PDHonline Course E537 (4 PDH)

Transmission Line Design - Volume 1

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Transmission Line Design
Volume I

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This course is based on a USDA document, “Design Manual for High Voltage Transmission Lines”, United States Department of Agriculture, Rural Utilities Service December, 2015.

Introduction

The primary purpose of this series of courses is to furnish engineering information for use in designing transmission lines. Good line design should result in high continuity of service, long life of physical equipment, low maintenance costs, and safe operation. These courses presents a generalized "how to" guide for the design of a high voltage transmission line.

The engineering information in this course is for use in design of transmission lines for voltages 230 kV and below. Designs should be adapted to various conditions and local requirements. Engineers should investigate local weather information, soil conditions, operation of existing lines, local regulations, and environmental requirements and evaluate known pertinent factors in arriving at design recommendations.

This course is based on the requirements of the National Electrical Safety Code® (NESC®). However, since the NESC is a safety code and not a design guide, additional information and design criteria are provided in this course as guidance to the engineer. The additional design criteria are based on practices of many utilities in the United States.

This series includes five volumes. For the best understanding of the material, they should be studied in order. The volumes are generally divided into the following categories.

Volume I. This volume is an introduction to transmission line design and addresses siting issues, plan and profile drawings, loading, and distribution underbuild.

Volume II. This volume is all about clearances. Ground clearances, horizontal clearances, clearances from other live parts, and clearances to supporting structures are addressed.

Volume III. This volume discusses the materials involved in transmission line design and construction including insulators, conductors and hardware.

Volume IV. This volume in the series is concerned with the structural aspects of transmission line design and includes foundations and guyed structures.

Volume V. The final volume in the series is concerned with the structural aspects of transmission line design and includes single-pole structures and H-frame structures.

Chapter 1
Transmission Line Siting

Transmission line routing requires a thorough investigation and study of several different alternate routes to assure that the most practical route is selected, taking into consideration the environmental criteria, cost of construction, land use, impact to public, maintenance and engineering considerations.

To select and identify environmentally acceptable transmission line routes, it is necessary to identify all requirements imposed by State and Federal legislation. State public utility commissions and departments of natural resources may also designate avoidance and exclusion areas which have to be considered in the routing process.

Maps are developed in order to identify avoidance and exclusion areas and other requirements which might impinge on the line route. Ideally, all physical and environmental considerations should be plotted on one map so this information can be used for route evaluation. However, when there are a large number of areas to be identified or many relevant environmental concerns, more than one map may have to be prepared for clarity. The number of maps engineers need to refer to in order to analyze routing alternatives should be kept to a minimum.

Typical physical, biological and human environmental routing considerations are listed in Table 1. The order in which considerations are listed is not intended to imply any priority. In specific situations, environmental concerns other than those listed may be relevant. Suggested sources for such information are also included in the table. Sources of information include,

- United States Geological Service (USGS),
- Federal Emergency Management Agency (FEMA),
- United States Department of the Interior (USDI),
- United States Department of Agriculture (USDA),
- Natural Resource Conservation Service (NRCS), and
- Numerous local and state agencies.

For large projects, photogrammetry can contribute substantially to route selection and design of lines. Preliminary corridor location is improved when high altitude aerial photographs or satellite imagery are used to rapidly and accurately inventory existing land use. Once the preferred and alternative corridors have been identified, the engineer should consult USGS maps, county soil maps, and plat and road maps in order to produce small scale maps to be used to identify additional obstructions and considerations for the preferred transmission line.

On smaller projects, the line lengths are often short and high altitude photograph and satellite imagery offer fewer benefits. For such projects, engineers should seek existing aerial photographs. Sources for such photographs include county planning agencies, pipeline companies, county highway departments, and land development corporations. A preliminary field survey should also be made to locate possible new features which do not appear on USGS maps or aerial photographs.

Table 1
Line Routing Considerations

Physical	**Sources**
Highways	USGS, state & county highway department maps
Streams, rivers, lakes	USGS, Army Corps of Engineers, flood insurance maps
Railroads	USGS, railroad
Airstrips	USGS, Federal Aviation Administration (FAA)
Topography	USGS, flood insurance maps (FEMA), Army Corps of floodplains, etc.)
Engineers	
Power Lines	USGS, local utility system maps
Underground Utilities	USGS, local utility system maps
Occupied buildings	Local tax maps, land use maps, local GIS maps
Biological	**Sources**
Woodlands	USGS, USDA - Forest Service,
Wetlands	USGS, Army Corps of Engineers, USDA National Conservation
Resource Service,	USDI, Fish and Wildlife Service
Waterfowl, wildlife refuge areas, endangered species & critical Habitat Areas	USDI, Fish and Wildlife Service, State Fish and Game Office

Human Environmental	**Sources**
Rangeland Cropland Urban development Industrial development Mining areas Recreation or aesthetic areas, national parks, state and local parks	USGS aerial survey, satellite mapping, county planning agencies, state planning agencies, state soil conservation NRCS U.S. Bureau of Land Management, USGS, soil surveys, USDA, NRCS, state department of agriculture, county extension agent
Prime or unique farmland	
Irrigation (existing & potential)	Irrigation district maps, applications for electrical service, aerial survey, state departments of agriculture and natural resources, water management districts
Historic and archeological sites	National Register of Historic Sites (existing), state historic preservation officer, state historic and archeological societies
Wild and scenic rivers	USGS maps, state maps, state department of natural resources, Department of Interior
Other	**Sources**
Federal, state and county controlled lands	USGS, state maps, USDI Park Service, Bureau of Land Management, state department of natural resources, county maps, etc.

Many electric transmission utilities are using Geographic Information Systems (GIS) to automate the route identification process. GIS technology enables users to easily consolidate maps and attribute information from various sources and to efficiently analyze what has been collected. When used by routing experts, automated computer processes help standardize the route evaluation and selection process, promote objective quantitative analysis and help select defendable routes. GIS tools have proven very beneficial to utilities whose goals are to minimize impact on people and the natural environment while selecting a constructible, maintainable and cost effective route.

Final route selection, whether for a large or small project, is a matter of judgment and requires sound evaluation of divergent requirements, including costs of easements, cost of clearing, and ease of maintenance as well as the effect a line may have on the environment. Public relations and public input are necessary in the corridor selection and preliminary survey stages.

Preliminary Survey

Once the best route has been selected and a field examination made, aerial photos of the corridor should be reexamined to determine what corrections will be necessary for practical line location.

Certain carefully located control points should then be established from an aerial reconnaissance. Once these control points have been made, a transit line using stakes with tack points should be laid in order to fix the alignment of the line. A considerable portion of this preliminary survey usually turns out to be the final location of the line.

In many instances, after route has been selected and a field examination made, digital design data on a known coordinate system such as the *State Plane* is used for centerline alignment and profile. This alignment is provided to surveyors in a universal drawing file format. The surveyors then convert it to a format used by their field recording equipment. Once the project location is known, base control monuments are established along the route at 2 to 5 mile intervals, depending on topography, with static Global Positioning System (GPS) sessions from known horizontal and vertical control monuments. GPS equipment and radio transmitter equipment occupying the base monuments broadcast a corrected signal to roving GPS unit(s). These GPS units, with the use of an on-board field computer, allow any point or any line segment along the route to be reproduced in the field. The roving unit can be used to locate and verify wire heights at crossings, unmarked property lines or any routing concerns that may come up locally. The equipment can also be used to establish centerline points in open areas so that conventional survey equipment can be used to mark the line in wooded areas for clearing purposes. Once the right-of-way has been cleared, all structures can be staked with the Real Time Kinematic-Global Positioning System (RTK-GPS) equipment. Since this entire process uses data of a known mapping plane, any position along the route can be converted to various formats and used within databases.

Right-of-Way

A right-of-way agent should precede the preliminary survey party in order to acquaint property owners with the purpose of the project, the survey, and to secure permission to run the survey line. The agent or surveyor should also be responsible for determining property boundaries crossed and for maintaining good public relations. The agent should avoid making any commitments for individual pole locations before structures are spotted on the plan and profile sheets. However, if the landowner feels particularly sensitive about placing a pole in a particular location along the alignment, then the agent should deliver that information to the engineer, and every reasonable effort should be made by the engineer to accommodate the landowner.

As the survey proceeds, a right-of-way agent should begin a check of the records (for faulty titles, transfers, joint owners, foreclosed mortgages, etc.) against the ownership information ascertained from the residents. This phase of the work requires close coordination between the engineer and the right-of-way agent. At this time, the right-of-way agent also has to consider any access easements necessary to construct or maintain the line.

Permission may also have to be obtained to cut danger trees located outside and inside the right-of-way. Costly details, misuse of survey time and effort, and misunderstanding on the part of the landowners should be avoided.

Line Survey

Immediately after the alignment of a line has been finalized a survey should be made to map the route of the line. Based on this survey, plan and profile drawings will be produced and used to spot structures.

Long corridors can usually be mapped by photogrammetry at less cost than equivalent ground surveys. The photographs will also contain information and details which could not otherwise be discovered or recorded. Aerial survey of the corridor can be accomplished rapidly, but scheduling and costs should be taken in to consideration. Also, there may be some areas where trees and other vegetation could conceal relevant ground features.

When using photogrammetry to develop plan-profile drawings, proper horizontal and vertical controls should first be established in accordance with accepted surveying methods. From a series of overlapping aerial photographs, a plan of the transmission line route can be made. The plan may be in the form of an orthophoto or it may be a planimetric map (see Chapter 10). The overlapping photos also enable the development of profile drawings. The tolerance of plotted ground elevations to the actual ground profile will depend on photogrammetric equipment, flying height, and accuracy of control points.

Survey data can be gathered using a helicopter-mounted laser to scan existing lines and/or topography. Three dimensional coordinates of points can be gathered while also taking forward and downward looking videos. These points can be classified into ground points, structure points and wire points.

If use of photogrammetry or laser-derived survey information for topographic mapping is not applicable for a particular line, then transit and tape or various electronic instruments for measuring distance should be used to make the route survey. This survey will generally consist of placing stakes at 100 foot intervals with the station measurement suitably marked on the stakes. It will also include the placement of intermediate stakes to note the station at property lines and reference points as required. The stakes should be aligned by transit between the hub stakes set on the preliminary survey. The survey party needs to keep notes showing property lines and topographic features of obstructions that would influence structure spotting. To facilitate the location of the route by others, colored ribbon or strips of cloth should be attached at all fence crossings and to trees at regular intervals along the route wherever possible.

As soon as the horizontal control survey is sufficiently advanced, a level party should start taking ground elevations along the center line of the survey. Levels should be taken at every 100 foot stations and at all intermediate points where breaks in the ground contour appear. Wherever the ground slopes more than 10 percent across the line of survey, side shots should be taken for a distance of at least 10 feet beyond the outside conductor's normal position. These elevations to the right and left of the center line should be plotted as broken lines. The broken lines represent side hill profiles and are needed, when spotting structures, to assure proper ground clearance under all conductors, and proper pole lengths and setting depths for multiple-pole structures.

Drawings

As soon as the route survey has been obtained, the plan and profile should be prepared. Information on the plan and profile should include alignment, stationing, calculated courses, fences, trees, roads, ditches, streams, and swamps. The vertical and plan location of telecommunications, transmission and other electric lines should be included since they affect the proposed line. The drawings should also show railroads and river crossings, property lines, with the names of the property owners, along with any other features which may be of value in the right-of-way acquisition, design, construction, and operation of the line.

Structure spotting should begin after all of the topographic and level notes are plotted on the plan and profile sheets. Prints of the drawings should be furnished to the right-of-way agent for checking property lines and for recording easements. One set of prints certified as to the extent of permits, easements, etc. should be returned to the engineer.

Rerouting

During the final survey, it may be necessary to consider routing small segments of the line due to the inability of the right-of-way agent to satisfy the demands of property owners. In such instances, the engineer should ascertain the costs and public attitudes towards all reasonable alternatives. The engineer should then decide to either satisfy the property owner's demands, relocate the line, initiate condemnation proceedings, or take other action as appropriate. Additional environmental review may also be required.

Clearing Right-of-Way

The first actual work to be done on a transmission line is usually clearing the right-of-way. When clearing, it is important that the environment be considered. Environmental commitments/mitigations should be included in the construction contracts. It is also important that the clearing be done in such a manner that will not interfere with the construction, operation or maintenance of the line. In terrain having heavy timber, prior partial clearing may be desirable to facilitate surveying. All right-of-way for a given line should be secured before starting construction.

Authorizations

The following is a list of permits, easements, licenses, franchises, and authorizations that commonly need to be obtained and is not meant to be exhaustive.

