

IEEE Guide for the Preparation of a Transmission Line Design Criteria Document

IEEE Power & Energy Society

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**Transmission and Distribution Committee
of the
IEEE Power & Energy Society**

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Abstract: A suggested outline for information that should be included in a design criteria for overhead transmission lines is presented in this guide. This guide is not a design criteria or a design manual, it is a listing of the information that is required during the design of a transmission line, and provides guidance for line designers in the collection and documentation of how the line was designed; including the sources of information used in design and the design approach used.

Keywords: design criteria, IEEE 1724, load factors, structure loads

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Introduction

This introduction is not part of IEEE Std 1724-2011, IEEE Guide for the Preparation of a Transmission Line Design Criteria Document.

The Line Design Methods Working Group of the Towers, Poles, and Conductors Subcommittee of the Transmission and Distribution Committee determined that guidance in the preparation and documentation of the data, methods of design, design approach, and sources of information used in the design of a transmission line was desirable to assist transmission line designers in gathering and documenting the material used in design so that a coherent design of the line structures, conductors, conductor support systems, and foundations would result. This guide does not cover every possible consideration in line design, but includes topics covering most of the considerations that a line designer will encounter. It does not offer design guidance, but rather offers guidance in the documentation of the basis of design.

The purpose of a design criteria is to gather and document the information required for the design of a transmission line in one convenient document. The information contained in a design criteria should include general information about the line, ambient conditions that the line will operate within, clearances, and electrical and structural requirements. This guide incorporates a representative list of items that could be included in design criteria. Not all of the topics listed in this guide are applicable to all lines. For example, ice-loading criteria are not applicable in certain warm climates. The outline of this guide is the suggested outline for any project-specific design criteria.

In designing a transmission line it is useful to consider the forces acting on a line and the response of the line to those forces separately. The environmental forces acting on a line are wind, ice, lightning, and pollution. These forces are resisted structurally by the physical strengths of the line structural components. They are resisted electrically by the electrical properties of the insulators, grounding system, and structure configuration.

The sections of this guide discuss the forces and reactions in regard to electrical and structural actions and reactions. This separation of forces from reactions recognizes that the forces are outside of the control of the line designer. The environment determines the ambient loads that will impact a line. Ambient loads are statistical in nature and are characterized by their severity and frequency. Knowledge of the ambient loads allows the line designer to determine how to resist the loads. If a line is required to be very reliable, it can be designed to resist severe loads that happen infrequently. If a line has a lower reliability requirement it can be designed to resist only loads that occur commonly, with the realization that there is a greater possibility of the line experiencing a more severe load during its operational life, and experiencing failure.

The line designer is responsible for determining the philosophy of design. One philosophy is that the line should not fail under the most severe anticipated conditions. This requires designing for the historically worst loading conditions, combined with appropriate safety factors or load factors. Another philosophy is that the line should be as low cost as possible. This philosophy may lead to selection of design loads that will occur more frequently, combined with lower safety or load factors. There is no “standard” guideline for the “right” philosophy which is more dependent on the business philosophy of the utility. This business case philosophy has to be applied by the line designer to suit the particular requirements of a line. It is equally wasteful to over design an unimportant line, as it is to undersign an important line. The first case can be classed as an “economic failure” and the second as a “physical failure.”

Transmission lines are designed subject to safety codes, such as the National Electrical Safety Code[®] (NESC[®])^a [B1].^b

^aNational Electrical Safety Code[®] (NESC[®]) is a registered trademark in the U.S. Patent & Trademark Office owned by The National Fire Protection Association.

^bThe numbers in brackets correspond to those of the bibliography in Annex A.

These codes specify loads and load factors that are considered necessary for the safety of employees and the public under specified conditions. The safety codes require the line designer to consider additional severe loads that are anticipated in a particular area. This design criteria guideline is prepared to assist line designers in the process of determining and systematically documenting loads and load factors applicable to a specific transmission line or transmission system.

The design criteria should list the philosophy of design, and the sources of information and data used to select the loads and strengths of the line components.

The outline of this guide is a suggested outline for a project-specific design criteria.

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1. Overview

1.1 Scope

This guide provides a template to assist line design engineers in gathering information and organizing it into a coherent design criteria document for use in the design of overhead electric power transmission lines, generally at voltages of 69 kV and higher. The guide will also be useful for the design of lower voltage lines.

1.2 Purpose

This guide assists in application to engineers for the preparation of a design criteria document used for overhead transmission lines. A design criteria documents the data and assumptions used; the sources of the data and assumptions; the conventions, standards, guides, and design manuals used; and the design method(s) used in the design of the transmission line. The guide offers a comprehensive table of contents of the important criteria that should be taken into consideration in the design of transmission lines. The guide discusses the various criteria. The guide does not recommend criteria values, as would a design manual, but lists and discusses the importance of the criteria. The design engineer must determine the values to use based on the location, ambient conditions, and importance of the line.

2. General overview and summary

The overview is a concise summary of the information covered in detail in the guide. It provides a concise overview of the major factors used in the line design.

2.1 Project name, voltage, date, length, location, etc.

This section lists data about the line such as its terminal points, voltage, location, length, construction date, number of circuits, and any other information that would assist in generally describing the line. If the design criteria is a generic criteria used for a class of lines, information on its range of applicability should be stated.

Long transmission lines, or lines that have great changes in topography, may require different design criteria for different sections of the line. For example, a line constructed partially in the mountains and partially in the plains could have two different loading criteria for the different line sections.

2.2 Applicable codes and standards used in the design

In this section, list the safety codes that govern the design, or were used in the design of the line. Safety codes could include the National Electrical Safety Code® (NESC®) (Accredited Standards Committee C2-2007) [B1]¹, California GO-95 [B4], Hawaii GO-6 [B7], REA Bulletin 1724E-200 [B10], etc. Other commonly used design manuals should be referenced if they are used in the design, such as the: ASCE Manual 74 [B3] for design loads. ASTM, ACI, and ANSI have standards that cover material and design of elements of transmission lines. The date and/or edition of the code or manual should be included since the requirements of the various codes may change over time.

