



IEEE Guide for Overhead Alternating Current (AC) Transmission Line Design

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IEEE Guide for Overhead Alternating Current (AC) Transmission Line Design

Developed by the

Corporate Advisory Group
of the
IEEE Standards Association Board of Governors

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Abstract: Covered in this guide are basic principles, methods, and experience for (design of 110 kV to 1000 kV) alternating current (ac) overhead transmission lines. This guide may also be used as a reference for the design of lower-voltage overhead transmission lines. Included in this guide are an introduction, definitions, meteorological design and criteria, electrical design, structural design criteria, design of foundations, experiment results, and design experience. This guide is a listing of the information and procedures that can be referenced during the design of ac transmission lines. Guidance is provided for transmission line designers in the data collection design stage.

Keywords: AC overhead transmission line, design experience, electrical design, IEEE 1863™, structure design

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Introduction

This introduction is not part of IEEE Std 1863-2024, IEEE Guide for Overhead Alternating Current (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 a reference for the design of lower voltage overhead transmission lines. Compared to the original guide, the range of scope remains the same, however, it has been rewritten to reflect the content of the document more clearly, including editorial changes and technical changes. Inconsistencies with the work of other international standards-developing organizations and incorrect design principles have been corrected.

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

- Clause 4 shows requirements and design principles of the main component.
- Clause 5 through Clause 9 propose principles and methods in terms of electrical and structural design, mainly including meteorological design, conductor, insulation, mechanical design, foundation, etc.

Annexes propose experimental data and design experience derived from different countries.

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IEEE Guide for Overhead Alternating Current (AC) Transmission Line Design

1. Overview

1.1 Scope

This guide covers basic principles, methods, and experience for designing ~~applies to three-phase overhead ac transmission line~~ (110 kV to 1000 kV alternating current (ac) overhead transmission lines. The guide may also ~~) design and construction, and it can~~ be used as a reference for the design of lower-voltage levels. This guide specifies design methodologies of the overhead transmission lines. This guide includes an introduction, definitions, meteorological design and criteria, electrical design, structural design criteria, design of ~~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, experiment results, and design experience. This guide is a listing of the information and procedures that are required during the design of overhead ac transmission line. It provides guidance for transmission line designers in the data collection design stage.

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 transmission line designer ~~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*).

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-[2020](#), Guidelines for Electrical Transmission Line Structural Loading ([Fourth Edition](#)).³

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.

³ ~~ASCE publications are available from the American Society of Civil Engineers, 1801 Alexander Bell Dr., Reston, VA 20191, USA (<https://www.asce.org/>).~~

[ASCE MOP 104, Recommended Practice for Fiber-Reinforced Polymer Products for Overhead Utility Line Structures \(Second Edition\).](#)

[ASCE MOP 123, Prestressed Concrete Transmission Pole Structures: Recommended Practice for Design and Installation.](#)

[ASCE MOP 141, Wood Pole Structures for Electrical Transmission Lines: Recommended Practice for Design and Use.](#)

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

[ASCE/SEI 48-19, Design of Steel Transmission Pole Structures.](#)

IEC 60071-2:2023, Insulation Co-ordination—Part 2: Application [Guidelines](#) [Guide](#).^{3 4}

IEC/TS 60815-1:2008, Selection and Dimensioning of High-Voltage Insulators Intended for Use in Polluted Conditions—Part 1: Definitions, Information and General Principles.

IEC/TS 60815-3:2008, Selection and Dimensioning of High-Voltage Insulators Intended for Use in Polluted Conditions—Part 3: Polymer Insulators for A.C. Systems.

[IEC 61284, Overhead Lines—Requirements and Tests for Fittings.](#)

[IEC TS 63042-202:2021, UHV AC Transmission Systems—Part 202: UHV AC Transmission Line Design.](#)

IEEE Std 80™-2013, IEEE Guide for Safety in AC Substation Grounding.^{4 5, 6}

⁴ IEC publications are available from the International Electrotechnical Commission (<http://www.iec.ch>) and the American National Standards Institute (<http://www.ansi.org/>).