Private property	Easement from owner and permission to cut danger trees
Railroad	Permit or agreement
Highway	Permit from state/county/city
Other public bodies	Authorization
City, county or state	Permit
Joint and common use pole	Permit or agreement
Wire crossing	Permission of utility

Table 2 list required federal permits or licenses required and other environmental review requirements. The following abbreviations pertain to Table 2:

BLM	Bureau of Land Management
CEQ	Council on Environmental Quality
CFR	Code of Federal Regulations
COE	Corps of Engineers
DOE	Department of Energy
EIS	Environmental Impact Statement
EPA	Environmental Protection Agency
FAA	Federal Aviation Agency
FERC	Federal Energy Regulatory Commission
FHA	Federal Highway Administration
FLPMA	Federal Land Policy and Management Act
FS	Forest Service
FWS	Fish and Wildlife Service
LWCF	Land and Water Conservation Fund Act
NEPA	National Environmental Protection Act
NPDES	National Pollutant Discharge Elimination System
NPS	National Park Service
PL	Public Law
SHPO	State Historical Preservation Officer
SPCC	Spill Prevention Control and Countermeasure
USC	United States Code

Table 2
Summary of Potential Major Federal Permits or Licenses and other environmental review requirements for transmission line construction and operation

Issue	Action Requiring Permit, Approval, or Review	Agency	Permit, License, Compliance or Review	Relevant Laws and Regulations
NEPA (National Environmental Protection Act) Compliance	Federal; Action to grant right-of-way across land under Federal jurisdiction	Lead Agency –	EIS and Record of Decision	NEPA (42 USC 4321), CEQ (40 CFR 1500-1508). DOE NEPA implementing Regulations (10 CFR to 1021)
Right-of-Way Across Land Under Federal Management	Preconstruction surveys; construction, operation, maintenance, and abandonment "Conversion of use" for a use other than recreation on lands reserved with Land and Water Conservation Fund Act (LWCF) monies	Bureau of Land Management (BLM)	Right-of-way grant and special use permit	Federal Land Policy and Management Act (FLPMA) of 1976 (PL 94-579) 43 USC 1761-1771 43 CFR 2800
		Bureau of Indian Affairs (BIA), tribe	Right-of-way grant across American Indian lands	25 CFR 169
		Forest Service (FS)	Special use authorization permit or easement	36 CFR 251
		National Park Service (NPS)	Authorization to cross National Park Service lands	18 USC, 36 CFR 14
		Fish and Wildlife Service (FWS)	Special use permit for crossing a national wildlife refuge	50 CFR 25
		NPS	Review of transmission line corridor to identify conflicts with recreational areas	Land and Water Conservation Fund Act PL 88-578, Section 6(f)(3)
	Construction, operation, maintenance, and abandonment of transmission line across or within highway rights-of-way	Federal Highway Administration (FHA)	Permits to cross Federal Aid Highway; 4 (f) compliance	Department of Transportation Act 23 CFR 1.23 and 1.27 23 USC 116, 123, and 315 23 CFR 645 23 CFR 771
Biological Resources	Grant right-of-way by federal land-managing agency	FWS	Endangered Species Act compliance by federal land-managing agency and lead agency	Endangered Species Act of 1973 as amended (16 USC 1531 et seq)

	Protection of migratory birds	FWS	Compliance	Migratory Bird Treaty Act of 1918 16 USC 703-712 50 CFR Ch 1
	Protection of bald and golden eagles	FWS	Compliance	Bald and Golden Eagle Protection Act of 1972 (16 USC 668)
Paleontological Resources	Ground disturbance on federal land or federal aid project	BLM	Compliance with BLM mitigation and planning standards for paleontological resources of public lands	FLPMA of 1976 (43 USC 1701-1771) Antiquities Act of 1906 (16 USC 431-433)
Ground Disturbance and Water Quality Degradation	Construction sites with greater than five acres of land disturbance	Environmental Protection Agency (EPA)	Section 402 National Pollutant Discharge Elimination System (NPDES) General Permit for Storm Water Discharges from Construction Activities	Clean Water Act (33 USC 1342)
	Construction across water resources	Army Corps of Engineers (COE)	General easement	10 USC 2668 to 2669
	Crossing 100-year floodplain, streams, and rivers	COE	Floodplain use permits	40 USC 961
	Construction in or modification of floodplain	Federal lead agency	Compliance	Executive Order 11988 Floodplains
	Construction or modification of wetlands	Federal lead agency	Compliance	Executive Order 11990 Wetlands
	Potential discharge into water of the state (including wetlands and washes)	COE (and states); EPA on tribal lands	Section 401 permit	Clean Water Act (33 USC 1344)
	Discharge of dredge or fill material to watercourse	COE; EPA on tribal lands	404 Permit (individual or nationwide)	Clean Water Act (33 USC 1344)
	Placement of structures and construction work in navigable waters of the U.S	COE	Section 10 permit	Rivers and Harbors Act of 1899 (33 USC 403)
	Protection of all rivers included in the National Wild and Scenic Rivers System	Affected land managing agencies	Review by permitting agencies	Wild and Scenic Rivers Act (PL 90- 542) (43 CFR 83.50)
	Potential pollutant discharge during construction, operation, and maintenance	EPA	Spill Prevention Control and Countermeasure (SPCC) plan for substations	Oil Pollution Act of 1990 (40 CFR 112)

Air Traffic	Location of towers in regards to airport facilities and airspace	Federal Aviation Administration (FAA)	A "No-hazard Declaration" required if structure is more than 200 feet in height	FAA Act of 1958 (49 USC 1501) (14 CFR 77)
			Section 1101 Air Space Permit for air space construction clearance	FAA Act of 1958 (49 USC 1501) (14 CFR 77)
Cultural Resources	Disturbance of historic properties	Federal lead agency, State Historical Preservation Officers (SHPO), Advisory Council on Historic Preservation	Section 106 consultation	National Historic Preservation Act of 1966 (16 USC 470) (36 CFR Part 800)
	Excavation of archaeological resources	Federal land managing agency	Permits to excavate	Archaeological Resources Protection Act of 1979 (16 USC 470aa to 470ee)
	Potential conflicts with freedom to practice traditional American Indian religions	Federal lead agency, Federal land managing agency	Consultation with affected American Indians	American Indian Religious Freedom Act (42 USC 1996)
	Disturbance of graves, associated funerary objects, sacred objects, and items of cultural patrimony	Federal land managing agency	Consultation with affected Native American group regarding treatment of remains and objects	Native American Graves Protection and Repatriation Act of 1990 (25 USC 3001)
	Investigation of cultural and paleontological resources	Affected land managing agencies	Permit for study of historical, archaeological, and paleontological resources	Antiquities Act of 1906 (16 USC 432-433)
	Investigation of cultural resources	Affected land managing agencies	Permits to excavate and remove archaeological resources on Federal lands; American Indian tribes with interests in resources must be consulted prior to issuance of permits	Archaeological Resources Protection Act of 1979 (16 USC 470aa to 470ee) (43 CFR 7)
	Protection of segments, sites, and features related to national trails	Affected land managing agencies	National Trails Systems Act compliance	National Trails System Act (PL 90-543) (16 USC 1241 to 1249)
Rate regulation	Sales for resale and transmission services	Federal Energy Regulatory Commission (FERC)	Federal Power Act compliance by power seller	Federal Power Act (16 USC 792)

In cases where structures or conductors will exceed a height of 200 feet, or are within 20,000 feet of an airport, the nearest regional or area office of the FAA must be contacted. Care must also be given when locating lines near hospital landing pads, crop duster operations, and military bases.

Chapter 2
Plan and Profile Drawings

Transmission line plan-profile drawings serve an important function in linking together the various stages involved in the design and construction of the line. Initially, the drawings are prepared based on a route survey. These drawings show the location and elevation of all natural and man-made features to be traversed by, or which are adjacent to, the proposed line which may affect right-of-way, line design and construction. They also indicate ownership of lands near the line. The drawings are then used to complete line design work such as structure spotting. During material procurement and construction, the drawings are used to control purchase of materials and they serve as construction specification drawings. After construction, the final plan-profile drawings become the permanent record and right-of-way data, useful in line operation and maintenance or future modifications.

Accuracy, clarity, and completeness of the drawings should be maintained, beginning with initial preparation, to ensure economical design and correct construction. All revisions made subsequent to initial preparation and transmittal of drawings should be noted in the revision block by date and brief description of revision. Originals of the plan-profile drawings, revised for as-built conditions, should be filed for future reference.

Drawing Preparation

Adequate control of field survey, including ground check of aerial survey, and proper translation of data to the plan-profile drawings are of utmost importance. Errors which occur during this initial stage will affect line design because a graphical method is used to locate the structures and conductor. Normally, plan-profile sheets are prepared using a scale of 200 feet to the inch horizontally and 20 feet to the inch vertically. On this scale, each sheet of plan profile can conveniently accommodate about 1 mile of line with overlap to connect the end span on adjacent sheets. On lines with abrupt ground terrain changes and on lines where there is need to minimize breaks in elevation view, plan-profile sheets may use a scale of one inch equal to 400 feet horizontally and one inch equal to 40 feet vertically.

A sample format for plan-profile drawing, detailing dimensions and stations is shown in Figure 1. Stationing and structure numbering increases from left to right and the profile and corresponding plan view are included on the same sheet.

> Note: Virtually all transmission line design is now done using CAD and frequently with LiDAR surveying. The manual processes shown in this series of courses is intended to show how the process works.

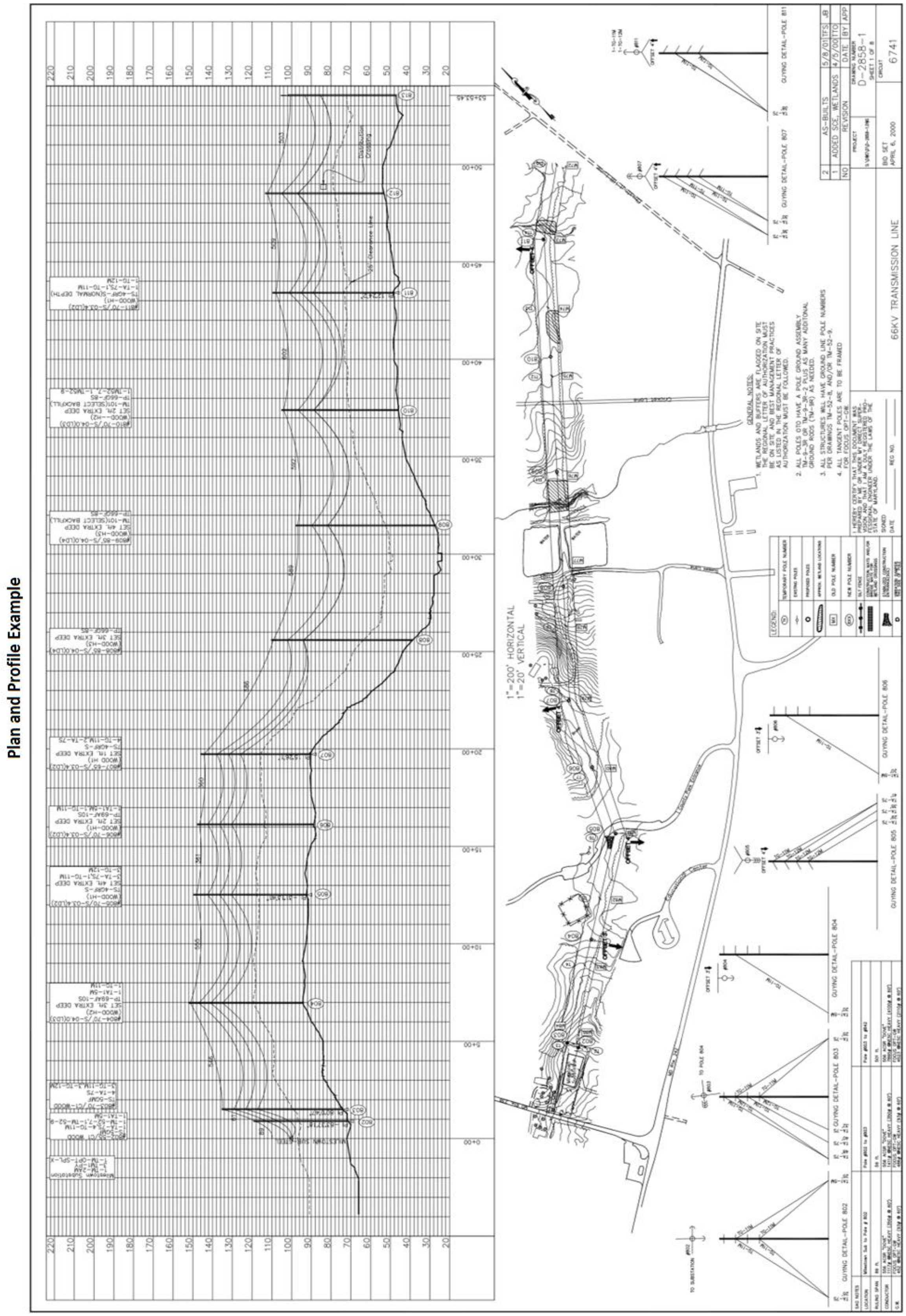

Plan and Profile Example
66KV TRANSMISSION LINE
GENERAL NOTES:
1"=200' HORIZONTAL
1"=20' VERTICAL

Figure 1

Features of existing obstacles, structures, etc. to be crossed by the transmission line, including the height and position of power and telecommunication lines, should be shown and noted by station and description in both the plan and profile views. The magnitude and direction of all deflection angles in the line should be included and referenced by “P.I. Station No. XX” in plan and elevation views. (P.I. refers to point of intersection). In rough terrain, broken lines representing side-hill profiles should be accurately plotted to assure final designs will provide for adequate conductor-to-ground clearances and pole heights. A drawing title block should be included. The block should identify the line and include the station numbers that are covered on the drawing sheet. The block should also include space for recording the names of personnel and the dates involved in various stages of drawing preparation, line design, checking, approval, and revisions.

Line design computer software should be used to import survey data and develop the land profile for the transmission line. Developments in surveying technologies have allowed the industry to go beyond the station-elevation-offset formats that have traditionally been used for transmission profile modeling. Use of three-dimensional Geographical Information System (GIS) modeling is becoming more common. Total station, geographical positioning system, photogrammetry, and electronic topographical maps (United States Geological Survey, USGS maps) have been employed to collect data in electronic format and to develop quick and accurate terrain plan and profile for transmission lines.

Design software can use a three-dimensional survey format and develop profile drawings of the terrain along the centerline of the line. Some software can create interpolated points on profiles by creating a *Triangular Irregular Network* (TIN). The TIN can be used to develop a three-dimensional rendering of a transmission line.

Once the alignment and profile have been developed, computer programs are then used to spot structures along the profile. For an established family of structures, the computer can be used to automatically spot structures for the most economical line cost or the user may manually spot structures. Programs have been developed to automatically plot the sag curve of the conductor and to check insulator swing, structure strength, and clearances. A material list is often developed from computer generated plan-profile drawings.

Computer aided drafting and design software may provide all or part of the following:

- Importing survey data, to model terrain, and to create a profile;
- Modeling of structure, including strength, geometry, insulator swing and complete bill of material;
- Calculating conductor sag and tension;
- Locating structures (spotting) on the profile drawing;

- Calculating conductor stringing and sagging, at almost any temperature, to check design conditions such as uplift, ground clearance or insulator swing;
- Checking the line plan-profile against specific design criteria;
- Displaying the plan-profile or structure analysis in three dimensions; and
- Preparing reports and construction documents showing all construction material units on the plan and profile, as well as developing material reports, staking tables, offset clipping reports, etc.

Some design programs provide more custom drafting capabilities. Traditional methods used to spot structures can be as much as 70-80 percent more conservative than the computer aided design and drafting approach.