2.2.1 Federal Aviation Administration (FAA) requirements

Lines located near airports or having tall structures may require FAA review. Note that any requirements characteristics of the line location or structures that might fall under FAA jurisdiction. Several states have regulations concerning tall structures intended to enforce and enhance FAA recommendations and determinations.

2.2.2 State, Federal, or Local regulations

Describe any State, Federal, or Local laws or regulations that apply to the design or location of the line, or that will affect the design of the line. Highway or railroad crossings or occupations may have special design or clearance requirements.

2.3 Physical details

2.3.1 Wire sizes and compositions

The physical data for the energized conductors, shield wires, and fiber optic wires is discussed in this section. The code name for the wires should be included along with diameters, weights, and rated tensile

¹ Information in brackets can be found in Annex A.

strength. If there are several different wire sizes, a tabular form is convenient for ease of reference. If there are bundled conductors data on the bundle including the number of subconductors, configuration of the bundle, and spacing should be included. If there are special project considerations that led to wire selection, describe those considerations. If optical fiber ground wire (OPGW) will be used, the number of fibers and the type of fibers should be specified. Details of the physical construction, such as number and type of metal strands, diameter, weight, and strength, should be specified. Strength, physical characteristics, and communication characteristics of all dielectric self-supporting (ADSS) fiber optic wires should be included if they are to be used.

2.3.2 Insulator types and configuration

Insulators are needed for electrically insulating the energized conductor and for physical support of the conductor. Electrically, the purpose of the insulators is to provide an acceptable deterrence against flashover to grounded objects, such as the structure, and the other phases and shield wire (OHGW or OPGW). Physically, insulators also withstand the physical forces of wind and ice, and the wire weight and tension.

In this section, indicate the type of insulators to be used (porcelain, composite, glass) and the configuration to be used (Vee or I string, Post, etc.). Any special requirements, such as extra leakage distance or high strength requirements should be noted. The electrical and mechanical properties of the insulators should be tabulated. The electrical properties, such as power frequency wet and dry flashover, impulse withstand, and critical flashover are important to the electrical performance of the line and should be stated. The mechanical strength of the insulators is important for the physical integrity and reliability of the line and should be listed.

Insulator material and physical configuration affect the mechanical and electrical properties. Selection of insulators should be based on strength requirements, resistance to physical damage from gun shot, pollution level, power frequency, and impulse voltage requirements. Requirements for live line work may influence the selection of insulation type, configuration, and insulation level. Properties of the insulators vary by manufacturer and type. The reasons for selection of the type and configuration should be documented. Electrical properties may be affected by altitude. Derating factors should be explained.

The contamination level that is expected should be described. The performance of lines in the area or similar exposures may be referenced.

2.3.3 Structure material, description, and configuration

Information on structures should be included in this section. The material selected should be specified; steel poles, lattice towers, wood poles, composite poles, or concrete poles. The finish; painted, galvanized, self-weathering, etc. should also be listed. The configuration, such as H-Frame, single pole, square base or window lattice tower should be included.

2.3.4 Foundation material and types

In this section, indicate the type of foundations to be used. For example, direct embedment with native or select backfill, drilled pier caisson foundations, pad and pier foundations, and earth grillages may be described. If different foundations are used on different sections of the line, or for different soil conditions, they should be specified.

2.3.5 Conductor accessories

In this section list the types of conductor accessories that will be used. Compression type or bolted types should be specified. Spacers for bundled conductor lines should be described, with any specific descriptive wording to cover special requirements. Minimum performance requirements should be specified.

2.3.6 Vibration protection methods

In this section indicate how the line will be protected from aeolian vibration. Low conductor tensions, cushioned supports, vibration dampers, and spacer dampers, or combinations of the forgoing are common. Information regarding vibration experience in the area or with lines of similar design should be included.

3. Climate

In this section, on climate the design criteria should accurately reflect the climatological conditions in the area of the project. Safety codes such as the NESC have divided the United States into loading districts with specified loads intended to promote a high degree of safety. The Codes recognize that there are occurrences of higher loading in specific areas within the loading districts. The Codes require that these loads be used in the design of lines. Experience in an area may indicate a greater ice or wind load than code-required loads. The National Climatological Data Center maintains records of climatological data that may be used to characterize the weather conditions in the area of the line. ASCE Manual 7 [B2] and ASCE Manual 74 [B3] provide excellent resources for extremes of weather that may be considered in the design of the line. The aim of selecting climatological factors is to determine a realistic set of weather conditions for use in design.

Climatology also affects the pollution and lightning performance of a line. Areas subject to frequent rainfall may have good contamination performance due to the natural cleaning effect of the rainfall on the insulators. Conversely, dry areas may be more susceptible to airborne contamination because there is no natural insulator washing. Discussion of climate should include the isokeraunic level for the area, and the desired lightning performance for the line number of flashovers per 100 km/year.

3.1 Wind experience in the project area

In this section, describe and document the wind loading that will be used in design. Several wind speeds may be specified for different design purposes. Data can be obtained from weather records or the utility's own experience. Care should be taken in using "folklore" about past high wind experiences. Wind speeds are typically overstated in newspapers and in oral tradition. Wind is characterized in terms of "fastest mile" or "3-second gust." These are commonly used measures. Prior to the 2002 NESC, wind loads specified in the code were "fastest mile" wind speeds. This measure was based on how fast a "mile of wind" would pass by an anemometer. This measure used a long averaging time. (For a 60 mph fastest-mile wind speed, the averaging time is one minute.) There are factors used to estimate gust wind speeds for various gust periods from fastest-mile data. Starting with 2002, Rule 250C of the NESC states extreme winds in terms of 3-second gusts based on ASCE Manual 7 [B2]. Many older references stated wind speeds in terms of fastest-mile wind speeds. Care should be exercised when comparing wind records from different sources to ascertain the basis of their recording.

The design criteria should consider both the magnitude and frequency of wind speeds. It has been common for transmission lines to be designed for 50-year return period winds, which is a wind speed that has a 2% probability of occurrence in any year. Lines requiring higher reliability have used 100- or 500-year return period winds having, respectively, a 1% or 0.2% probability of occurrence in any year. Structures placed on

high points or exposed to concentrated winds should receive extra attention. REA Bulletin 1724E-200 [B10] provides wind maps for the US for various return periods.