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^{5 6} IEEE publications are available from The Institute of Electrical and Electronics Engineers (<http://standards.ieee.org/>).

IEEE Std 516™-~~2021~~ 2009, IEEE Guide for Maintenance Methods on Energized Power Lines.

IEEE Std 691™-~~2001~~, 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.~~

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. ⁶⁷

~~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.~~

⁶ *IEEE Standards Dictionary Online* is available at: <http://dictionary.ieee.org>.

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

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/cm^2 .

icing stress product (ISP): 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, $(\text{g}/\text{cm}) \times (\mu\text{S}/\text{cm})$.

leakage distance: The shortest distance, or the sum of the shortest distances, along the insulating parts of the insulator between those parts ~~that~~ ~~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.^{7,8}

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 1:2008.⁸

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.

⁸ [Information on references can be found in Clause 2.](#)

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/cm^2 .

~~**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.

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, [and](#) 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:[2008](#).

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 [B18 B29]⁹ for the definition of *statistical switching overvoltage* (E2).

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.

transmission line structures support: A general term referring to ~~of structures of~~ various types that structure ~~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 the number of six-pulse bridges in series and V_d is the dc-rated voltage per valve bridge. Unified specific creepage distance (USCD) is generally expressed in mm/kV and specified as a minimum value.

NOTE 1—This definition in IEC/TS 60815-1:2008 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 3 times that given by the definition of *specific creepage distance* in IEC/TS 60815 1:2008.

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

AC alternating current

AAC all aluminum conductor

⁹ The numbers in brackets correspond to those of the bibliography in Annex F.

<u>AAAC</u>	<u>all aluminum alloy conductor</u>
<u>AACSR</u>	<u>aluminum alloy conductor steel reinforced</u>
<u>ACSR</u>	<u>aluminum conductor steel reinforced</u>
<u>ACSS</u>	<u>aluminum clad steel strand</u>
AN	audible noise
EDS	everyday stress
EHV	extra-high voltage (<u>voltages of ac transmission systems between 330 kV and 750 kV</u>)
<u>EPE</u>	<u>experimental plastic elongation</u>
<u>HTLS</u>	<u>high temperature low sag</u>
HV	high voltage (<u>voltages of ac transmission systems between 35 kV and 220 kV</u>)
ISP	icing stress product
<u>OHGW</u>	<u>overhead ground wires</u>
<u>OPGW</u>	<u>optical power ground wires</u>
OSHA	Occupational Safety and Health Administration
RI	radio interference
RTS	rated tensile strength
RTV	room temperature vulcanizing (silicone rubber)
SLA	A-weighted sound level
<u>UBGW</u>	<u>underbuilt ground wires</u>
UHV	ultra-high voltage (<u>highest voltages of ac transmission systems exceeding 800 kV</u>)

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_{cre}	~~coordination withstand voltage, in kV~~
U_{req}	~~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 [the following](#):

- a) International and national standards, such as the National Electrical Safety Code® (NESC®) [10 9](#)
- b) Laws and regulations issued by relevant government bodies such as aviation, navigation, traffic, land, and environment
- c) Local laws and regulations: provisions applicable to the design of lines in laws or rules issued by local governments

[10 9](#) The NESC is available from The Institute of Electrical and Electronics Engineers (<http://standards.ieee.org/>).

4.2 Components and selection

4.2.1 Conductors

Conductors should be capable ~~As one~~ of transmitting ~~the most important components of transmission lines, conductors are expected to fulfill the main function of lines: transmit power while meeting the requirements of safety, reliability, and~~ , operate safely and reliably, and meet environmental protection . Particularly, the conductors used for mountain areas, icing areas, and large spans may be selected to have sufficient ~~requirements. Therefore, the electrical and mechanical strength.~~ 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 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.~~

The types of conductors used in overhead transmission lines include all aluminum conductor (AAC), all aluminum alloy conductor (AAAC), aluminum conductor steel reinforced (ACSR), aluminum clad steel strand (ACSS), etc. ACSR has been most widely used in both ultra-high voltage (UHV) and extra-high voltage (EHV) overhead transmission lines. For the characteristics of aluminum alloy conductor steel reinforced (AACSR), refer to chapter 8.2 of IEC 63042-202:2021.