Sag Template

In the rare case when computers are not used to spot structures and draw the conductor sag curve, manual techniques are used. Once the profile of the line has been drawn, the next step is to develop a sag template. The *sag template* is a scaling device used for structure spotting and for showing the vertical position of conductor (or ground wire) for specified design conditions. A sample conductor sag template is shown by Figure 2. The template is used on plan-profile drawings to graphically determine the location and height of supporting structures required to meet line design criteria for vertical clearances, insulator swing, and span limitations. The sag template permits alternate layout for portions of the line to be investigated and thereby aids in optimizing line design for economy.

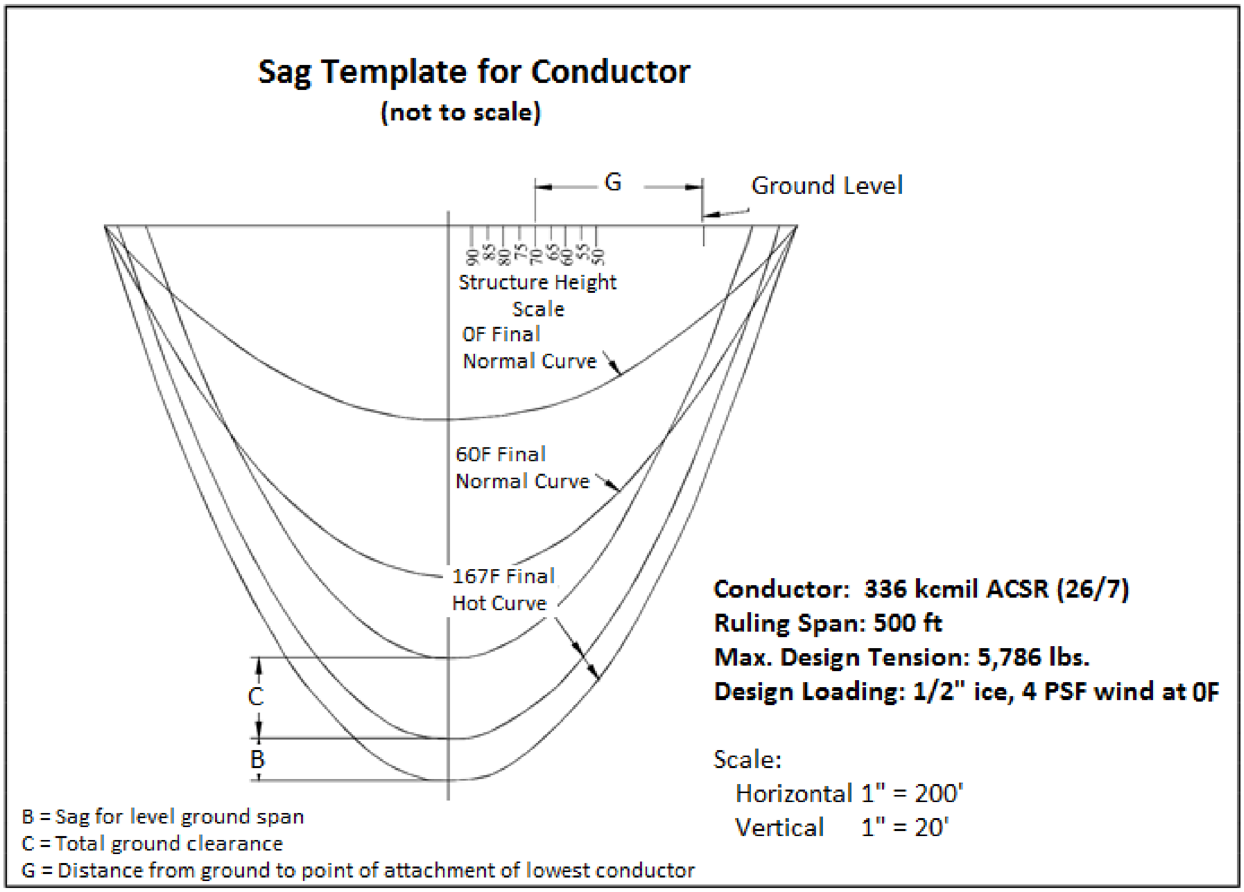


Figure 2

Generally, the conductor sag curves control the line design. The sag template for the overhead ground wire is used to show the position of the wire in relationship to the conductors for special spans or change in conductor configuration. An uplift condition at the overhead ground wire may be checked by using the template cold curve.

Sag Template Curves:
The sag template should include the following sag curves based on the design ruling span:

- Hot (Maximum Sag) Curve: At maximum operating temperature, no ice, no wind, final sag curve, the hot curve is used to check for minimum vertical clearances. However, if the maximum sag occurs under an icing condition, this sag curve should be used for the sag template.

- Cold Curve: At minimum temperature, no ice, no wind, initial sag curve, the cold curve is used to check for uplift and insulator swing.

- Normal Curve: At 60F, no ice, no wind, final sag curve, the normal curve is used to check normal clearances and insulator swing.

Sag curves are also used to locate the low point of sags and determine the vertical span lengths as illustrated by Figure 5. The curve intersection with the vertical axis line represents the low point position of sag.

Conductors of underbuild lines may be of different types or sizes than the transmission conductor. The hot curve of the lowest distribution conductor should be used for checking ground clearance. Cold curves may be required for each size of conductor to check for uplift or insulator swing.

Sag Template Design

Sag templates may be developed from information provided by the manufacturer of the conductor or from a graphical calculation method. Sag values needed to construct the template are available from the conductor manufacturer for a given conductor, ruling span, design condition and temperature. The template should be made to include spans three or four times as long as the normal level ground span to allow for spotting structures on steep terrain.

The form of the template is based on the fact that, at the time when the conductors are installed, horizontal tensions have to be equal in all level and inclined spans if the suspension insulators are plumb in profile. This is also approximately true at maximum temperature. To obtain values for plotting the sag curves, sag values for the ruling span are extended for spans shorter and longer than the ruling span. Generally for spans up to 1000 feet, it is sufficiently accurate to assume that the sag is proportional to the square of the spans (unless more accurate computed sag values are unavailable). The sag values used for the template may be determined as follows:

For the ruling span and its sag under each appropriate design condition and temperature, calculate other sags by the relationship:

$$\mathbf{S} = \left(\frac{\mathbf{L}}{\mathbf{RS}}\right)^{2} * \mathbf{S_{RS}}$$

Where:
S = sag of other span, ft.
S_{RS} = sag of ruling span, ft.
L = length of other span, ft.
RS = ruling span, ft.

Apply catenary sag correction for long spans having large sags.

The template should be cut to include a minimum of one foot additional clearance to account for possible minor shifts in structure location and error in the plotted profile. Where the terrain or the surveying method used in obtaining ground profile is subject to greater unknowns or tolerances, the one foot additional clearance should be increased. The vertical offset between the upper two maximum temperature (hot) curves is equal to the total required clearance, including the specified additional clearance. It is shown as dimension "C" in Figures 2 and 3. The minimum temperature and the 60F curves may be placed in any convenient location on the template.

A sag template drawing similar to Figure 2, made to the same scales as the plan-profile sheets, should be prepared as a guide for cutting the template. This template is made for a specified conductor, ruling span, and loading condition. A new template should be prepared for each line where there is any variation in voltage, conductor size, loading condition, design tension, or ruling span. A change in any one of these factors may affect the design characteristics of the template.

Sag Template Construction

The sag template should be made of dimensionally-stable transparent plastic material. A contrasting colored material (for example, red) is very helpful when the template is used to check plan-profile blueprint drawings.

Curves are first plotted on paper using the correct scales and then reproduced or copied on the plastic material. To cut a template, the transparent material is fastened securely over the curves drawn on paper and the centerline and upper curves are etched lightly by a sharp-pointed steel scriber. The outside edges of the template should be etched deeply so that the template can be easily broken out and the edges sanded smooth. Structure height scales may also be drawn or etched on the sag template, or a separate template, for determining the pole height required for each type of structure used. Etched lines should be filled with ink to make them easier to see when the template is used.

Conductor size, design tension and loading condition as well as ruling span and descriptive data for each curve should be shown on the template.

Structure Spotting

Structure spotting is the design process which determines the height, location, and type of consecutive structures on the plan-profile sheets. Actual economy and safety of the transmission line depends on how well this final step in the design is performed. Structure spotting should closely conform to the design criteria established for the line. Constraints on structure locations and other physical limitations encountered may prevent spotting of structures at optimum locations. Success of the effort to minimize or overcome these special conditions can be judged by how closely the final line layout follows the original design parameters.

Desired objectives of a well-designed and economical line layout are:

- Spans should be approximately uniform in length, equal to or slightly less than the design ruling span. Generally, differential conductor tensions are minimized and may be ignored if adjacent span lengths are kept below a ratio of 1.5 to 1.

- Maximum use should be made of the basic structure of equal height and type. The basic structure is the pole height and class which has been selected as the most economical structure for the given design condition.

- The shape of the running conductor profile, also referred to as the grading of the line, should be smooth. If the conductor attachment points at the structures lie in a smooth-flowing curve, the loadings are equalized on successive structures.

For a generally level and straight line, with few constraints on structure locations, there is no conflict between these objectives. They can be readily achieved. Greater skill and effort are needed for lines with abrupt or undulating ground profile and for those where constraints on structure location exist. For example, there may be high or low points in the profile or features such as line angle points, crossings over highway, railroad, water, power and telecommunication lines, and ground with poor soil conditions. Structure locations and heights are often controlled or fixed by these special considerations. Alternative layouts between fixed locations may then be required to determine the best arrangement based on factors of cost and effective design.

Design Factors for Structure Spotting

The following design factors are involved in structure spotting and are covered in subsequent courses in this series:

- Vertical Clearances
    - Basic, level ground
    - Crossings
    - Side hill
    - Underbuild

- Horizontal Clearances
    - For insulator side swing condition
    - To edge of right-of-way, vertical obstructions and steep side hills

- Uplift

- Horizontal or Vertical Span Limitations Due to:

    - Vertical sag - clearance requirement
    - Conductor separation
    - Galloping
    - Structure strength
    - Crossarm strength

- Angle and Deadend
    - Guying arrangements
    - Guy anchors

The following are necessary for structure spotting:

- Plan-profile drawings of the transmission line,
- Sag template of the same scale as the plan-profile prepared for the design temperatures, loading condition, and ruling span of the specified conductor and overhead ground wire,
- Table of minimum conductor clearances over ground features and other overhead lines,
- Insulator swing charts
- Horizontal and vertical span limitations due to clearance or strength requirements, and
- Guy arrangement and anchor requirements for angle and deadend structures.

A height scale prepared for each structure type will aid in structure height determination. Supporting calculations should be summarized in chart or tabular form to facilitate application during structure spotting. This is especially advisable for the standard suspension structure which has a greater range of pole height and class, as well as bracing variations for H-frame structures. Selection of the proper pole may be affected by various criteria, such as span-controlled-by-clearance or span-limited-by-pole strength, for a given pole height and class or bracing.

Process of Spotting

The process of spotting begins at a known or established conductor attachment point such as a substation take-off structure. For level terrain, the profile is essentially a straight line. When a sag template is held vertically and the ground clearance curve is held tangent to the ground profile, the edge of the template will intersect the ground line at points where structures of the basic height should be set. This relation is illustrated for a level span in Figure 3. Curve 1 (lowest conductor sag position) represents the actual sag of the conductor. Curve 2 (basic ground clearance curve) represents the actual position of the lowest conductor plus the required total ground clearance, "C".

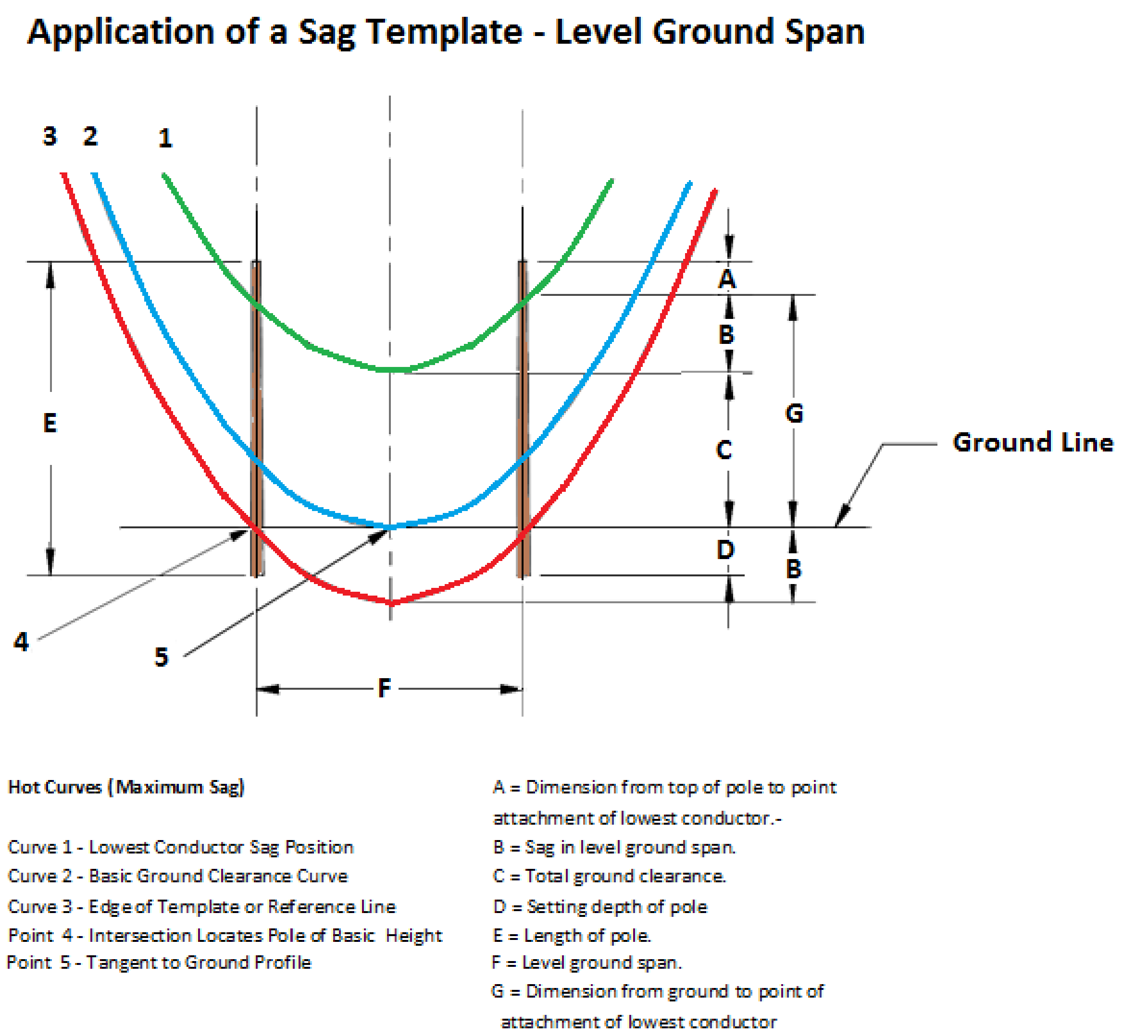


Figure 3

The point where Curve 3 intersects the ground line determines the location of the next structure. This new location is found by drawing an arc along the edge of the template from Point 4 to the next point where Curve 3 intersects the ground line. The template should then be shifted and adjusted so that with the opposite edge of the template held on the conductor attachment point previously located with the clearance curve again barely touching the profile. The process is repeated to establish the location of each succeeding structure. After all structures are located, the structures and lowest conductor should be drawn in.