Microbursts are very localized wind events characterized by a high vertical wind velocity, localized in a small area. When the vertical “column” of wind hits the ground it spreads horizontally. The horizontal extent is small, and is characterized by a vertical ground speed profile that increases with elevation. There is evidence that microbursts are responsible for a high percentage of wind failures. Since their frequency and magnitude are not well understood, there is no accepted method of designing structures to resist microbursts.

3.2 Ice experience in the project area

In this section, detail the ice loading expected to occur in the area of the line that will be used for line design. Data can be obtained from weather records or the utility’s own experience or both. As with wind, speeds care should be taken in using “folklore” about past heavy ice experiences. Ice thicknesses are typically overstated in newspapers and in oral tradition. NESC Rule 250D, ACSE Manual 7 [B2] and REA Bulletin 1724E-200 [B10] have excellent ice loading maps.

The design criteria should consider both the magnitude and frequency of ice thicknesses. The 2002 NESC divides the United States into three ice loading districts. There are many areas where ice accumulations frequently exceed the NESC ice loading requirements. A realistic assessment of heavy ice accumulations should be made as a basis for structure design. ASCE Manual 74 [B3] is a good source for ice thickness information. Another method of determining ice loading is by using computerized physical icing models that calculate ice accretion from hourly meteorological data.

Glaze ice, in-cloud ice, and rime ice are three different icing phenomena. The geographic patterns of rime ice and in-cloud ice will differ greatly. Rime ice and in-cloud ice have lower densities than glaze ice, but often have very large thicknesses. Often the best source of information on the frequency and magnitude of rime and in-cloud ice formation is from the utility’s own data.

In some cases, wet snow loads are greater than glaze ice loads or rime ice. In these situations, wet snow loads should be included in the design criteria.

The utility’s own data may well be limited to only verbal comments from staff. Accounts of icing on wires usually include the total diameter, that of the wire and ice covering. Any history of icing is a worthwhile source of information.

3.3 Combined ice and wind loading in the project area

Information on combined ice and wind loading is usually not readily available. Safety codes usually specify a combined ice and wind load. Often the best source for combined ice and wind loads will be the utility’s own records. Care must be taken in using oral reports of loadings, since the loads are usually exaggerated and almost always estimated rather than measured. As in the case for determination of ice loads, computer based icing models can be used to predict values of combined loads.

3.4 Unusual climatology (tornados, hurricanes, extreme ice, and microbursts)

The design criteria should note if weather conditions such as tornados, hurricanes, extreme ice, and microburst occur in the project area and if they are frequent or rare occurrences. The design of the line should acknowledge these events, although the geographic extent of the occurrences and their

consequences may be different. Hurricanes and extreme ice events cover large geographic areas. Tornadoes usually impact small areas of a project.

Designing for tornadoes is a rare practice. However, “straight” winds often accompany tornadoes and cover a wider area but are rarely recorded for reference.

The design criteria should document the design philosophy used relative to any unusual climatological events.

3.5 Pollution levels and sources

Insulator contamination from salt deposition in seacoast areas and/or industrial or agricultural contamination should be taken into account in the selection of insulators. The contamination performance of lines in the same or similar areas may be used for guidance. The insulation level of the proposed line may be calibrated in terms of the performance level of a line that is similarly exposed. The expected level of contamination, and the source of the information used to select the contamination level should be documented. REA Bulletin 1724E-200 [B10] has an excellent section on selecting insulators in contaminated areas.

4. Electrical design criteria

Overhead lines should be designed to maintain all applicable code and regulatory clearance requirements in the field at high assurance levels (NESC Annex A, GO-95 [B7], Corps of Engineers (COE) Permits, etc). This line design strategy recognizes that code and regulatory clearances specify fundamental requirements for safety of reasonably anticipated activities under or adjacent to the line. The line design process may add clearance buffers to code and regulatory clearance requirements to obtain design clearances. With a high level of assurance these clearance buffers are intended to provide design clearances that are adequate to maintain code clearances in the field when assumed climate extremes are exceeded, and allow for natural design and construction tolerances.

Design clearances are a primary parameter in the line design process, largely influencing the location and height of all supporting structures. The loading conditions used with design clearances typically include an iced condition and a maximum design conductor temperature condition. This section of the guide should tabulate the clearances used in design and the conditions under which the clearances apply (maximum conductor temperature, initial or final sag, ice loading, etc.). It is useful to separately specify the code-required clearance and the clearance buffer that has been applied. Any special clearances applicable in specific circumstances for activities reasonably anticipated in the area of the line, and/or working and maintenance clearances should be listed.

4.1 Code clearances

All applicable codes and regulatory clearance requirements should be calculated and listed. Include the code edition applicable for the line and other specified documents such as permit numbers, Federal Registries, or Local and State requirements that affect the design should be listed. Often code requirements are interpreted and retained by a utility as either a design document or drawing, which could also be either referenced or attached to the design criteria, if available.

4.1.1 Clearances to buildings and ground

Safety codes provide tables or formulas for minimum clearances to ground for lines of various voltage levels, based on the land use under or adjacent to the line. The specified clearances are designed to protect the public and construction/maintenance workers. The conductor temperature and wind or ice loading used to determine that the code clearance will be met should be documented.

The NESC clearances in this category specify minimum clearances for safety between the energized phase conductors and other anticipated activities or features not attached to the line. These activities or features include ground, forest land, agricultural land, roads, foreign lines, buildings, bridges, etc. The primary clearance strategy is to keep the energized conductors adequately separated from reasonably anticipated adjacent activities or features.

The type of method used to compute code clearances should be documented, if appropriate, including the switching surge value if used in the calculation. Any other applicable clearance strategies should be documented, such as purchasing land rights, restricting buildings, gas pipelines, or swimming pools from the line's right-of-way. Clearances should specify if they are for wires in their normal position or displaced by wind. If displaced by wind, the wind pressure should be stated.

4.1.2 Electrical clearances to structures

The code clearances in this category specify minimum clearances for the safe operation and maintenance of the line. Most codes specify minimum clearances under a wind displaced condition to minimize the probability of structure flashover during switching when the public may be adjacent to the line. Additionally, minimum clearances are also typically specified under a light wind condition to protect electrical workers who might be climbing or working on structures. Such loading conditions and their corresponding minimum clearances should be part of the design criteria document.