For consideration factors for the selection of conductors, refer to chapter 8.1 of IEC 63042-202:2021.

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.~~

4.2.2 Insulators

~~For the general requirements for insulating~~ The materials and type of insulators of UHV transmission line, refer to chapter 7.3 of IEC TS 63042-202:2021. IEC 60071-2:2023 and IEC TS 60815-1:2008 show the basic principles of insulators of EHV transmission lines. ~~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 the selection of insulators:

- a) ~~Glass insulator (fog Frog profile) possesses cap and pin disc insulators have~~ long ribs under sheds and a large creepage distance, which can reduce ~~The protected leakage distance reduces~~ the effect of moisture. It is ~~, 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 severely polluted areas and severe corrosion areas (coastal areas ~~(no more than 3 km from the sea), near salt lakes, etc.) lake, salt treated roadway, or other heavily polluted areas.~~
- c) Composite insulators are more suitable for severely polluted areas in terms of ~~that can retain excellent hydrophobicity and~~ hydrophobicity transfer performance and are more convenient to maintain ~~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,~~
- d) V-type and inverted-V-type insulator strings. ~~These measures~~ can be used for reducing ~~minimize~~ the probability of bridging of insulators through icicles and ~~the probability of~~ icing flashover. Farzaneh et al. [B12 B16] provide ~~lists~~ many other available methods to improve the performance of insulators under icing conditions.

4.2.3 Fittings

For general requirements for link fittings, refer to IEC 61284.

4.2.4 Supporting structure

A general term for structures supporting conductors, ground wires, and other components of overhead transmission lines, including steel angle towers, steel tubular towers, steel, concrete, and wood poles, etc.

~~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 Meteorological investigation

Meteorological design data such as wind and ice should be investigated by qualified meteorological experts.

5.2 Basic wind speed ~~and icing~~

The basic wind speed based on the ~~is associated with the return period and is obtained by probability statistics based on the data~~ observed data at a time interval of 3 s or in 10 min at a height of 10 m above the open and ~~ground in local~~ flat ground in the local area is estimated through statistical analysis. Usually, the ~~and open terrains. Generally, a~~ shorter the ~~wind acquire~~ time interval, the ~~corresponds to a~~ higher the 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 fluctuation ~~fluctuates~~, the larger the ratio ~~is~~. ASCE MOP 74-2020 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 certain ~~50-year~~ return period.

5.3 Icing

The ice thickness anticipated by the design should be determined with reference to historical icing data or the ice map with a combination of ice observation on the transmission line sites.

If a reliable ice accretion model is available to estimate values for yearly maximum ice within a certain number of years, it can be used to generate ice data based on statistical analysis. Information about the line site can be obtained from experience with existing transmission or distribution lines, from field observations, or the effect of icing on vegetation. This information is needed to validate and adjust the prediction model.

If there is a comprehensive ice zone division map of the line site, which can reflect the icing situation of the area, such as the ice map in ASCE MOP 74-2020, the design ice thickness can be analyzed and selected based on the historical ice cover investigation of the project site.

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 the a transmission line passes through a watershed, mountain crest, cliff, wind gap, or other micro-topographical and area micro-meteorological areas such as watersheds, mountains, cliffs, and valleys, the design for wind speed and design ice thickness should may be increased appropriately strengthened based on practical experience.

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

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

(Deleted)

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:

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

(Deleted)

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 current and ~~ampacity, as well as the~~ short-circuit current. In addition, the requirements of the electromagnetic environment and economic efficiency ~~effectiveness~~ may be taken into account ~~consideration~~. Generally, for ~~high-voltage (HV)~~ lines, most common ~~commonly-used~~ conductors meet the requirements of the electromagnetic environment. For EHV lines and UHV lines ~~, 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 requirements of the electromagnetic environment ~~requirement~~ rather than the ampacity. See 6.2 for more details on the electromagnetic environment ~~requirement~~.