The above procedure can be followed only on lines that are approximately straight and which cross relatively flat terrain with the basic ground clearances. When line angles, broken terrain, and crossings are encountered, it may be necessary to try several different arrangements of structure locations and heights at increased clearances to determine the arrangement that is most satisfactory. Special considerations often fix or limit the structure locations. It is advisable to examine the profile for several span lengths ahead, take note of these conditions and adjust the structure spotting accordingly. Sometimes, a more balanced arrangement of span lengths is achieved by moving ahead to a fixed location and working back.

The relationship between the ground clearance and conductor curves is also used for spans other than level-ground spans. This is done by shifting the sag template until ground profile touches or is below the clearance curve with the previously established conductor attachment point is positioned on the conductor curve. The conductor curve would then indicate the required conductor height for any selected span. Structure height may be determined by scaling or by use of the proper structure height template, taking into account the change in the embedded pole length for poles other than the basic pole. Design limitations due to clearance or structure strength should be observed.

Crossings

For spans-crossing features such as highway and power lines, with different clearance requirements than the normal clearance, the ground clearance curve should be adjusted accordingly. In California, adequate ground clearance has to be maintained over all railroads, major highways, major telecommunication and power lines when there is a broken conductor condition in either of the spans adjacent to the crossing span. Other states are governed by the NESC, which does not require the broken conductor condition. The increase in sag due to a broken conductor in an adjacent span is usually significant only where suspension-type structures are used at crossings and for voltage at 230 kV or above. For tension structures, and for suspension structures at lower voltages, the sag increase normally will not seriously affect the clearance.

Insulator Side Swing - Vertical Span

Horizontal conductor clearances to supporting structures are reduced by insulator side swing under transverse wind pressure. This condition occurs where the conductor is supported by suspension-type insulators. Conductors supported by pin-type, post, or tension insulators are not affected and horizontal clearance of the deflected conductor position within the span becomes the controlling factor. Suspension insulators also deflect laterally at line angle locations due to the transverse component of conductor tension.

At each structure location the charts are used to determine if insulator swing is within the allowed limit for the vertical and horizontal spans and line angle conditions. For suspension insulators supported on horizontal crossarms, a minimum vertical span has to be maintained to avoid excessive side swing. To maintain adequate clearance for insulators attached directly to the pole, and for some types of angle structures, the vertical span cannot exceed a maximum value (as indicated by the insulator swing chart).

The vertical span is the distance between the conductor low points in spans adjacent to the structure. The horizontal span is the average value of the two adjacent spans to a structure. Where conductor attachments are at different elevations on adjacent structures, the low point is not at mid-span and will shift its position as the temperature changes. This shift can be readily seen by comparing the low point for the hot curve with its position for the cold curve. The vertical span value used to check the insulator swing should be based on the low point position which yields the most critical condition for the structure type.

Where minimum vertical span or uplift is the concern, the cold curve should be used. The normal temperature is more critical and should be used if the vertical span is limited by a maximum value. Figure 5 shows some examples of the relationship of conductor low points and vertical spans which may occur in a line profile.

If insulator swing is unacceptable, one of the following corrective steps, in order of preference, is recommended:

- Relocate structures to adjust horizontal-vertical span ratio;
- Increase structure height or lower adjacent structures;
- Use a different structure, one with greater allowable swing angle or a deadend structure; or
- Add weight at insulators to provide the needed vertical force.

Uplift

Uplift is defined as negative vertical span and is determined by the same procedure as vertical span. On steeply inclined spans when the cold sag curve shows the low point to be above the lower support structure, the conductors in the uphill span exert upward forces on the lower structure. The amount of this force at each attachment point is related to the weight of the loaded conductor from the lower support to the low point of sag. Uplift exists at a structure (see Structure No. 4 in Figure 5) when the total vertical span from the ahead and back spans is negative. Uplift has to be avoided for suspension, pin-type, and post insulator construction. For structures with suspension insulators, the check for allowable insulator swing is usually the controlling criteria on vertical span.

A rapid method to check for uplift is shown by Figure 4. There is no danger of uplift if the cold curve passes below the point of conductor support on a given structure with the curve on the point of conductor support at the two adjacent structures.

Designing for uplift, or minimizing its effects, is similar to the corrective measures listed for excessive insulator swing, except that adding of excessive weights should be avoided. Double deadends and certain angle structures can have uplift as long as the total force of uplift does not approach the structure weight. If it does, hold-down guys are necessary.

Care should be exercised to avoid locating structures that result in poor line grading.

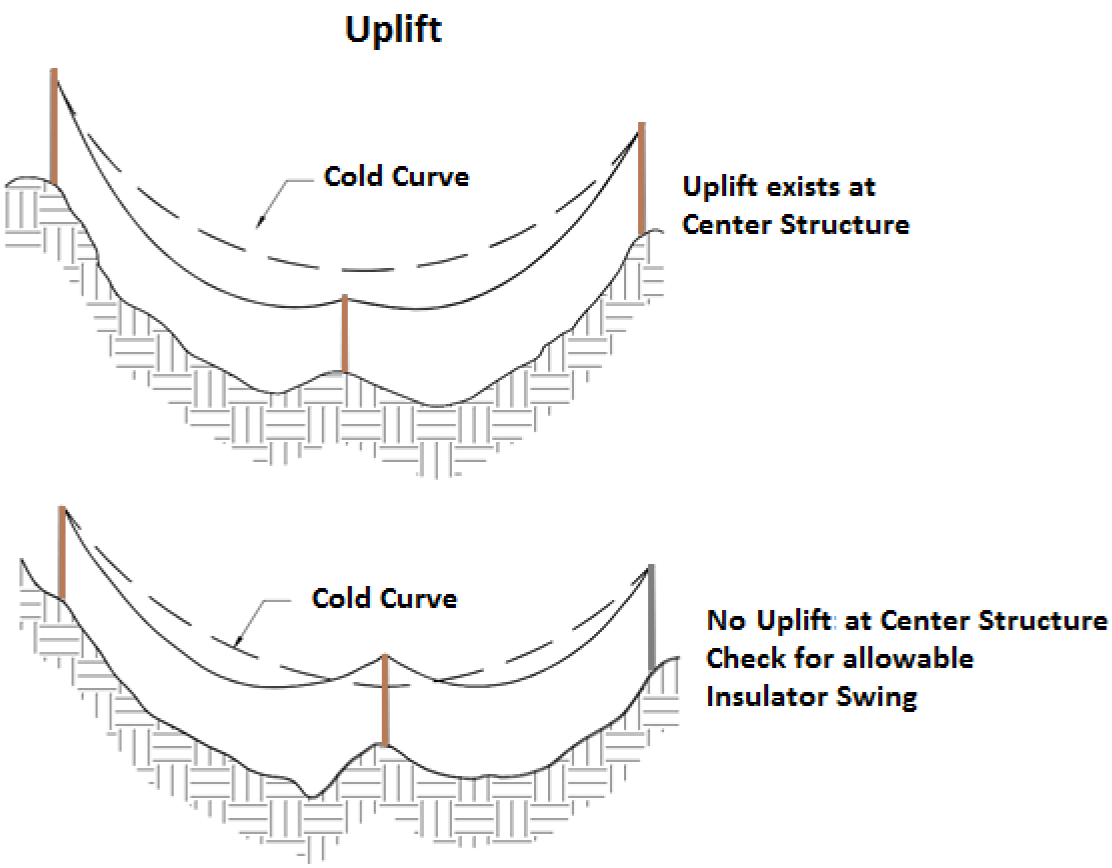


Figure 4

Other Considerations

If maximum conductor tension or other limits are not exceeded, it may be preferable to use one long span with adequate conductor separation over a depression in the profile rather than use two short spans with a deadend structure at the bottom of the depression. A structure at the bottom of the depression may be subjected to considerable uplift at minimum conductor temperature. Also, poorer soil foundation conditions usually exist in the depression.

Care has to be exercised at locations where the profile falls sharply away from the structure to see that the maximum allowable vertical span as limited by the strength of the crossarm or insulator is not exceeded. Structure No. 2 in Figure 5 illustrates this condition. For maximum accuracy in the heavy or medium loading zone, the vertical span for this purpose should be determined with a curve made for the sag under ice load, no wind, at 32F. For most conductors, however, the maximum temperature final sag curve will closely approximate the curve for the ice loaded conductor, and it may be used when checking for maximum vertical span. For guyed structures, the maximum vertical loads added to the vertical components from guy loads should be checked against the buckling strength of the pole.

The profile in rough country where side hills are encountered should be prepared so that the actual clearances under the uphill and downhill conductor may be checked. For some long spans it may be necessary to check side hill clearance with the conductors in their maximum transverse swing position. H-frame type structures installed on side hills may require different pole heights to keep the crossarm level or one pole may be set a greater than normal setting depth.

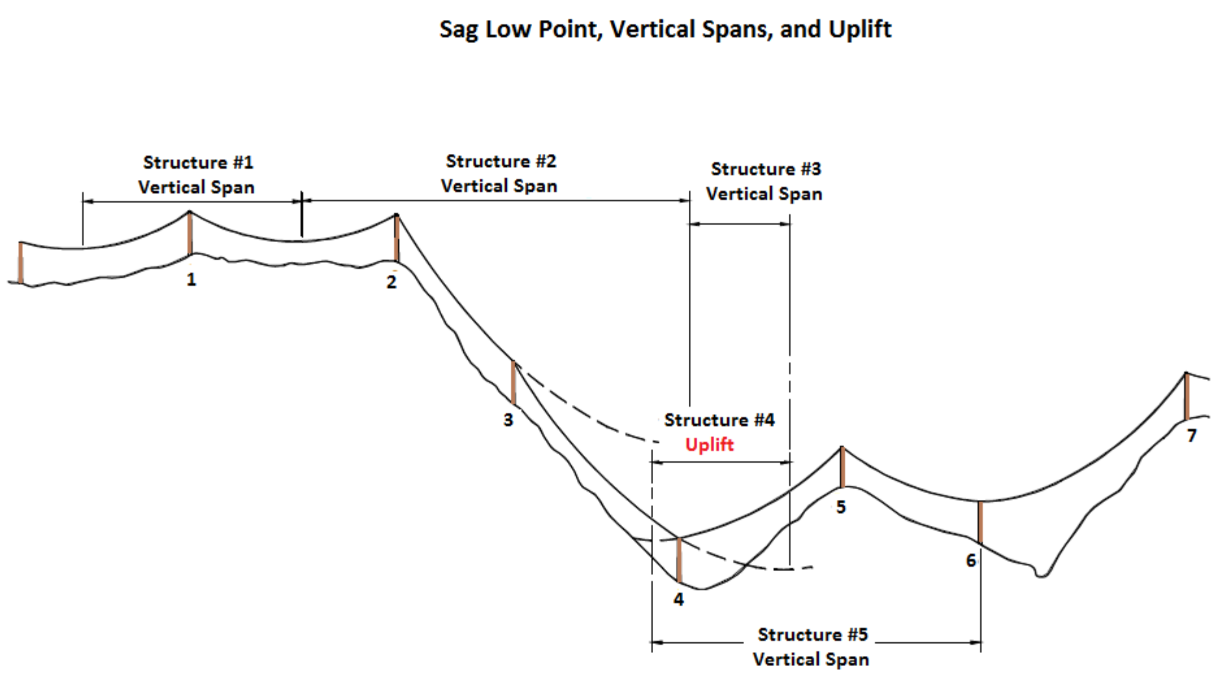


Figure 5

Structures with adequate longitudinal strength (guyed deadends usually) are required at locations where longitudinal loading results from unequal line tensions in adjacent spans. For lines subject to heavy ice and extreme wind conditions and with long, uninterrupted section of standard suspension structures, consideration should be given to inc0lude some structures with in-line guys or other means to contain and prevent progressive, cascading-type failure. This is especially important for H-frame type structures with lower strength in the longitudinal direction when compared with its transverse strength. Measures to prevent cascading failures are also important for lines without overhead ground wire which tends to restrain the structure from collapsing longitudinally. A maximum interval of 5 to 10 miles is suggested between structures with adequate longitudinal capacity (guyed deadends usually), depending on the importance of the line and the degree of reliability sought.

Other Design Data

Conductor and ground wire sizes, design tensions, ruling span, and the design loading condition should be shown on the first sheet of the plan-profile drawings. For completeness, it is preferable that these design data be shown on all sheets. A copy of the sag template reproduced on the first sheet could serve as a record of design in case the template is misplaced or lost. \

Design data for underbuild and portions of the line where a change in design parameters occurs should similarly be indicated. The actual ruling spans between deadends should be calculated and noted on the sheets. This serves as a check that the actual ruling span has not deviated greatly from the design ruling span. Where spans are spotted at lengths less than one-half or over twice the ruling span, deadending may be required.