Other considerations that might influence electrical clearances to a line's supporting structures should be documented. For example, providing additional clearance for live-line maintenance or bare-handing should be included. Additionally, special clearances for specific switching surge values, or to accommodate helicopter maintenance activities, should also be part of the design criteria document.

4.1.3 Insulation coordination for suspension insulators

Insulators are designed to withstand the normal line voltage plus normal operating overvoltage and impulse voltage events such as lightning impulses and switching impulses. Insulation coordination is the process of coordinating the air gaps between the conductors and grounded portions of the structure. Insulation coordination may include insulator/air gap designs for power frequency operation, lightning impulses, and switching impulses.

Lightning impulses generally control the dimensions of the air gap for lines 230 kV and below. Switching impulses generally control the dimensions of the air gaps for lines 345 kV and above, and may require surge control measures in the substations.

Suspension insulators are free to swing under the influence of wind. Power frequency voltage is always present. The air gap insulation requirements used in the design of the line for the various conditions of voltage and wind should be documented.

4.1.4 Lightning performance

The lightning stroke density of the area should be specified. The line's target lightning performance should be stated. It is usually given in terms of outages/100mi/year. It may also be stated in terms of lightning withstand in terms of kA. There are several computational techniques used but all depend on the flashover characteristics of the insulators, the air gap geometry, the structure ground resistance, and the configuration and geometry of the conductors and shield wires.

Lightning performance depends on the ground resistance of the grounding system, the configuration of the structure, the spacing between wires, and the geometry of the shield wires. The required ground resistance and geometric requirements, including shield angle should be stated if known. If those parameters will be determined during the detailed design, then only the required performance level and means anticipated to produce that level need be stated.

Line surge arresters may be used to provide the required lightning performance. Where they are used the maximum continuous operating voltage (MCOV) should be specified. Surge arresters may also be used in conjunction with shield wires where soil resistance is high and adequate grounding cannot be obtained to achieve the lightning protection level required. The spacing between structures with arresters, and the arrangement of the arresters on the phases should be documented.

4.1.5 Shielding

Where shield wires are used for lightning protection, specify the size and type of wire to be used. Specify if the shield wire is to be grounded at every structure or insulated from the structure. For insulated shield wires, specify the insulation level and means to be used. Underbuilt shield wires are sometimes employed for fault return current paths or to supplement the shield wire protection system. If used, specify the location, size, and type. Specify any geometric requirements for coordination of spacing and sags with the phase conductors.

4.1.6 Grounding

For a specified geometry and insulator system, the structure ground resistance must be below the specified design level to provide the required design lightning performance. Ground rods and counterpoises may be used to obtain ground resistance below the maximum allowable. The required maximum ground resistance to produce the desired outage rate should be specified. The preferred method of grounding to obtain that resistance should be stated.

4.1.7 Galloping conductors

If galloping conductors are possible, the clearances between phases and phases to shield wires should be specified to account for the expected conductor motion. Shorter spans are anticipated to gallop in single loop configuration, and long spans are anticipated to gallop in two or more loops. The design separation should take into account the line voltage, the magnitude of galloping amplitude and the design philosophy. Common design practices are to allow a slight overlap of the ellipses, or to maintain phase to phase power frequency separation between the ellipses. REA Bulletin 1724E-200 [B10] provides one method for determining the size and shape of the ellipses and CIGRÉ Report 322 [B5] provides another method for lines with both single and bundled conductors.

4.2 Clearance buffers for design clearances

Clearance buffers may be specified in addition to the code required clearances to be used in the design of the line. The clearance buffers may account for design and construction measurement tolerances.

Values for clearance buffers and their basis should be documented including, if known, the type of tolerances or uncertainties the clearance buffers are intended to mitigate.

4.3 Structure spotting on design maps

The process of locating structures and specifying their heights on design profile maps (structure spotting) is influenced by many considerations. All the major design parameters and related considerations should be documented in the design criteria document. Typical design parameters that should be documented include the following:

- a) Design clearances for various loading conditions (maximum conductor temperature, specified ice loading, etc.)
- b) Maximum design temperature for clearances
- c) Maximum design ice loading for clearances
- d) Structure load limits and maximum design line angles
- e) Conductor uplift loading condition
- f) Maximum design wind and weight spans for the structures
- g) Minimum H/V ratios to control insulator swing to acceptable levels

Each line will usually have many unique considerations, which should also be documented. Examples might be land-use restrictions, varying right-of-way widths, or applicable codes.

4.4 Ampacity ratings and ampacity rating criteria

The maximum conductor design temperature for clearances is also the line's maximum operating temperature for ampacity ratings. The ampacity ratings are greatly influenced by ambient weather conditions. An ampacity weather model is used to calculate allowable current levels based on the line's maximum design temperature. The ampacity weather model identifies significant weather parameters, and their values, which significantly impact conductor cooling and heating. Typical parameters include air temperature, wind speed and direction, solar radiation, elevation, line orientation, and conductor surface properties. The line's maximum operating temperature, ampacity ratings, and the ampacity weather model should be documented in the design criteria document. IEEE Std 738™-2006 [B9] is an excellent procedure for determining ampacity ratings for conductors. CIGRÉ 299-2006[B6] provides a logical process for the selection of weather conditions, by study or by default values.

4.5 Corona and field effects

This section should indicate how the electric and magnetic field strengths will be calculated, including voltage (maximum operating voltage) and current that will be used in the calculations. If phase arrangement will be used to reduce fields, then consideration should be specified. The clearance to ground for the calculations should be specified.

The limits for electric field strength and magnetic field strength on the right of way and at the edge of the right of way should be specified.

Design limits for audible noise (AN), radio interference voltage (RIV), and television interference voltage (TVI) at the edge of the right of way should be specified. If insulators will be tested or specified with limits on RIV, the limit should be specified.

The levels of E and M fields can be compared to limits specified in the state where the line will be built, or if none are specified, compared with limits in other states.

The computer program used to calculate the levels should be specified.