6.1.2 Conductor ampacity

The mechanical strength of conductors may be reduced ~~degraded~~ when the temperature rises to a certain level, therefore, the heating of conductors should be limited. The maximum allowable conductor temperature under the current-carrying capacity ~~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 specified ~~listed~~ in standards or technical codes or may ~~can~~ be determined by ~~with~~ reference to guaranteed values from product testing ~~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 conductor cross-section required ~~for conductors~~ can be calculated from ~~with~~ the required current, the permissible temperature ~~allowed~~, and the duration.

The conductor ampacity can be calculated ~~using based-on~~ the heat balance principle. The ~~permissible allowable~~ ampacity of overhead ~~transmission~~ line conductors can normally be calculated by Equation (1 ~~2~~).

$$I = \sqrt{\frac{q_c + q_r - q_s}{R(T_c)}} \quad (1)$$

where

I is the ~~current-carrying capacity ampacity-rating~~ of ~~the~~ conductor, in A

T_c is the maximum ~~permissible allowable~~ conductor temperature for long-term operation, in °C

q_c is the ~~convective 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 ~~solar~~ heat gain rate ~~from-the-sun~~ per unit length of conductor, in W/m

$R(T_c)$ is the ac resistance of ~~the~~ conductor at T_c , in Ω/m

The detailed calculation of conductor ampacity can be found in IEEE Std 738TM-2006. The following factors ~~that ,which~~ affect ~~the~~ conductor ampacity~~7~~ 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. ~~The external ambient For environmental~~ conditions ~~are generally taken from~~ , meteorological data ~~collected in various regions~~ or ~~empirical~~ design ~~experience~~ values ~~from different regions are generally use~~. Refer to CIGRE 299 [B6 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, ~~should meet~~ the thermal ~~capacity requirements for the short-circuit current.~~ ~~The calculation stability~~ of the ~~conductor or ground wire, especially the ground wire, should be guaranteed before the fault current is eliminated.~~

Calculation of ~~the~~ 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 ~~conductors~~, the thermally permissible short-circuit current ~~can~~ ~~may~~ be calculated ~~using with reference to~~ the simplified formula in Equation (2) and Equation (3).

$$I = \sqrt{\frac{Q}{T}} = \sqrt{\frac{C}{\alpha_r R_r T} \ln \frac{\alpha_r (t_m - t_r) + 1}{\alpha_r (t_a - t_r) + 1}} \quad (2)$$

$$C = c_p \times \rho \times S \quad (3)$$

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 sectional area ~~section~~ of the metallic material of the current-carrying part, in cm^2

α_r is the thermal coefficient of resistance ~~resistivity~~ at the 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 temperature, in $^\circ\text{C}$; refer to IEC 60865-1:2011 [B15 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 capacities ~~capacity for most materials~~ are listed or can be calculated using ~~determined by calculation with reference to~~ IEEE Std 80-2013 for most materials.

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 design of the conductor type and configuration ~~design~~ should meet the requirements for ~~on~~ radio interference (RI), audible noise (AN), and other electromagnetic environment ~~environmental~~ requirements.

6.1.5 Capital cost and loss evaluation ~~Cost effectiveness~~

For transmission lines, the conductor cross-section ~~of conductors~~ affects both the construction investment and the operational electrical ~~operating electric~~ energy losses. Local conditions can be taken into account when analyzing the cost-effectiveness of the conductor design ~~scheme, the local conditions can be considered~~. Generally, in addition to ~~besides~~ the construction investment, the costs of electrical ~~electric~~ energy losses including resistance heating losses and corona losses, operation and maintenance costs, and the time value of funds may be considered as well. The comparison of conductor schemes may be considered ~~viewed~~ in terms of cost-effectiveness over ~~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 an engineering ~~the~~ perspective ~~of engineering~~, the time value of each fund can be included ~~considered~~ in the cost-effectiveness assessment ~~of cost-effectiveness~~. The discount rate and the economic life of a project are the main parameters related to the time value of funds in the economic assessment. The present value ~~cost~~ method or the annual cost method can be applied to economic comparisons of conductor schemes for a transmission line project. The principles ~~of them~~ are the same, and the scheme with a lower present-value cost or a lower annual cost is ~~will be~~ preferred.