As conductor sags and structures are spotted on each profile sheet, the structure locations are marked on the plan view and examined to insure that the locations are satisfactory and do not conflict with existing features or obstructions. To facilitate preparation of a structure list and the tabulation of the number of construction units, the following items, where required, should be indicated at each structure station in the profile view:

- Structure type designation,
- Pole height and class,
- Pole top, crossarm, and brace assemblies,
- Pole grounding units,
- Miscellaneous hardware units (vibration dampers at span locations), and
- Guying assemblies and anchors.

The required number of units or items required should be shown in parenthesis if greater than one. Successive plan-profile sheets should overlap. For continuity, and to avoid duplicate count, the end structure on a sheet should be shown as a broken line on the following sheet. The number and type of guying assemblies and guy anchors required at angle or deadend locations, based on guying calculations or application charts, should also be indicated. Design check, line construction, and inspection are facilitated if an enlarged guying arrangement, showing attachments and leads in plan and elevation, is added on the plan-profile sheet adjacent to each guyed structure. Any special notes or large-scale diagrams necessary to guide the construction should be inserted on the plan-profile sheet. This is important at locations where changes in line design or construction occur, such as a slack span adjacent to a substation, line transposition, or change in transmission and underbuild circuits.

Drawing Check and Review

The completed plan-profile drawings should be checked to ensure that:

- The line meets the design requirements and criteria originally specified,
- Adequate clearances and computed limitations have been maintained, and
- Required strength capacities have been satisfied.

Chapter 3
Loadings Issues

The strength to be designed into a transmission line depends to a large extent on wind and ice loads that may be imposed on the conductor, overhead ground wire and supporting structure. These loadings are related generally to the geographical location of the line.

When selecting appropriate design loads, the engineer should evaluate climatic conditions, previous line operation experience and the importance of the line to the system. Conservative load assumptions should be made for a transmission line which is the only tie to important load centers.

Structure and component strength should take into account temporary loads. Temporary loads imposed on a structure or component may include lifting of equipment, stringing operations, or a worker on a structure or component. This design manual does not address temporary loads.

Loads

The NESC divides the country into four weather or loading districts, as shown in Figure 6.

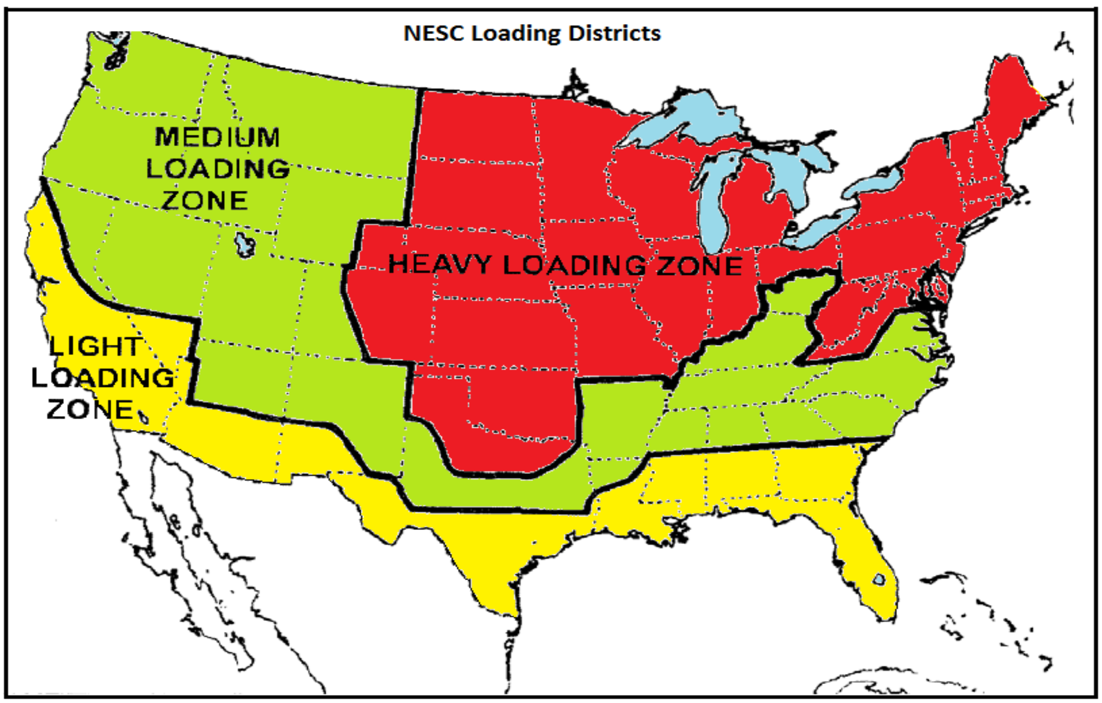


Figure 6

Note: Figure 6 is taken from IEEE C2-2012, National Electric Safety Code® (NESC®), Copyright IEEE 2012.

The minimum design conditions associated with each loading district are given in Table 3. Constants in this table are to be added to the vector resultant for tension calculations only.

Table 3
Ice, Wind, Temperature, and Constants

NESC Loading		Design Temp. (F)	Radial Ice Thickness (inches)	Wind Loading	Constants (lbs/ft)
Loading District	Heavy	0°	0.50	4 PSF	0.30
	Medium	15°	0.25	4 PSF	0.20
	Light	30°	0	9 PSF	0.05
Extreme Wind		60°	0	See Fig. 7	NA
Extreme Ice with Concurrent Wind		15°	See Fig. 8	See Fig.8	NA

Designing to these minimum requirements may not be sufficient. Extreme winds and special ice conditions should be investigated. Determination of an appropriate design load to account for extreme winds is easier than determining a heavy ice design load. Meteorological data may be available on high winds, but little data is available on extreme ice loads. Heavy ice combined with a relatively high wind should also be considered.

Extreme Ice

In certain areas of the country heavy ice may be predominant. The number and frequency of outages in the area due to ice storms, and the design assumptions used for existing lines in the area should be examined. From this data, the engineer can reasonably decide if a heavy ice condition greater than what is required by the NESC needs to be included in the design.

If historical data on icing conditions is lacking, the engineer should consider designing the line for extreme wind conditions without ice, and for loading zone conditions. The engineer would then calculate the maximum ice load the structure could sustain without wind and evaluate this specific ice condition.

Extreme Winds

Although the NESC requires that structures over 60 ft. sustain high winds, it is good practice for all transmission lines to meet extreme wind requirements. Required values for temperature and wind are listed in Table 3 and Figure 7. The NESC allows linear interpolation when considering locations between isotachs. Local meteorological data should also be evaluated in determining a design high wind speed.

Equations in Tables 250-2 and 250-3 of the NESC should be incorporated in computer programs as part of the structure analysis. These equations are included in the definitions for the variables in equations of this course. Tables 4, 5, 6, and 7 provide calculated values for the parameters in these equations.

The following should be used to calculate the load in the unit wind load on a circular wire in pounds per linear foot.

$$\mathbf{p = 0.00256 * V^2 * k_z * G_{RF} * d / 12}$$

Where,
p = unit load per unit foot, lbs./ft.
V = Basic Wind Speed, 3 –second gust wind speed in miles per hour at 33 ft. above ground with an annual probability of .02 (50 year return period), Figure 7.
d = diameter of the conductor in inches

k_Z = Velocity Pressure Exposure Coefficient, shown in Table 5 or by the equation:

$$\mathbf{k_Z = 2.01(h/900)^{(2/9.5)}}$$

Where,
h = height of the wire at the structure and is between 33 feet and 900 feet

G_{RF} = Gust Response Factor, shown in Table 11 or by the equation:

$$\mathbf{G_{RF} = \frac{1 + (2.7 * E_W * \sqrt{B_W})}{k_V^2}}$$

Where,
$E_W = 0.346\ (33/h)^{(1/7)}$
$B_W = 1/(1+0.8L/220)$
$k_v = 1.43$
h = Height of the structure
L = Design Wind Span (HS)

Table 4 Wire Velocity Pressure Exposure Coefficient (K_z)	
Height of Wire(ft)	k_Z
≤ 33	1.00
34 – 50	1.10
51 – 80	1.20
81 – 115	1.30
116 – 165	1.40

Table 5 Wire Gust Response Factor, G_{RF}				
Height of Wire At the Structure h (ft.)	Wire, G_{RF}, for Various Span Lengths in feet			
	251 - 500	501 - 750	751 - 1000	1001 -1500
≤33	0.86	0.79	0.75	0.73
34 – 50	0.82	0.76	0.72	0.70
51 – 80	0.80	0.75	0.71	0.69
81 – 115	0.78	0.73	0.70	0.68
116 – 165	0.77	0.72	0.69	0.67

Table 6 Combined Factor k_Z*G_{RF} for Common Wire Heights				
Height of Wire At the Structure h (ft.)	Wire, G_{RF}, for Various Span Lengths in feet)			
	251 – 500	501 - 750	751 - 1000	1001 -1500
34 - 50	0.90	0.84	0.79	0.77
51 - 80	0.96	0.90	0.85	0.83
81 - 115	1.01	0.95	0.91	0.88

For simplicity, the designer may wish to use the height of wire to be the height to the overhead groundwire at the structure.

To calculate the wind load on a structure in pounds, the following equation should be used.

$$\mathbf{P = .00256 * V^2 * k_z * G_{RF} * C_f * A}$$

Where,
P = wind load in pounds
V = Basic Wind Speed, 3-second gust wind speed in miles per hour at 33 ft. above ground with an annual probability of .02 (50 year return period), Figure 7.
k_Z = Velocity Pressure Exposure Coefficient, shown in Table 7 or by the equation:
$k_z = 2.01(0.67h/900)^{(2/9.5)}$
h = height of the structure above groundline
C_f = drag coefficient
A = projected wind area in square feet

G_{RF} = Gust Response Factor by the equation:

$$\mathbf{G_{RF}} = \frac{\mathbf{1 + (2.7 * E_s * \sqrt{B_s})}}{\mathbf{k_V^2}}$$

Where,
$E_S = 0.346\ (33/h)^{(1/7)}$
$B_S = 1/(1+0.8L/220)$
$k_v = 1.43$
h = height of the structure above groundline
L = design wind span (also known as HS)

Table 7
Structure k_Z, G_{RF}, and Combined k_Z G_{RF} Factor

Height of Structure, ft	k_Z	G_{RF}	Combined 'k_Z G_{RF}' factor
≤ 33	0.9	1.02	0.92
34 – 50	1.0	0.97	0.97
51 – 80	1.1	0.93	1.02