5. Structural design criteria

Overhead lines are continuous structural systems with discrete elements (structures) and linear elements (conductors and shield wires). Typically they are designed to a high reliability standard. The high reliability helps to protect the public and utility workers from harm and provides for the continuity of electric service to the public. There are a number of codes and standards that are applicable to the design of overhead transmission lines. Among them are the NESC Annex A, GO-95 [B4], GO-6 [B7], ASCE Manual 74 [B3], REA Bulletin 1724E-200 [B10]. These documents mandate rules and offer guidance for the structural design of transmission lines. Often, structural design is referred to in the industry as “mechanical” design. Those terms may be used interchangeably in this document. Structures, through their geometric configuration, serve to isolate the high voltage they are carrying from normal public activity, providing a degree of safety to the public and to utility workers. They also affect the electrical performance of the line by providing shielding from lightning strokes and providing proper clearances to allow for insulator swing.

Structures are required to support themselves (guys may be required) and the wires and insulators they carry for the loads that the design weather criteria impose on the system. Wind and ice are loads imposed by nature. Loads that occur only during construction and maintenance must also be supported, and the occasional load caused by failure of a structural component must be supported.

The loads imposed by nature are statistical in nature. The strengths of the structural members that resist those loads are also statistical in nature. The design criteria should accurately describe the ambient conditions that the line will operate in, and the desired reaction of the line to those ambient conditions. Codes, such as the NESC, specify meteorological loadings for “safety.” These loads may not be sufficient for reliable line design. The loadings specified in the design criteria should reflect actual loadings anticipated for the area of the line. Loads are often specified as “return period” loads, reflecting the statistical nature of the loads. Generally, selecting loads with longer return periods produces a higher reliability line design.

5.1 Conductor and conductor support hardware

Conductors consist of an electrically conducting element and, for certain constructions, a strength element. The conducting element may also be the strength element. Conductors are affected by electrical current producing heat, and ice and wind loading from nature. Conductor temperature changes constantly under the influences of changing ambient temperature, ice, and wind. Changing temperature, ice, and wind cause changes in the conductor’s tension. Mechanical design of the conductor system should consider the ice and wind loads that are likely to occur in the area of the line over the expected life of the line. The ice and wind loads that the wires will support are also transmitted to the structures. Different loadings on adjacent spans of wire, such as ice dropping from conductors on one span but not the adjacent span will produce an unbalanced load on the structure. Wires are subject to aeolian vibration under the influence of winds blowing across the conductors and inducing vibration. The aluminum in conductors has a low tolerance to vibration. Measures to control vibration activity or to minimize the effect of vibration on the conductor, such as reduced tensions, installation of vibration dampers, or special support hardware, should be specified in the design criteria.

5.1.1 Conductor tension limits

Conductors are subject to wind loads and ice loads, separately or in combination. For each of the loadings used in the design, a tension limit for the conductors needs to be selected. Safety codes (NESC [B1], GO-95 [B4], GO-6 [B7], etc.) also specify tension limits for their specified loading cases. In addition to code requirements, many utilities have adopted additional tension limits, based on experience in their service area. Limits may be specified as a percent of the conductor's rated tensile strength or as a ratio of tension to mass.

Conductors spend most of their life in an "unloaded" condition (no ice or wind). Under these everyday conditions, conductors are subject to Aeolian vibration. Tension limits for unloaded conditions should be specified to minimize vibration damage. It should be noted that the tension limits specified in the codes and elsewhere are usually based on the assumption that vibration control devices, such as dampers, are correctly applied.

The design criteria document should indicate the tension limit for each of the loads used for design and indicate whether the limit is for the conductor in its initial or final sag condition. The limits used for vibration control should also be documented. Tension limits may be different for phase conductors and overhead ground wires and both should be documented.

5.1.2 Insulators

Insulators are an integral part of the transmission line structural/mechanical system. Insulators are utilized in three basic configurations: post, suspension, and dead-end (strain). Insulators should be specified taking into account both mechanical strength requirements and electrical requirements.

For suspension insulators, the mechanical strength is usually based on the resultant of the vertical and transverse components of the design loadings for the structure, including the tension component of transverse load for those structures having line angles. The basis for selecting insulator strength should be documented.

Post insulators are subject to cantilever forces, but may also support axial tension and compression loads. Manufacturers provide combined load curves showing the limits of allowable cantilever and tension/compression loads. The strength requirements of post insulators should be specified for both cantilever and combined loads.

For structures where the conductors are dead-ended, the mechanical strength of the insulators is determined by the conductor tensions under the various design loading conditions. The basis for selecting insulator strength should be documented.

Required insulator strength is based on the load being a maximum allowable percentage of the rated insulator strength. The allowable percentages vary, depending on the loading condition, and are specified in manufacturer's literature and codes. It should be noted that allowable loadings for composite insulators are different than for porcelain and glass insulators.

The design criteria should document the strength of suspension and dead-end insulators, and the basis for selection. Reasons for selection of insulator type, such as glass and porcelain, composite, should also be recorded.

5.1.3 Support hardware

Support hardware is an important component of the overall line design, and its strength can have a very significant impact on the overall performance of the line. For example, failure of suspension or dead-end hardware can trigger a longitudinal cascade line failure.

Strength requirements for support hardware are often based on the same criteria as insulators. For suspension hardware, the mechanical strength is usually based on the resultant of the vertical and transverse components of the design loadings for the structure, including the tension component of transverse load for those structures having line angles. For structures where the conductors are dead-ended, the mechanical strength of the dead-end hardware is determined by the conductor tensions under the various design loading conditions.

The basic philosophy used for hardware design should be documented, as well as the design loads for the hardware required for each type of structure. Any additional requirements, such as impact properties, fatigue properties, or material requirements (steel versus aluminum) should be noted, along with the reasons for the requirements. Any relationships between the strength requirements of the hardware as related to the strength of the conductors or insulators should be recorded.

Also record any considerations of failure sequence associated with hardware selection such as dead-end hardware to fail after conductor.

5.1.4 Conductor accessories

Conductor accessories typically include splices, dead-ends, terminals, dampers, spacers, and spacer dampers. In order to provide satisfactory service for the life of the line, the maximum loading and other mechanical requirements for these components must be given careful consideration. The components must have adequate mechanical strength to resist the loads imposed by the design conditions (ice and wind) for the line, as well as fatigue loadings resulting from vibration and other “everyday” loadings experienced by the line.