6.2 Corona and electric field, magnetic field effects

6.2.1 Introduction

The corona phenomenon that occurs at conductors tends to cause the electromagnetic environmental effects induced ~~impacts produced~~ by HV high-voltage transmission lines. These include power-frequency electric field and magnetic field, accompanied by RI as well as radio interference and AN, which may have harmful effects on ~~audible noise resulting from the conductors' coronas. See IEEE Std 539™ [B27] for definitions and terms regarding electromagnetic environmental impacts. They~~ affect the physical health ~~quality~~ of people ~~the human~~ living nearby. As EHV and UHV transmission lines have higher ratings for voltage and current, the effects of the electromagnetic environment are more severe than other lower ratings ~~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 can ~~may~~ be evaluated in the economic comparison of conductors.

6.2.2 Radio interference

6.2.2.1 Limits

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

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

The lowest protected radio signal level may be determined by ~~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 ($\mu\text{V/m}$).

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

6.2.2.2 Methods of prediction

6.2.2.2.1 Introduction

The main methods for predicting RI ~~are 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 consider the effect ~~take account~~ of the ~~impact from the~~ number of sub-conductors in a bundle, and the formula is appropriate ~~suitable~~ when conductor bundles have no more than four sub-conductors.

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

$$RI_i = 3.5E_{\max i} + 12r_i - 30 + 33 \log \frac{20}{D_i} \quad (4)$$

where

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

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

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

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

If the radio noise field strength of a particular ~~certain~~ phase is 3 dB higher ~~more~~ than the value of either of the other two phases, the radio noise field strength of the three-phase can be taken ~~deemed~~ as the field strength value of the phase with the highest ~~largest~~ value; otherwise, the radio noise field strength can be calculated by Equation (5 6).

$$RI = \frac{RI_1 + RI_2}{2} + 1.5 \quad (5)$$

where

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

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

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

For the multiple circuits erected on a tower, the radio noise field ~~generated~~ ~~produced~~ by each phase conductor is calculated by Equation (5 6). ~~The~~ ~~Via adding together the~~ radio noise field strength of the lines is obtained by adding the radio noise fields generated ~~produced~~ by the conductors of the same phase, ~~the radio noise field of the three-phase line is formed.~~

The value calculated ~~by using~~ Equation (4 5) is the average radio noise field for ideal weather conditions and ~~a the~~ frequency of 0.5 MHz, on the basis of which 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 for any altitude uses the additive correction of ~~increases at an increment of about~~ Alt./300, where ~~with the rise of altitude, in which~~ Alt. ~~is~~ refers to the altitude in m.

The corresponding correction When ΔRI ~~under 0.5 MHz is converted to that under the reception frequency of the affected object, the~~ to be applied is calculated by Equation (6 7), which applies is applicable to the frequency range of ~~from~~ 0.15 MHz to 4 MHz, when the value of RI at 0.5 MHz is converted to the value at the receiving frequency of the subject.

$$\Delta RI = RI - RI_0 = 5 \left[1 - 21 \lg(10f)^2 \right] \quad (6)$$

where

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

f is the frequency ~~expressed~~ in MHz

6.2.2.2.3 Excitation function approach

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

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

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

$$\Gamma_1 = 70 - \frac{585}{E_{\max}} + 35 \log(d) - 10 \log(n) \quad (7)$$

where

Γ_1 is the excitation function in heavy rain, in dB

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

d is the diameter of 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 80% ~~a~~ confidence ~~of~~ can be obtained by subtracting 10 dB to 15 dB ($\mu\text{V/m}$) from that in heavy rain.