81 – 115	1.2	0.89	1.07
116 – 165	1.3	0.86	1.12

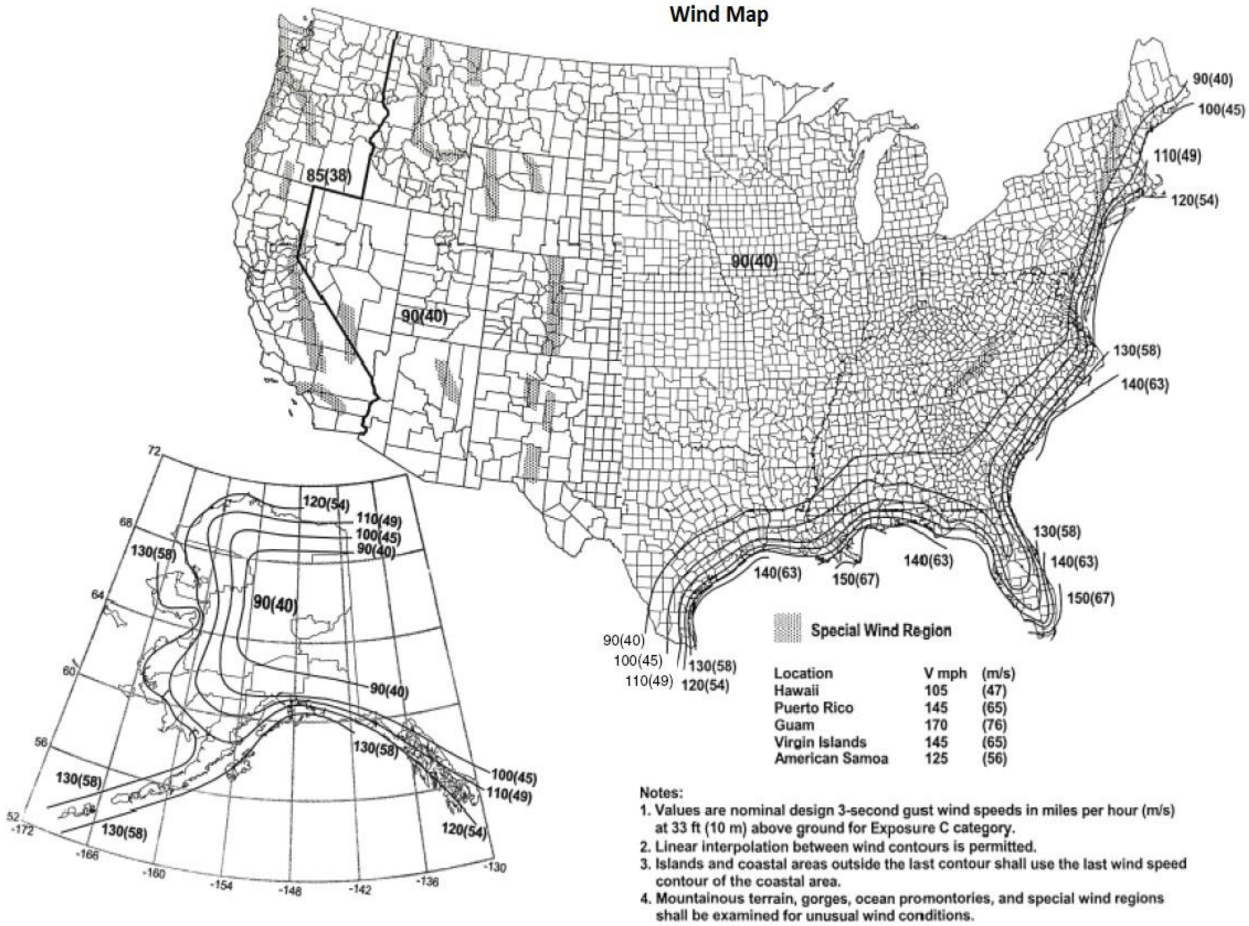


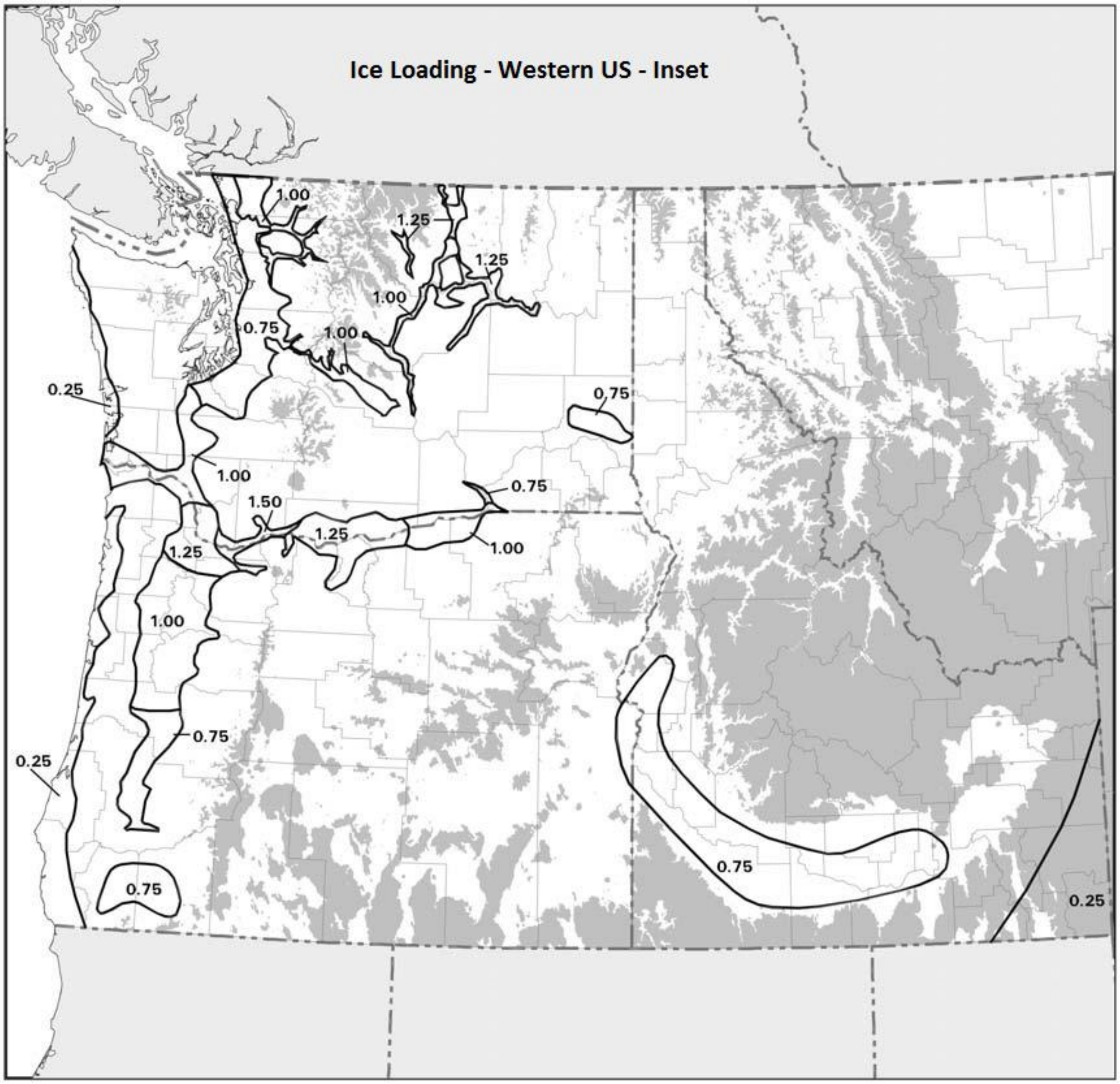
Figure 7

<u>Extreme Ice with Concurrent Wind Loads</u>

The NESC requires that structures over 60 ft. be designed to withstand the ice and wind loads associated with the Uniform Ice Thickness and Concurrent Wind Speed specified in NESC Figure 250-3 and in Figures 8 through 11of this course; however, it is recommended that all transmission lines meet these requirements. Required values for temperature, ice and wind are listed in Table 3.


Ice Loading - Western US
See Western Inset
60 mph
.5"
.25"
50 mph
.25"
.5"
.75"
40 mph
0"
.25"
40 mph
30 mph
.75"
.5"
.25"
Ice Load Zones
Wind Speed Zones
Notes
1. In the Appalachian Mountains, indicated by the gray fill, ice loads may vary significantly over short distances.
2. Ice loads on structures in exposed locations at elevations higher than the surrounding terrain and in valleys and gorges may be higher than the mapped loads.

Figure 8



Notes:

1. Ice thickness is shown in inches.
2. Unless otherwise specified use 0.50 inch ice thicknesses.
3. Freezing rain is unlikely to occur in the shaded mountainous regions above 5,000 feet.
4. Apply a concurrent 3-sec gust of 50 mph to the appropriate ice thicknesses.

Figure 9

Ice Loading - Eastern US

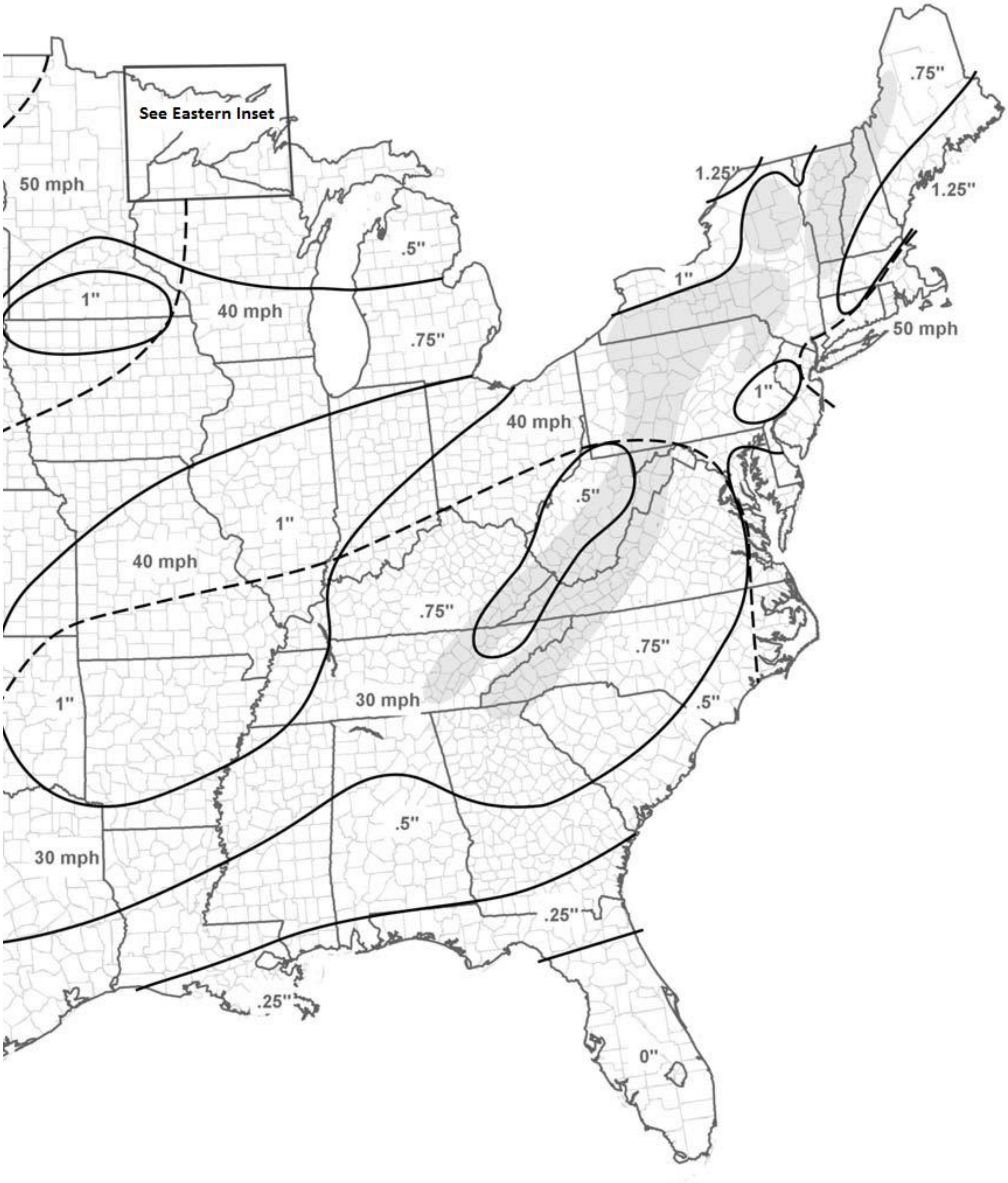


Figure 10

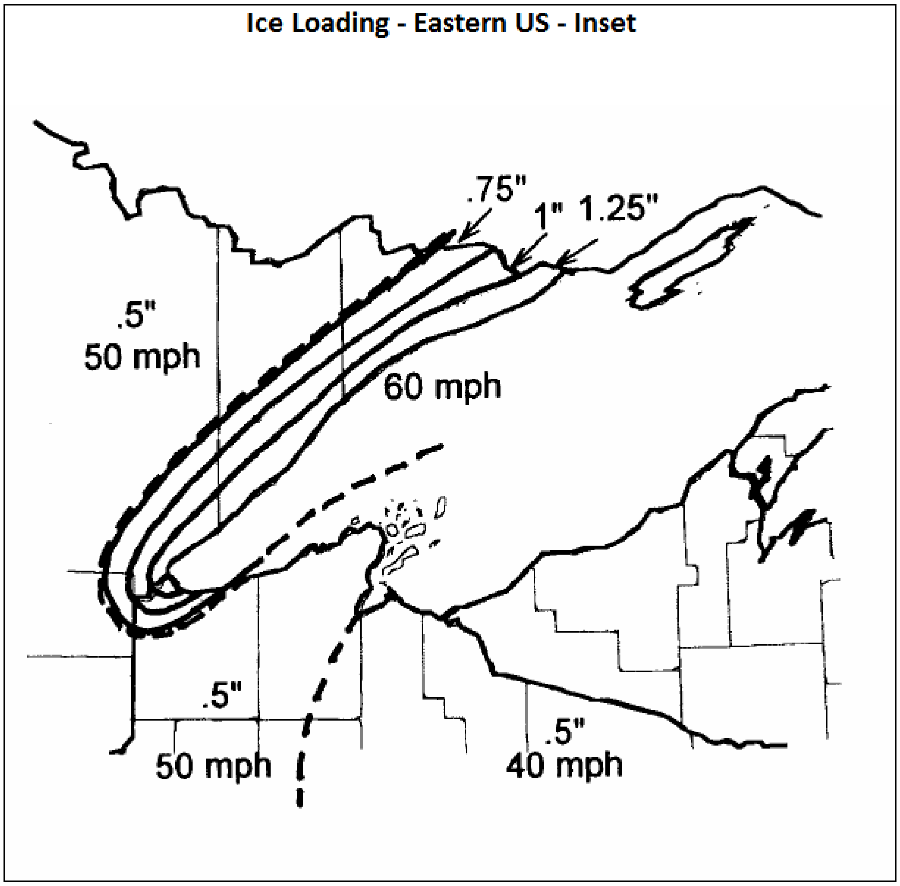


Figure 11

Longitudinal Loads

Unbalanced longitudinal loads on a line may occur because of:

- Unequal wind load and/or differential ice
- A broken wire conditions on equal or unequal spans
- Stringing loads
- Construction and maintenance activities
- A change in ruling span

Traditionally, standard tangent wood pole structures have not been designed for broken conductor longitudinal loads and have relied on the restraining capacity of deadends. The 2012 edition of the NESC recommends that structures having a longitudinal strength capability be provided at reasonable intervals along the line.

Several methods to reduce the risk of cascading transmission line structures due to broken wires have been recommended in the American Society of Civil Engineers (ASCE) Manual and Report on Engineering Practice No. 74 "Guidelines for Electrical Transmission Line Structural Loading," copyright 2010. They are summarized below.

Method 1, Install "Stop" Structures at Specified Intervals: This method consists of placing deadend structures, longitudinal guys, or regular tangent structures designed to resist deadend loads at intervals along the line to limit the number of cascading structures to a manageable number. This method is most practical for H-frames or narrow-based lattice towers which do not possess enough inherent longitudinal capacity to resist longitudinal loads. In these cases, stop structures are used because the cost to strengthen each structure to resist cascading may be high and the addition of guys at each structure may not be desirable.

Method 2, Install Release Mechanisms**:** Slip or release-type suspension clamps may be used as "fuses" to limit the longitudinal loads applied by broken wires. This is actually very similar to Method 1. The major difference between Method 1 and this Method is that "fuses" are used to minimize the unbalanced loads used to design each structure. The structures also have to be capable of withstanding construction and maintenance loads without endangering line crew personnel. Where heavy ice buildups are frequent, this could be an insurmountable problem. As such, this method is not recommended in areas of heavy ice, since unbalanced ice loads could result in unexpected failures.

Method 3, Design All Structures for Broken Wire Loads: Rigid lattice towers, guyed tangents (guyed in four directions) and single-shaft pole structures have an inherent longitudinal capacity. In many instances, such structures can be economically designed to resist longitudinal loads. The loads are typically based on the *residual static load* (RSL). The RSL is a load at a wire support after breaking one phase or a ground wire under every day conditions (no ice, no wind, 60F). Considerations in determining the RSL include insulator swing, structure deflection and suspension clamp slippage. Some designers have used 60 percent to 70 percent of the everyday tension for conductors and 100 percent of the everyday tension for ground wires. The suggested longitudinal loading consists of applying RSLs in one direction to a nominal one-third of conductor support points or to one (or both) ground wire support point. The suggested vertical loading consists of one-half or more of the vertical load imposed by the broken wire along with all of the vertical loads imposed by the other intact wires. Although every structure is designed to resist cascading, in the event of the catastrophic loss of a single structure, localized failures in adjacent structures should be expected.

