Assessment of Wind Loads On Power Lines—Methodology and Applications

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REPORT SUMMARY

Wind load on electrical conductors is one of the most critical design loads for transmission structures, but many methods of determing wind load have only recently been validated experimentally. This document draws on EPRI field research to assist engineers in accurately determining design wind loads for conductors and helping utilities construct new transmission lines and upgrade existing lines at minimum cost while retaining reliability.

Background

Many factors, such as wind gusts, span effort, drag coefficient, and air density, can affect wind loads. The methods employed to determine wind loads on conductors can be quite simple or very complex. Although wind loads on conductors are one of the most critical design loads for transmission structures, until recently, many of the methods for measuring them had not been validated experimentally. For this reason, the determination of extreme wind loads in design practice varies substantially from one utility to another as a function of the method chosen. Since 1991, EPRI has conducted extensive field wind loading experiments and has published a series of six research reports on the these experiments and related topics. However, this information is analytical in nature; and the application of the recommendations to the design or evaluation of an actual line may not be easy or direct. It was necessary to transform these important research results into design equations and guidelines that engineers can use to improve line design and evaluation.

Objectives

To provide a usable tool for design engineers to perform reliability assessments of transmission line systems based on conductor wind loading; to provide guidance to utilities for the assessment and modification of wind loading design criteria for current and future applications; to provide information to governing bodies to encourage necessary changes to applicable codes and standards.

Approach

The project team used the data previously published by EPRI and others to develop a tool for engineers to evaluate the accuracy of the various conductor wind load calculation options. They discussed the available methods and models for determining wind loads for transmission line design, including wind load procedures practiced by several utilities. They reviewed some of the important factors that affect wind loads, presented the results of EPRI field experiments, and discussed ways to improve current

wind load calculation methods. They documented the procedure for assessing wind loads on power lines, including the selection of design wind speeds, determination of various design parameters, calculation of wind loads, estimation of the return periods of wind loads, and evaluation of results. They demonstrated the application of these procedures with five examples.

Results

The procedure outlined in this document can be used for designing new lines or evaluating existing power lines for upgrade or maintenance. The document also provides a useful tool, based on wind loading, for assessing the reliability of power line systems. Guidance is provided to help utilities assess and modify their current wind loading design criteria for efficient design in future applications. The information presented in this document and previous EPRI publications can also help governing bodies of design codes, standards, and guidelines in making necessary changes to their respective codes and standards.

EPRI Perspective

The primary goal of EPRI wind loading research is to provide utilities with the information needed to define more realistic wind loads on transmission lines. The results in this document achieve that goal for wind loading on overhead conductors. The extensive analyses performed as part of the EPRI research to evaluate existing wind load models show that current practice in selecting design wind speeds is not consistent across the utility industry. Loads predicted by some wind load methods may yield unconservative results. Improved understanding of wind load methods based on field experiments can help engineers better determine wind-related loads and enable utilities to achieve long- and short-term savings for new lines and upgrade projects. The equation developed from the EPRI field experiments is not presented as a new, additional wind load calculation, but as a demonstration of how the terms in the current methods can be interpreted to generate more realistic conductor wind load estimates. The examples presented in this report will help readers understand the implications of using different methods in determining extreme wind loads. With reasonable effort engineers can apply these concepts to improve wind load procedures for designing new lines or evaluating existing lines for upgrade and maintenance. Improving these procedures can benefit utilities by reducing the costs of new lines and upgrades while maintaining current levels of reliability.

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Interest Categories

Overhead transmission structures and foundations

Key Words

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Conductor loads
Overhead transmission

ABSTRACT

This document was prepared to assist engineers in accurate determination of design wind loads for conductors and to help electric utilities realize the economic benefits associated with efficient and reliable lines.

Wind load on electrical conductors is one of the most critical design loads for transmission structures. However, many of the current wind load methods have only recently been validated experimentally. In the past several years, EPRI has conducted extensive field wind loading experiments including a comprehensive evaluation of current wind load methods. The subsequent recommendations to improve wind load prediction have appeared in several, recently published EPRI reports. Nevertheless, the application of these recommendations to the design or evaluation of an actual line requires organizing these important research findings into design equations and guidelines that can be used by engineers in practice.

This document examines some of the methods and models that are currently available for determining wind loads for transmission line design, reviews many important factors that affect wind loads, presents the results from the EPRI field experiments, and discusses ways to improve wind load calculations. A general procedure for the assessment of wind loads on power lines, which includes the selection of design wind speeds, determination of various design parameters, calculation of wind loads, estimation of the return periods of the wind loads, and evaluation of the results, can be found in this document. Examples are also provided to help readers understand the implications of using different methods in determining extreme wind loads.