Strength requirements of splices are normally specified in terms of a minimum percentage of the rated strength of the conductor. Combined mechanical/optical splices for OPGW or other optical fiber components have requirements that are quite different than those of conventional conductors and overhead ground wires, and the appropriate requirements should be determined and documented.

Design requirements for spacers and spacer dampers usually include mechanical loading requirements that would be imposed by differential subconductor tensions and other situations, plus fatigue requirements that would represent the effects of vibration over the life of the line. An important aspect of spacer and spacer damper design is the criteria for placement, that is, damper design is the method of locating of the spacers and the length of subspans.

Conductor accessories are also designed to operate at temperatures that would be equivalent to those expected for the conductors. High temperature requirements should be noted and documented.

The design criteria described above should be documented, for each hardware component. This will ensure, among other things, any future replacement hardware may be obtained with full knowledge of the requirements employed in the original design.

5.2 Guys and hardware

5.2.1 Guy strand

If structures will be guyed, document the size, stranding, type, and strength rating of the guy wire. If several sizes will be used, provide a list of the details. Guy wires are usually one of two types: galvanized steel or aluminum-clad steel. If a material is chosen for a particular reason, such as corrosion resistance, or because it is a company standard, the reason for selection should be documented.

In many cases, the size of the guy wire will not be determined until after design is underway. For these cases, the method of determining the required strength and load factors should be specified. If guys will be grounded and/or insulated, the reasons for the decision should be given, along with a description of the grounding and insulating methods.

5.2.2 Guy hardware and anchors

The types of hardware to be used on the guys should be specified along with the method used to select their strength ratings. The types of anchors to be used and the expected holding strengths should be documented. If special anchor-rod treatment to resist corrosion will be used it should be specified.

5.3 Structures

5.3.1 Strength reduction factors

Materials used in structures are subject to normal manufacturing processes and variations. Materials are manufactured under standards such as ASTM. The standard specifies strength and usually a testing procedure to demonstrate that the material meets the required strength. Typically the material tests will exhibit a range of strengths, and the standard will specify how the rated strength is to be stated based on the tests. Many standards use a “lower 5% exclusion limit” (but not all use that limit). The definition of a lower 5% exclusion limit is that all but 5% of the items manufactured will have strengths exceeding the rated strength. NESC has two design methods. One uses loads multiplied by a “load factor” 1.0 or greater and applies those loads to structures with “strength reduction factors” of 1.0 or lower. ASCE is promoting a design concept where loads are multiplied by a load factor that accounts for their variability, and strengths are multiplied by a strength reduction factor to account for their variability.

Structural materials often lose strength over time due to rot, decay, or wear. The design criteria may note these effects by utilizing a strength reduction factor applied to the rated strength (or nominal strength) of structural members to account for the deterioration.

The design criteria should make reference to any sources of information used in the design. Edition or revision number of the documents should be indicated. The information may include design manuals such as ASCE Manual 74 [B3] to explain how the loadings and strengths were determined.

The design criteria should include manufacturer’s rated strengths, or ASTM required strengths of structural components.

5.4 Loads and load factors

In this section, list and provide information on all load cases used, such as weather loads, construction loads, and failure containment loads. A good way to describe the load cases is in paragraph form, giving the wind, ice, temperature, and any other items in the load. Naming the load is also a recommended practice i.e., “NESC Heavy Load,” or “GO-95 Light Load.”

Reference any design guides used. The source of the load, if from a design guide, should be stated.

Provide overload factors for each loading and basis for selecting that value. For each of the described load cases, provide the load factors that will be applied. It is recommended that the load factors for transverse, vertical, and longitudinal loads be stated individually.

5.4.1 Wind load cases

Provide basis of loading such as 50-year return period loading and reasons for choosing this loading. For transmission line designs, it is very important to document the wind loading used for the design and the reasons for using these values. Most transmission lines (except possibly those in very sheltered locations) are likely to be subjected to high wind loads during their life. In order to provide reliable service, lines are designed to withstand reasonably anticipated values of wind loading. Wind loadings are calculated on the basis of return period, with 50-year return period values typically being used for transmission line design. For lines that are required to have a higher level of reliability, higher return period loadings may be used, for example 100-year return winds, which impose increased loadings. Not only should the values of design wind loading be documented, but also the reasons for choosing those values (with reference to the reliability requirements of the line, etc.). For example, the most recent edition of the NESC has extensive information on the calculation of wind loading for power lines using a 50-year return period.

The NESC describes wind speeds for terrain that is relatively open. For reference, ASCE Manual 74 [B3] and ASCE Manual 7 [B2] show photographs of typical terrain falling in exposure categories A, B, C, and D. The winds given in the NESC are for category C exposure. Where the line crosses terrain with large hills, steep valleys, or similar terrain features that might increase the line’s exposure, or funnel winds increasing their speed, adjustments in the standard wind speed should be considered, and the results of such consideration documented. In those situations where weather data is collected from local sources to verify or calculate wind loadings, the sources of this data and the results of the analysis should be recorded. Reference should be made to any wind loading maps from design or other codes. In addition to the basic or adjusted wind loading values used for the design, the value of the various load factors used to calculate the loads applied to the various structure types should also be documented.

Documentation of the loads and load factors used in the design of the line is essential for the field operations staff, who must know the capability of the line and for design engineers for future line uprating or the replacement of structures. And lastly, in the event of a major line failure, the documentation will be needed for emergency restoration and to answer the questions from regulators and other interested parties.

5.4.2 Ice load cases

Provide the basis for choice of ice loading. For example, it may be the same return period as wind loading. Indicate source of ice data, such as published ice maps, ice model analysis, experience, etc. Indicate load factors used, basis for choice, and values for each structure type (if values are different).

5.4.3 Combined wind and ice load cases

Provide the basis for choice of combined ice and wind loading. (Note that the worst case for each individually may not occur simultaneously.) Indicate the source of ice and wind data, such as published ice maps, wind maps, ice model analysis, ice and wind model analysis, or experience. Indicate load factors used, the basis for choice, and values for each structure type (if values are different).