A blend of Methods 2 and 3 would involve designing the main body of the structure for slightly larger longitudinal loads than those used for the design of the support arms and/or ground wire peak. The idea is to limit the loads applied to the body of the structure by "sacrificing" the arms or ground wire peak, thereby reducing the number of poles damaged from a broken wire event and decrease the likelihood of an unmanageable cascade. If such an event occurred, it could result in damage to several (perhaps numerous) support arms and/or ground wire peaks.

Example of Extreme Wind Calculations

A proposed 161 kV line using an H-Frame structure is expected to have spans ranging from 501 to 900 feet and to be composed of structures with wood poles 60 to 90 feet high. The line is expected to be located in northern Mississippi and will have a 795 26/7 ACSR conductor. Calculate the extreme wind load to be used in the design.

Extreme wind calculations are made for wind on the wires and wind on the structure. For wind on the wires, the engineer should calculate the wind on the overhead groundwires and the wind on the conductors. For wind on the overhead groundwires, a review of Table 6 indicates that 0.9 to 0.85 is to be used for the combined factor of '$k_Z * G_{RF}$' for spans 501 to 1000 feet and for wire heights 51 feet to 80 feet above ground (for structures using 60 to 90 foot poles). The conductors are located approximately 13 feet from the top of the pole. The height from the ground to the conductors at the structure will range from 39 to 63 feet above ground. For wind on the conductors, review of Table 6 indicates that values of 0.9 to 0.79 may be used as the combined factor of '$\mathbf{k_Z * G_{RF}}$' for spans 501 to 900 and for wire heights 39 to 63. (Poles are 51 feet to 80 feet above ground).

For wind on the structures, use Table 7. For structures of heights 52 to 79 feet above ground, Table 7 indicates that the combined '$\mathbf{k_Z * G_{RF}}$' factor for the structure is 1.02.

Wind pressure (PSF) on the overhead groundwires:

$$\mathbf{p = 0.00256 * V^2 * k_z * G_{RF}}$$

$$p = 0.00256 * 90^2 * 0.9$$

p = 18.66 PSF; use 19 PSF in design

Wind pressure (PSF) on the conductors:

$$\mathbf{p = 0.00256 * V^2 * k_z * G_{RF}}$$

$$p = 0.00256 * 90^2 * 0.9$$

p = 18.66 PSF; use 19 PSF in design

Wind pressure (PSF) on the structure:

$p = 0.00256 * V_2 * k_z * G_{RF}$

$p = 0.00256 * 90^2 * 1.02$

p = 21.15 PSF; use 21 PSF in design

For 21 PSF, the unit transverse load on the conductor p_t = 1.9390 lbs/ft

Therefore, for 19 PSF, the unit load will be 1.7543 lbs/ft (or 1.9390 * 19 / 21).

Example of Extreme Ice/Wind Calculations

Using the same example line in the previous paragraph, the line located in northern Mississippi has a combined ice and wind load of 0.75 inch of ice and a 30 PSF wind. Calculate the transverse and vertical unit loads on the conductor.

For the transverse unit load:

The diameter of the conductor including ice = 1.108 in + (0.75 * 2) = 2.608 in.

The unit wind load on the conductor,

$p_t = 30 \text{ lbs/ft}^2 * 2.608 \text{ inches/12in/ft} * 1\text{ft} = 6.520 \text{ lbs/ft}$

For the vertical unit load:

The vertical unit load, w_c, is the dead weight of the conductor plus the ice load per foot of conductor =

$1.0940 \text{ lbs/ft} + [3.1416((1.108 + (2* 0.75))^2 – (1.108)^2)/4/144 * 1 \text{ ft}] * 57 \text{ lbs/ft}^3 = 2.8269 \text{ lbs/ft}$

Load Factors for New Construction

Transmission lines are to be built to Grade B construction. Table 8 gives the recommended minimum load factors to be applied to the light, medium, and heavy loading districts of the NESC and also the recommended strength factors to be applied in the design of guys, anchors, crossarms, and structures.

Recommended load factors and strength factors to be applied to extreme wind loadings are in Table 9. The factors are intended to take into account approximations made in the design and analysis.

Application of Load Factors and Strength Factors

In the application of the load factors and strength factors, the objective is to design a structure with resistance greater than the maximum load expected during the lifetime of the structure and to design the structure with an acceptable level of safety and reliability. The use of load factors and strength factors can be expressed as follow:

$$\text{Ø} * R \geq LF * Q$$

where:
R = measure of material strength or resistance
Ø = a strength factor, less than 1.0
Q = load
LF = load factor, greater than 1.0

'Ø' is a multiplier which limits the resistance, R, and accounts for the variability of the resistance property. 'LF' is a multiplier that compensates for uncertainty in the load or assumptions made in the analysis. 'Ø' and 'LF' may be based on statistics, past engineering judgment, past practice, or may be legislated. The traditional view of a safety factor (or load factor) may be expressed as 'LF' divided by 'Ø'.

Example Calculation Showing the Use of Strength and Load Factors

A Douglas fir, 55 ft. tangent pole is to sustain a 750 lbs. transverse load two feet from the top. Assume this load is based on NESC heavy loading district loads. What class pole should be used for this construction? The pole is embedded 7.5 feet. The length of the moment arm used to calculate the induced moment at groundline is 45.5 feet.

In this case, R is the moment capacity of the pole at groundline and 'Q' is the horizontal load (750 lbs.). Using the strength factors (Ø=0.65) and load factors (LF=2.5) from Table 8, the equation becomes:

$$\text{Ø}*R \geq LF*Q$$

$$0.65*M_{\text{Moment capacity at the groundline}} \geq 2.50 * 750 \text{ lbs} * 45.5 \text{ feet}$$

$$M_{\text{Moment capacity at the groundline}} \geq 131{,}250 \text{ ft.-lbs}$$

The pole should have a moment capacity of 131 ft-kips at the groundline. A class 3 Douglas fir pole would provide this moment capacity at the groundline.

Table 8 Recommended Load Factors and Strength Factors to be Applied to NESC District Loads (Grade B New Construction) (NESC Tables 253-1 And 261-1) (Note 5)	
Load Factors	**NESC**
Vertical Loads	1.50
Transverse Loads Wind	2.50
Wire Tension	1.65
Longitudinal Loads At crossings General	1.10
Deadends	1.65
Elsewhere General	1.00
Deadends	1.65
Strength Factors (Note 3)	**NESC**
Steel and Prestressed Concrete Structures	1.00
Wood and Reinforced Concrete Poles (Note 4)	0.65
Wood Crossarms and Crossbraces (Note 4)	0.65
Fiber-Reinforced Polymer Poles, Crossarms, and Braces	1.00
Guy Wire Assemblies	0.90
Guy Anchors and Foundations	1.00
Guy Attachment Assemblies (includes guy hardware)	1.00
Conductor Support Hardware (Note 6)	1.00

Notes:

1. A value different than 0.65 may be used, but should not exceed 0.9.
2. This strength factor of 0.65 may be increased for steel and prestressed concrete poles.
3. It is recognized that structures will experience some level of deterioration after installation. These strength factors are for new construction.
4. For wood structures, when the deterioration reduces the structure strength to 2/3 of that required when installed, the wood structure should be replaced or rehabilitated. If the structure or structure component is replaced, the structure or structure component needs to meet the strength for the original grade of construction. The rehabilitated portions of the structures have to be greater than 2/3 of that required when installed for the life of the line.

5. When calculating the additional moment due to deflection, deflections should be calculated using loads prior to application of the load factor.
6. Conductor Support Hardware is any hardware not a part of the structure, guy assembly, or guy attachment. Conductor support hardware may be splices, extension links, insulator string yokes, y-clevis balls, ball hooks, deadend clamps, etc.

Table 9
Recommended Load Factors and Strength Factors
To be Applied to Extreme Wind Loads (Rule 250c of the NESC)
and to Extreme Wind/Ice Loads (Rule 250d of the NESC)
(Grade B New Construction)
(NESC Tables 253-1 And 261-1) (Note 5)

Load Factors	**NESC**
Vertical Loads	1.00
Transverse Loads Wind	1.00
Wire Tension	1.00
Longitudinal Loads	1.00
Deadends	1.00
Elsewhere General	1.00
Deadends	1.00
Strength Factors (Note 3)	
Steel and Prestressed Concrete Structures	1.00
Wood and Reinforced Concrete Poles (Note 4)	0.75
Wood Crossarms and Crossbraces (Note 4)	0.75
Fiber-Reinforced Polymer Poles, Crossarms, and Braces	1.00
Guy Wire Assemblies	0.90
Guy Anchors and Foundations	1.00
Guy Attachment Assemblies (includes guy hardware, bracket and guy attachment assemblies)	Not Specified
Conductor Support Hardware (Note 6)	0.80

Notes:

1. A value different than 0.65 may be used, but should not exceed 0.90.
2. This strength factor of 0.65 may be increased for steel and prestressed concrete poles.
3. It is recognized that structures will experience some level of deterioration after installation. These strength factors are for new construction.
4. For wood structures, when the deterioration reduces the structure strength to 2/3 of that required when installed, the wood structure should be replaced or rehabilitated. If the structure or structure component is replaced, the structure or structure component needs to meet the strength for the original grade of construction. The rehabilitated portions of the structures have to be greater than 2/3 of that required when installed for the life of the line.
5. When calculating the additional moment due to deflection, deflections should be calculated using loads prior to application of the load factor.
6. Conductor Support Hardware is any hardware not a part of the structure, guy assembly, or guy attachment. Conductor support hardware may be splices, extension links, insulator string yokes, y-clevis balls, ball hooks, deadend clamps, etc.

Chapter 4
Underbuild

Placing of underbuild distribution or communications circuits on transmission lines is a practice that is becoming more prevalent as available rights-of-way decrease. Although underbuild distribution lines increase the initial cost of a transmission line, common sharing of a right-of-way is sometimes necessary in order to build the line.

Among the factors that should be considered in designing a common use line are design loads and clearance requirements added to the structures by the additional circuits, hazards to personnel and property, costs, difficulties of construction, operation and maintenance. Adequate structure arrangement and conductor separation should be provided to minimize the possibility of conductor contacts, and to provide safe working conditions. Adequate electrical protection involves prompt and positive de-energization of power circuits in the event of conductor contact or flashover. Obtaining and maintaining a low ground resistance to earth is desirable to limit the magnitude of voltage rise, duration of hazardous voltage, and lightning damage.

Distribution circuits can be added to existing transmission structures only if the original transmission structure was designed for the new particular underbuild facilities or the total structure facilities meets the current edition of the NESC.

Strength Requirements

Standard distribution construction is required to meet NESC Grade C construction in accordance with 7 CFR Part 1724. However, underbuild distribution on transmission circuits, with the exception of the crossarms, are to be built to meet all requirements of NESC Grade B construction. This means that the loading on the pole due to the distribution circuits has to be calculated using NESC Grade B overload capacity factor and strength factors, it also means that all guying for the underbuild must meet the guying requirements for transmission. Distribution crossarms on transmission structures may be designed for NESC Grade C construction, except at angles where they have to be designed for NESC Grade B construction.

Line-to-Ground Clearances

Since the lowest conductors on a transmission line with underbuild will usually be those of the distribution circuits, the clearances to ground and clearances in crossing situations will in most instances be limited by the requirements stipulated in the NESC for distribution circuits.

The problem of providing satisfactory clearance becomes more involved when multiple distribution circuits or conductors cross on the same structure. In these instances, very careful attention need to be given to the allowable clearance the NESC.

Particular attention should be given to the use of reduced size distribution neutrals since the clearance to ground for the neutral, by virtue of its increased sag and position on the pole or crossarm, may be the controlling factor for pole height. In some cases, it may be more economical to increase the size of the neutral to reduce its sag.

Separation between Transmission and Underbuild Distribution Circuits

The clearances discussed in this section are intended to provide not only operating clearances but also sufficient working clearances. A distribution line worker has to be able to access and work on the distribution underbuild without encroaching upon the required safety clearances of the transmission conductors.

Horizontal Separation

The horizontal separation at the support between the lowest transmission conductor and the highest distribution conductor or neutral should be at least 1 foot if possible as illustrated in Figure 12.

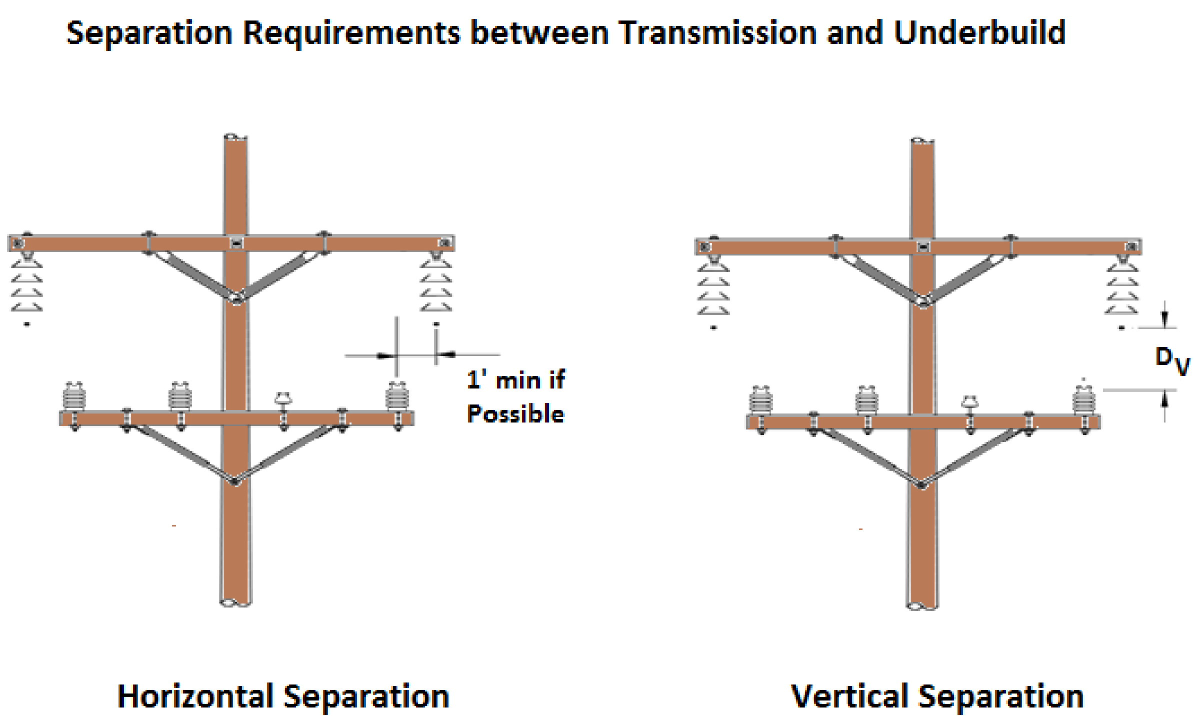


Figure 12

Vertical Clearance to Underbuild at Supports

Recommended minimum vertical clearances between the transmission conductors and the underbuild conductors at the support are shown in Table 10. These clearances apply regardless of the amount of horizontal separation between transmission and underbuild conductors.