6.2.3 Audible noise

6.2.3.1 Limits

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

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

6.2.3.2 Methods of prediction

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

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

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

$$AN = AN_0 + k_1 f_1(E_{\max}) + k_2 f_2(n) + k_3 f_3(d) + k_4 f_4(D) + k \quad (8)$$

where

$f_i()$ is the functional expression of each factor

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

n is the number of sub-conductors in a bundle

d is the diameter of the sub-conductor, in cm

D is the distance from the measuring ~~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:

$$SLA = 10 \log \sum_{i=1}^{N_p} 10^{\frac{AN_i}{10}} \quad (9)$$

where

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

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

Countries have proposed formulae for predicting ~~AN audible noise~~ from HV transmission lines based on their ~~own~~ long-term ~~measurement measured~~ data. ~~The predicting~~ Representative ~~prediction~~ methods include the Electric Power Research Institute (EPRI) method, ~~the~~ Ente Nazionale per L'Energia Elettrica (ENEL) method, ~~the~~ Bonneville Power Administration (BPA) method, ~~the~~ Hydro Quebec Institute of Research (IREQ) method, ~~the~~ FGH, Germany method, and ~~the~~ Electricite de France (EDF) method, as well as the empirical formulae developed by the Czech Republic, Belgium, Romania, and Japan. Among ~~these them~~, the ~~BPA BPA's~~ method (Chartier and Stearns [B9 B11]) is ~~the~~ 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 ~~recommended by BPA~~ for predicting ~~the AN of audible noise from~~ HV transmission lines ~~as recommended by BPA~~ is defined as ~~follows follow~~:

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

$$PWL(i) = -164.6 + 120 \log E_{\max} + 54 \log d_{eq} \quad (11)$$

where

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

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

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

d is ~~the diameter of~~ 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 at the conductor surface of 10 kV/cm to 25 kV/cm.

BPA suggests that the [AN for any altitude uses the additive correction](#) ~~audible noise increases at an increment of~~ about $Alt./300$ ~~, where with the rise of altitude, in which, Alt. is refers to~~ the altitude in m. The validity of this correction method [has been](#) ~~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 [help](#) prevent transient electric [shocks that cause pain](#) ~~shock causing discomfort~~, 2) [to help](#) prevent steady-state electric shock current [greater](#) ~~larger~~ than the [release](#) ~~let-go~~ threshold, and 3) [to limit adverse biological](#) ~~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) [guidelines \(International Commission on Non-Ionizing Radiation Protection \[B21 in 2010 \(ICNIRP B31\)\]](#)), the reference level [for](#) ~~of~~ exposure to 50 Hz and 60 Hz power-frequency electric [fields](#) ~~field~~ is specified [as](#) 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.

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

See Subclause A.3 for gives the design limits of 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 assume assumed that transmission lines are infinitely long and parallel to the ground and that the ground is an ideal conductor, allowing the electric field in the of a space to be simplified as a two-dimensional field. For the calculation of Considering the maximum electric field at produced on the ground, the height of the conductors to ground is taken as the minimum distance to ground at the center of the conductors. Bundled lowest point of the central conductor sag i to the ground. Bundle conductors, if used, can be substituted by an equivalent single conductor.

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

- a) Calculate the equivalent charge on the conductors Q using with Maxwell's equation, Equation (12 13), the of voltage U and the potential coefficient of λ :

$$[Q] = [\lambda]^{-1} [U] \quad (12)$$

where

Q is the equivalent charge on conductors

Λ is the potential coefficient

U is the voltage on the conductor

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

- b) Calculate the horizontal component E_x and [the](#) vertical component E_y of the electric field generated by [the](#) charge Q at any point in space [according to](#) ~~based on~~ the superposition principle.
- c) Calculate the maximum value of the resultant electric field at any point in space. ~~Since~~ [As](#) the resultant electric field at any point in space is a rotating elliptical field [whose](#) ~~the~~ magnitude and direction ~~of~~ which vary constantly with time, its maximum value cannot simply be calculated [using](#) ~~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, [the](#) finite difference method, finite element method, or other numerical methods can also be used.

[Specific calculation methods are given in](#) CIGRE 61 [[B3](#) [B6](#)], Chartier et al [[B8](#) [B10](#)], and EPRI [[B10](#) [B14](#)] [[B11](#) [B15](#)] ~~give specific calculation methods.~~

6.2.4.3 Measures for limiting power-frequency electric field strength

The electric field induced on [the](#) ground [decreases as](#) ~~reduces with the increase of~~ the height of conductors above [the](#) ground [increases; it can](#) ; therefore, ~~it can~~ be reduced by increasing the height of [the](#) conductors above [the](#) ground.