5.4.4 Broken wire and unbalanced ice loads

Indicate criteria for broken wire loads and any unbalanced ice loads (due to ice shedding in adjacent spans). Explain why these particular loads were chosen. Provide information on failure containment to be achieved with broken wire and unbalanced ice loads. Provide information on each broken wire load, indicating load values, load factors, and other relevant information. Provide information for unbalanced ice loading, indicating load values, load factors, and other relevant information. Provide loads for each structure type (if different). The desired reaction of the structure to the broken wire and unbalanced ice loads (e.g., bent arms, conductor slippage, damaged structure, or the frequency of containment structures, may also be specified, along with the method used to produce that reaction).

5.4.5 Construction and maintenance loads

Indicate criteria for construction and maintenance loads—structure assembly and erection, wire stringing and pull downs, maintenance operations—including live line maintenance as shown in REA Bulletin 1724E-200 [B10]. Provide information on each construction and maintenance load, indicating load values, load factors and other relevant information. Provide loads for each structure type (if different) load factors values selected may recognize safety for workers during construction and maintenance activities.

5.5 Structure design loads

Basic load tree configurations or tables are often used to specify the loads used in the design process. All the design cases considered should be included, even though only one will govern the design. It is often useful to describe the loading cases in terms of the wind, ice, and tension to document the ambient conditions considered in the design. The application of those loads to structures of different types (tangent versus dead-end) may differ, but the loads should be consistent throughout the design. The code mandated loads should be listed along with other loads to be used in the design for the area that the line will operate within.

A separate list indicating how the loads are applied to each type of structure, including the applied load factor will form the basis for structure design. For example, a load described as NESC Heavy Load may be applied to a tangent tower with “all wires intact using NESC required load factors.” It may be applied to a dead-end tower with “all wires on one face of the tower broken, with NESC Load Factors.” These load case descriptions and load application descriptions form the basis for the preparation of structure load trees.

5.5.1 Tangent and suspension angle structures

5.5.1.1 Intact cases

The design criteria should provide a loading tree or loading table showing all loads. The vertical, transverse and longitudinal component of each load should be indicated. The point of application for loads should be clearly indicated. Indicate line angle, wind direction, and wind and weight spans used for calculation of loads.

5.5.1.2 Construction and maintenance cases

The design criteria should provide a loading tree or loading tables showing design level construction loads. OSHA requirements should be incorporated. Wire stringing loads may include conductors jammed in a sheave and vertical and longitudinal loads due to wire stringing at the pull and tension sites. Loads associated with maintenance operations such as insulator change outs, dropping a wire for repair, or other maintenance activities, should be calculated and specified.

The vertical, transverse and longitudinal component of each load should be indicated. The point of application for loads should be clearly indicated. Indicate line angle, wind direction, wind and weight spans, and the geometry of the wires at pull or tension sites used for calculation of loads. Since workers are on the structures in the locations where loads are applied, the weight of workers and rigging and tools should be included. Often, special load factors are applied to these loads recognizing the presence of workers during these operations.

Provide values for all points of wire attachment (conductors and overhead shield wires). Indicate whether the load factors are included in the given load values or that the given values are to be multiplied by the load factors. Indicate the wind pressure to be applied to the structure.

5.5.1.3 Broken wire and unbalanced ice load cases

If these are required in the design, provide loading tree or loading table showing all loads. Show vertical, transverse and longitudinal component of each load. Clearly indicate point of application for loads. Indicate line angle used for calculation of loads. Indicate the wind pressure to be applied to the structure.

Provide values for all points of wire attachment (conductors and overhead shield wires).

Indicate whether the load factors are included in the given load values or that the given values are to be multiplied by the load factors.

5.5.2 Strain and dead-end structures

Dead-end structures are designed to withstand unbalanced pull from all of the conductors in one direction together with wind and vertical loads. Strain structures are designed to support the net unbalanced pull resulting from differential tensions from the conductors in both directions together with wind and vertical loads.

5.5.2.1 Intact cases

Provide loading tree or loading table showing all loads, including the weight of the jumper strings. Show the vertical, transverse and longitudinal component of each load. Clearly indicate points of application for loads. Indicate line angle used for calculation of loads. Indicate the wind pressure to be applied to the structure.

Provide values for all points of wire attachment (conductors and overhead shield wires). Indicate whether the load factors are included in the given load values or that the given values are to be multiplied by the load factors.

5.5.2.2 Construction and maintenance cases

The design criteria should provide loading tree or loading tables showing design level construction loads. Wire stringing loads may include conductors dead-ended on one face of a structure or vertical and longitudinal loads due to wire stringing at the pull and tension sites. Loads associated with maintenance operations, such as insulator change outs, dropping a wire for repair, or other maintenance activities, should be calculated and specified.

The vertical, transverse and longitudinal component of each load should be indicated. The point of application for loads should be clearly indicated. Indicate line angle, wind direction, wind and weight spans, and the geometry of the wires at pull or tension sites used for calculation of loads. Since workers are on the structures in the locations where loads are applied, the weight of workers and rigging and tools should be included. Often, special load factors are applied to these loads recognizing the presence of workers during these operations.

5.5.2.3 Dead-end and strain cases

Provide loading tree or loading table showing all loads, including jumper strings. Indicate whether wire can be dead-ended on only one face of structure, and number of phases that can be dead-ended. Indicate the wind pressure to be applied to the structure.

For multi-circuit structures, indicate if only one circuit can be strung.

Show vertical, transverse and longitudinal component of each load. Clearly indicate points of application for loads, including attachment points for stringing blocks and other construction or maintenance equipment.

Indicate line angle (or dead-end angle) used for calculation of loads. Provide values for all points of wire attachment (conductors and overhead shield wires). Indicate whether the load factors are included in the given load values or that the given values are to be multiplied by the load factors.

5.5.3 Containment structures

These structures are used to contain the extent of potential longitudinal cascade events.

5.5.3.1 Intact cases

The information provided should be the same as for dead-end structures discussed in section 5.5.2.1.

5.5.3.2 Broken wire cases

Since a containment structure has the purpose of withstanding a loading that could fail a normal line structure, the loads should be the same, but the application of those loads to the structure should consider that the structure must withstand a load in excess of the loads normally encountered by the line structures and should therefore have a higher design strength. Higher load factors may also be applied to provide increased strength. Another philosophy of designing for cascades is to select a load case exceeding the loads that are anticipated in the area and designing the containment structure to withstand that load case, with all wires on one face broken and the wires on the other face intact. This load application is the essence of a cascade load. Under this philosophy, the other line structures may fail, but the containment structure will be designed to withstand the load and limit the extent of the cascade.