Vertical Clearance to Underbuild at any Point in the Span

Recommended minimum vertical clearances at any point along the span are shown in Table 10.

These clearances apply for the condition below which yields the least separation between the upper and lower conductor. An upper conductor final sag at a temperature of 32F, no wind, with radial thickness of ice for the applicable loading district; an upper conductor final sag at a temperature of 167F; Upper conductor final sag at a maximum design temperature, no wind. For high voltage bulk transmission lines of major importance to the system, consideration should be given to the use of 212F as the maximum design conductor temperature.

The sag of the underbuild conductor to be used is the final sag, at the same ambient temperature as the upper conductor without electrical loading and without ice loading.

If the transmission line or portion thereof is at an altitude which is greater than 3,300 feet, an additional clearance (as indicated in Table 10) has to be added to both clearances at the structure (Category 1) and clearances at the midspan point (Category 2).

Additional Clearance Requirements for Communication Underbuild

For communication underbuild, the low point of the transmission conductors at final sag, 60F, no wind, should not be lower than a straight line joining the points of support of the highest communication underbuild.

Table 10 **Recommended Minimum Vertical Clearances to Distribution or Communication Underbuild on Transmission Lines in Feet** **(Circuits may be of the same or different utilities)** **(Based On NESC Rule 235 And Table 235-5)**							
Transmission Nominal voltage, Phase kV_{L-L} to Phase	**34.5**	**46**	**69**	**115**	**138**	**161**	**230**
Max. Operating Voltage, Phase to Phase kV_{L-L}	36.2	48.3	72.5	120.8	144.9	169.1	241.5
Max. Operating Voltage, Phase to Ground kV_{L-G}	20.2	27.9	41.8	69.7	83.7	97.6	139.4
Vertical Clearances Between Transmission and Distribution Conductors	**Clearances in Feet**						
Category 1. Clearance at the support from point of suspension of transmission conductor to point of suspension of underbuild distribution or communication conductor. Nominal underbuild voltage in kV line-to-line: (Note A)							
a. 25 kV and below (including communications conductors)	4.7	5	5.4	6.4	6.8	7.3	8.7
b. 34.5 kV	4.9	5.2	5.6	6.5	7.0	7.5	8.9
Category 2. Clearance at any point in span from transmission conductor to underbuild conductor. Nominal underbuild voltage in kV line-to-line (Note A):							
a. 25 kV and below (including communications conductors)	3.7	3.8	4.2	5.2	5.6	6.1	7.5
b. 34.5 kV	3.8	4.0	4.3	5.4	5.8	6.3	7.7
ALTITUDE CORRECTION TO BE ADDED TO VALUES ABOVE *Additional feet of clearance per 1000 feet of altitude above 3300 feet* 0.08 0.12	-	0.02		0.02	0.05	0.06	

Note:
(A) An additional 0.5 feet of clearance is added to the NESC clearance to obtain the recommended design clearances.

(B) Values for lines 1.a and b are based on,

$$V = \frac{40}{12} + \frac{0.4}{12} * (kV_{LG1} + kV_{LG2} - 8.7) + \frac{6}{12} * (Note\ A)$$

where:
kV_{LG1} = Line to ground voltage circuit one, kilovolts.
kV_{LG2} = Line to ground voltage circuit two, kilovolts.

(C) *Values for Lines 2.a and b are based on,*

$$V = 0.75[\frac{40}{12} + \frac{0.4}{12} * (50 - 8.7)] + \frac{0.4}{12} * (kV_{LG1} + kV_{LG2} - 50) + \frac{6}{12} * (Note\ A)$$

Span Length and Clearance to Underbuild

The conditions mentioned above will dictate what the minimum clearance to underbuild at the structure should be. Vertical separation at the structure may depend upon the relative sags of transmission and underbuild conductors. Since the span length has an effect on relative sags, the resulting maximum span as limited by vertical clearance to underbuild should be calculated to ensure that the vertical separation at the support is correct for each span.

The formula for maximum span as limited by clearance to underbuild is:

$$\mathbf{L_{max}} = \mathbf{RS} * \sqrt{\frac{\mathbf{A} - \mathbf{B}}{\mathbf{S_\ell} - \mathbf{S_u}}}$$

Where:
L_{max} = maximum span in feet
RS = ruling span in feet
A = allowable separation at midspan in feet
B = vertical separation at supports in feet
S_ℓ = underbuild sag at the same ambient temperature as the transmission conductor, final, in feet
S_u = transmission conductor sag at condition resulting in least separation to underbuild, final sag, in feet

Climbing Space

Climbing space through the lower circuits should be preserved on one side of the pole or in one quadrant from the ground to the top of the pole as required by the NESC. Working space should be provided in the vicinity of crossarms. Jumpers should be kept short enough to prevent their being displaced into the climbing space.

Overhead Ground Wires and Distribution Neutrals

Standard distribution underbuild construction has its own neutral. This neutral may be tied to the transmission pole ground wire in order to improve its grounding. Depending on the characteristic of the circuits, a common ground or a separate ground is acceptable. If separate grounds are used, the pole ground wires should be located on opposite sides of the pole. Similar materials should be used for both the transmission pole ground wire and for the distribution pole ground wire and ground rod. For example, if copper is used for the transmission pole ground, then copper and/or copper clad should be used for the distribution ground rod and pole ground wire. Use of similar materials will reduce the possibility of galvanic corrosion. Likewise, the distribution anchors and transmission anchors should be of similar material as the ground rods and wire used for the pole butt wraps.

For distribution underbuild on concrete transmission poles, the neutral may be tied to the external pole ground using a compression connector in locations where the neutral is to be grounded. A lead from the pole ground should then be tied to a separate ground rod via a compression connector six inches to one foot above the ground level. Similarly, in the case of steel poles, there may be situations where the neutral of the distribution underbuild is to be grounded. In these instances, the pole may be used as the ground path but not as a ground electrode. A grounding connector mounted on the pole needs to be specified just below the location of the neutral on the pole. The ground pad near the ground line should then be used to connect a driven ground rod to the pole.

Addition of Poles for Underbuild

There may be structures where it is either desirable or necessary to transfer distribution circuits to separate poles. Such situations include:

- Large Line Angles
- Substation Approaches
- Deadends
- Transformers or Regulators (Figure 13)
- Tap-offs
- Capacitors

- Sectionalizing Structures

Location of transformers on structures carrying both transmission and distribution lines should be avoided. Not only does the transformer create an unbalanced load on the structure, but the additional conductors necessary for service drops may make working on the structure hazardous to personnel. A ground rod should be installed at every pole location with a transformer and the transformer grounded per NESC requirements.

"Separation Pole" used to mount a Distribution Transformer

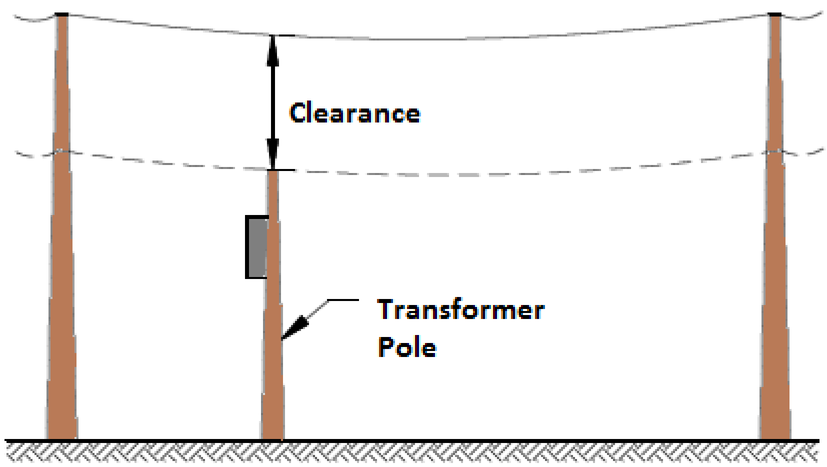


Figure 13

Guying

The need to provide additional guys to compensate for the effect of underbuild on structures is readily apparent. However, there are locations where special attention has to be given to the guying being proposed. One example is a common use pole with a line tap.

Guying Distribution Underbuild

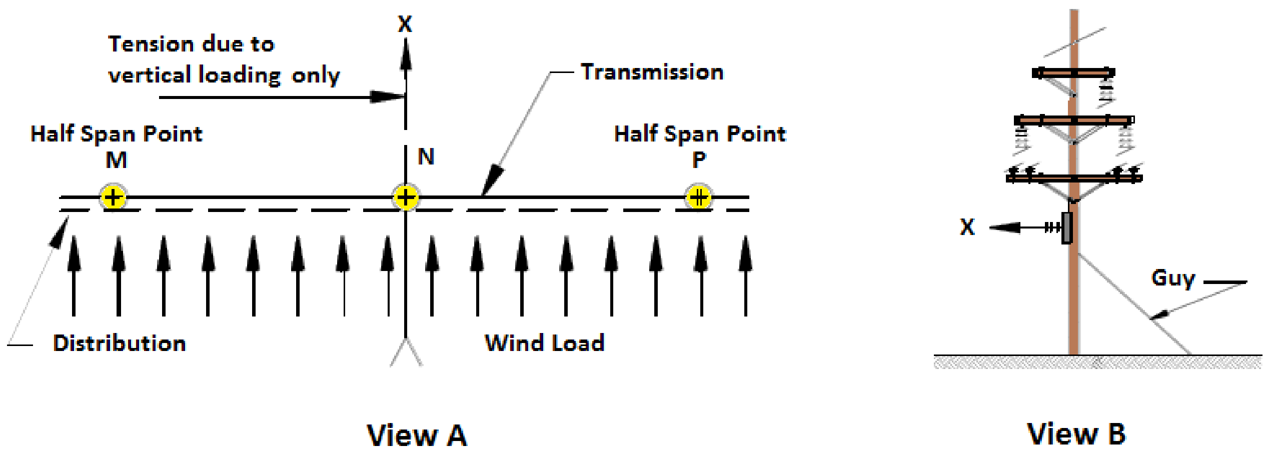


Figure 14

For winds perpendicular to the transmission line, the guying described in Figure 14 may be insufficient. This will be true if consideration has been given only to underbuild deadend tension shown as forces (x) in the figure. The maximum transverse load acts on half the sum of adjacent spans, (MN+NP)/2, of the transmission and distribution circuits.

These forces have to be added to the tensions of tap conductors in order to determine the proper amount of guying required. If winds are parallel to the transmission line, the deadend loading of the tap is larger and this load should be used. Guying of the distribution underbuild is to meet Grade B construction.

A general rule is that where the transmission circuit or the distribution circuit requires guys, both circuits should be guyed. The guys should be designed to carry the entire transverse load on the structure at maximum loading conditions. All drawings should show location and slope of guys to assure adequate clearances when guys are required. Positions of guys should be clear from other hardware or electrical connections, such as connectors between neutral and pole ground wire. Where guys may pass close to conductors, minimum required clearances must be met.

Example: Maximum Span as Limited by Clearance to Underbuild

A 69 kV single pole transmission is to be built with a 25 kV underbuild distribution circuit. Determine maximum span as limited by clearance between transmission conductors and underbuild.

Given:

- Vertical separation between transmission and distribution conductors at the structure is 11.0 ft.
- Ruling span: 300 ft.
- NESC Heavy loading district
- Conditions for the conductor:
  - Transmission conductor is at 32F with ½" ice while the distribution conductor is at an ambient temperature of 0F during the winter.
  - Transmission conductor is at 212F maximum design temperature while the distribution conductor is at an ambient temperature of 0F during the winter.
  - Transmission conductor is at 212F maximum design temperature while the distribution conductor is at an ambient temperature of 90F during the summer.

	Transmission Conductor 477 kcmil 26/7 ACSR		**Distribution Conductor 4/0 6/1 ACSR**	
	Loading Condition	**Final sag (ft.)**	**Ambient Temp**	**Final sag (ft.)**
(a)	32F 1/2" ice	4.40	0F	1.60
(b)	212F	6.73	0F	1.60
(c)	212F	6.73	90F	3.98

Solution.

From Table 10 (Category 2) the required vertical clearance at mid-span between the transmission and distribution conductors is 4.2 feet.

Next, calculate the separation between the upper and lower conductor for each loading condition given above:

11' - 4.40' + 1.60' = 8.20'
11' - 6.73' + 1.60' = 5.87'
11' - 6.73' + 3.98' = 8.25'

The condition (b) results in the least separation between the transmission and underbuild conductors; therefore, the condition (b) conductor sag values will be used in the following equation:

$$L_{max} = RS * \sqrt{\frac{A - B}{S_\ell - S_u}}$$

RS = 300
A = 4.2
B = 11
S_ℓ = 1.6
S_u = 6.73

$$L_{max} = 300 * \sqrt{\frac{4.2 - 11}{1.6 - 6.73}}$$

L_{max} = 345 feet

The maximum span as limited by the separation between the transmission conductors and the distribution underbuild is 345 feet.

For situations where greater span lengths are necessary, the separation at the structure should be increased.

Summary

The primary purpose of this series of courses is to furnish engineering information for use in designing transmission lines. Good line design should result in high continuity of service, long life of physical equipment, low maintenance costs, and safe operation. These courses presents a generalized "how to" guide for the design of a high voltage transmission line.

This first course in transmission line design has been an introduction to transmission line design including siting, plan and profile drawings, and distribution underbuild.

This series includes five volumes. For the best understanding of the material, they should be studied in order.

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