_{hi} is the impulse grounding resistance of the horizontal electrode, in Ω

The impulse utilization factor of electrode is listed in Table E.2.

Table E.2—Impulse utilization factor of electrode η_i

Type of electrode	Number of ground wire	Impulse utilization factor	Remarks
n horizontal radial (each with a length of 10 m to 80 m)	2 3 4 to 6	0.83 to 1.0 0.75 to 0.90 0.65 to 0.80	Smaller values apply to relatively short radials
Vertical electrodes connected with horizontal electrode	2 3 4 6	0.80 to 0.85 0.70 to 0.80 0.70 to 0.75 0.65 to 0.70	Smaller values apply when $\frac{S}{l} = 2$. where S is the spacing between vertical electrodes l is the length of vertical electrode
Natural electrode	Between guy rod and guy anchor Between tower foundations Between foundations of gantry structures and various guy structures	0.6 0.4 to 0.5 0.7	

Annex F

(informative)

Reference data for mechanical design of conductors, insulators, and support hardware

F.1 Recommended everyday stress values for conductors

CIGRE 273 proposed recommended values for the everyday stress (EDS) of seven conductors configured with different anti-vibration devices, as listed in Table F.1, which have greatly influenced the design of transmission lines worldwide.

Table F.1—EDS panel recommendations for safe design tensions by CIGRE (as a percentage of ultimate tensile strength [UTS])

	Bare conductors	Conductors equipped with anti-vibration devices		
		Armor rods	Dampers	Armor rods and dampers
Copper conductors	26			
Aluminum conductors steel reinforced (ACSR)	18	22	24	24
Aluminum conductors	17			
Aldrey conductors	18		26	
Steel conductors				
1 Rigid clamps	11			
2 Oscillating clamps	13			

F.2 Empirical values of EDS of conductors and ground wires (in China)

F.2.1 Upper limits on EDS of conductors and ground wires

In China, the safety factor of conductors is taken as 2.5 under such normal load cases as wind load, ice load, or combined wind and ice load, and taken as 1.3 under rare wind speed and rare icing conditions.

F.2.2 Values of EDS of conductors and ground wires

The EDS of conductors and corresponding anti-vibration measures may normally be as specified in Table F.2. These design values have been used in China for years, and operational experience proves they can yield satisfactory results.

Table F.2—Upper limits on EDS of conductors and ground wires and corresponding anti-vibration measures

Case	Upper limits on EDS (percentage of UTS)		Anti-vibration measures
	ACSR with an aluminum-steel section ratio of no less than 4.29	Galvanized steel conductor	
Open area with a span of no more than 500 m	16	12	Not required
Areas other than open area with a span of no more than 500 m	18	18	Not required
A span of no more than 120 m	18	18	Not required
Any span	22	—	Armor rods
Any span	25	25	Vibration damper (damping wire) or a combination of vibration damper and armor rods

F.3 Empirical values of the safety factor of insulators (in China)

The safety factor for the mechanical strength of insulators shall be no less than the values given in Table F.3 in China. For double and multiple insulator strings, the mechanical strength with one string broken may be checked, and the load and safety factor may be considered based on the string breakage scenario.

Table F.3—Mechanical strength safety factor for insulators

Case	Maximum working load		Normal load over years	Check load	Line breakage load	String breakage load
	Cap-and-pin insulator	Rod insulator				
Safety factor	2.7	3.0	4.0	1.8	1.8	1.5

NOTE—*Normal load over years* refers to the load imposed on the insulator under the annual average temperature. *Check load* refers to the load imposed on the insulator under check conditions. The meteorological condition for *line breakage load* corresponds to the condition of icing, no wind, -5°C . *String breakage load* corresponds to the condition of no icing, no wind, and -5°C . In the design of suspension strings, the value of EDS of conductors and ground wires can be determined based on the meteorological conditions corresponding to the tower load.

F.4 Empirical values of the safety factor for support hardware (in China)

The safety factor for the strength of support hardware in China can be:

- No less than 2.5 for maximum working load
- No less than 1.5 for line breakage, string breakage, and check loads

Annex G

(informative)

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Bibliographical references are resources that provide additional or helpful material but do not need to be understood or used to implement this standard. Reference to these resources is made for informational use only.

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