5.5.4 Guying

If guying is used, then the allowable loading of the guys should be specified, and shown on the structure load trees. This may be in terms of percentage of rated strength, or in pounds. For structures with multiple guys, it is sometimes a requirement that the structure stand with one guy missing, or at some unbalanced tension. Any special structural requirements should be specified.

5.5.4.1 Buckling loads and limits

The suggestions of design guides such as ASCE [B2] and [B3] are often reproduced for the design calculations.

5.6 Foundation design

5.6.1 Loads and load factors

The loads used for designing foundations should be documented. They may be documented in terms of the forces they are designed to support, or in terms of the load cases they are designed to support. Because foundations are difficult to repair or replace after structure damage, they are often designed with added load factors so that they are stronger than the structures they support which makes it easier for structure restoration in the event of damage to a structure. The basis for selecting the design loads and the philosophy for selection of load factors should be documented.

Soil properties, including allowable bearing and lateral pressures, and elevation of the water table, are important in the design and application of foundations or pole settings.

5.6.2 Compression/uplift foundations

The loads transmitted to the foundations in lattice towers, X-Braced H-Frames, and similar structures are principally compression/uplift loads. The soil properties used for foundation design may be based on a geotechnical investigation of the soil or on the basis of geotechnical properties typical of the soils encountered in the project area. The soil properties used in the design, for example: allowable bearing pressure, unit weight (dry or submerged), friction angle, and any other input data required for the calculation method or computer program used for the design should be listed, along with soil properties for special locations. The calculation method or computer program used for the design should be specified.

5.6.2.1 Design philosophy

The philosophy of design should be described. This should include allowable settlement/movement and the load cases where the allowable movement applies.

5.6.2.2 Settlement and uplift limits

Any limits to settlement, translation, or uplift under normal and extreme loads should be specified.

5.6.3 Moment foundations

Single shaft structures typically have large overturning loads (moment loads), smaller lateral loads (shear loads), and bearing loads. The foundations should be designed based on a geotechnical investigation of the soil properties or on the basis of geotechnical properties typical of the soils encountered in the project area. The soil properties used in the design, for example: allowable bearing pressure, unit weight (dry or submerged), subgrade modulus, cohesion, friction angle, and any other input data required for the calculation method or computer program used for the design should be documented. The calculation method or computer program used for design should be specified.

5.6.3.1 Design philosophy

The most common way to determine size and strength for a structural component is to establish stress criteria. For foundations, establishing stress criteria along with deflection criteria is common. When designing a moment foundation on a transmission line, the deflection criteria is important. If the foundation of a pole moves (i.e., rotates) the wire tensions will change to some degree and the wires will sag more than a sag tension calculation indicates. If there is any sensitive crossing in the spans adjacent to the moment foundation the sag changes should be considered. Movement of the foundation also introduces additional loads in the structure, which translate into foundation loads due to the added moment of the vertical loads moving farther from the structure's axis.

Some design requirements may be stated in terms of non-recoverable deflection at the ground line under a specified load. The deflection may also be stated as an allowable angular rotation. The basis for the design should be clearly stated.

5.6.3.2 Deflection limits

Deflection of moment foundations affects the appearance of the line and the deflected unbalance of the structure. It is common to have two limits: one under code loading and one under extreme loading. The deflection criteria selected by the designer should be clearly described.

5.6.3.2.1 Total deflection

Total deflection is the deflection of the foundation under the extreme design load. It consists of recoverable and non-recoverable deflection. The allowable total deflection in terms of inches of movement or angle of rotation should be specified in the design criteria.

5.6.3.2.2 Non-recoverable deflection

Non-recoverable deflection is a result of exceeding allowable soil pressures, and permanently deforming the soil so that the foundation does not return to its original location when the load is removed. Non-recoverable deflection can have an impact in the loads in the structure members and the allowable limits should be stated, and should be included in the load information used for structure design.

Annex A

(informative)

Bibliography

- [B1] Accredited Standards Committee C2-2007, National Electrical Safety Code® (NESC®).²
- [B2] ASCE Manual 7, American Society of Civil Engineers (ASCE), “Minimum Design Loads for Buildings and Other Structures,” New York: ASCE, 2006.³
- [B3] ASCE Manual 74, American Society of Civil Engineers (ASCE), “Guidelines for Electrical Transmission Line Structural Loading,” New York: ASCE, latest revision.
- [B4] California GO95, California Public Utilities Commission., General Order 95/128 Manual 1997.
- [B5] CIGRÉ Report 322, State of Art Conductor Galloping, 2007.
- [B6] CIGRÉ Technical Brochure 299–2006, Guide for Selection of Weather Parameters for Bare Overhead Conductor Ratings.
- [B7] Hawaii GO-6, Public Utilities Commission of the State of Hawaii, Revised General Order No. 6, 22 November 1966, General Order No. 2345.
- [B8] IEEE Std 516™-2009, IEEE Guide for Maintenance Methods on Energized Power Lines.⁴
- [B9] IEEE Std 738™-2006, IEEE Standard for Calculating the Current-Temperature of Bare Overhead Conductors.
- [B10] REA Bulletin 1724E-200, Rural Electrification Administration, 2009.⁵

² The National Electrical Safety Code is available from the Institute of Electrical and electronics Engineers, Service Center, 445 Hoes Lane, Piscataway, NJ 08854, USA; and from the Sales Department, American National Standards Institute, 11 West 42nd Street, 13th Floor, New York, NY 10036, USA.

³ ASCE manuals are available from American Society of Civil Engineers Book Orders P.O. Box 79404, Baltimore, MD, 21279-0404, <http://www.asce.org/>.

⁴ The IEEE publications are available from the Institute of Electrical and Electronic Engineers, 445 Hoes Lane, Piscataway, NJ 08854, USA (<http://standards.ieee.org/>).

⁵ REA publications can be found at http://www.rurdev.usda.gov/SupportDocuments/UEP_Bulletin_1724E-200.pdf.