The procedure outlined in this document can be used for designing new lines or evaluating existing power lines for upgrade or maintenance. Additionally, the information presented in this and related EPRI publications can be used by individual utilities and governing bodies of design codes, standards and guidelines in making necessary changes to their respective design approaches.

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INTRODUCTION

1.1 Background

Wind loads on electrical conductors are one of the most critical design loads for transmission structures. Many factors, such as wind gust, span effect, drag coefficient, and air density, can affect wind loads. The methods employed to determine wind loads on conductors can be quite simple or very complex. The simple methods, however, often neglect some of the important contributing factors while the complex methods often attempt to include most of the factors. Until recently, many of these current methods had not been validated experimentally. As such, the determination of extreme wind loads in design practice varies substantially from one utility to another.

In the past several years, EPRI has conducted extensive field wind loading experiments in Rocky Flats, Colorado, and in Haslet, Texas. These experiments were designed to investigate the major factors affecting wind loads on conductors. Extensive analyses were also performed to evaluate existing wind load models and this research yielded the following conclusions:

Current practice in selecting design wind speeds is not consistent across the utility industry;

- Loads predicted by some wind load methods may yield unconservative results;
- Use of the correct conductor drag coefficient and air density is essential in wind load calculations; and
- Improved understanding of wind load methods, based on field experiments, can help engineers better determine wind-related loads and enable utilities to achieve long- and short-term savings for new lines and upgrade projects.

Since 1992, EPRI has published a series of research reports [1, 2, 3, 4, 5, 6] on these experiments and related topics. One of these reports, *Conductor Wind Loading—Results of EPRI Field Validation Studies* (6), includes a comprehensive evaluation of current wind load methods and provides a number of recommendations to improve wind load prediction significantly in everyday practice. However, this information is analytical in nature, and the application of the recommendations to the design or evaluation of an actual line may not be easy and direct. Therefore, it is necessary that these important research results be transformed into design equations and guidelines that can be considered directly by engineers to improve line design and evaluation.

1.2 Goal

This document was prepared to assist engineers to accurately determine design wind loads for conductors and to help utilities realize the economic benefits associated with efficient and reliable lines. Specifically, the project objectives are:

- To provide a usable tool for design engineers to perform reliability assessments of transmission line systems based on conductor wind loading;
- To provide guidance to utilities for the assessment and modification of wind loading design criteria for current and future applications and;
- To provide information to governing bodies to encourage necessary changes to applicable codes and standards.

1.3 Approach

Various methods and approaches can be used to determine wind loads on conductors and frequently the methods yield different estimates of wind loads for the same set of conditions. Section 2 of this document discusses the methods and models that are currently available for determining wind loads for transmission line design. Wind load procedures practiced by several utilities are also included in the discussion.

While wind is a random phenomenon that varies in time and space, it has certain characteristics that influence the response of conductors to its force. Section 3 of this document reviews some of the important factors that affect wind loads, illustrates the results from the EPRI field experiments, and discusses approaches to improve wind load calculations. The span gust load equation, which is based on the results of the EPRI full-scale field wind loading experiments, is described in detail to demonstrate approaches to improve wind load calculations and evaluate and compare current methods.

A good wind load model alone does not guarantee that wind loads at desired reliability levels can be obtained for transmission line design and evaluation. The selection of proper design wind speeds, a task that is performed outside of the wind load model, is one of the most difficult and important tasks in the design and evaluation process. Reliance on the 50-year return period wind speed values from the current U.S. wind map (7) can sometimes lead to inefficient designs (due to the large uncertainty inherent in these values). In addition to design wind speeds, other environmental and structural parameters need to be carefully considered for use in a wind load model. Section 4 describes the procedure for the assessment of wind loads on power lines, including the selection of design wind speeds, determination of various design parameters, calculation of wind loads, estimation of the return periods of the wind loads, and evaluation of the results.

To demonstrate the application of the procedure described in Section 4, five examples are presented in Section 5. The first three examples compute conductor wind loads using several different methods and then estimate their equivalent return periods (an important component for line design and evaluation) using the wind loads computed by the span gust load equation. The purpose in presenting this equation is to demonstrate how the outcome of the recent EPRI field research can be included in wind load calculations to improve the accuracy of wind loads on power lines. The fourth example evaluates the effect of the NESC Extreme Wind loads on the NESC District loads (wind-on-ice loads), and the fifth example illustrates the use of local wind data in determining design wind speeds. These examples will help readers to understand the implication of using different methods in determining extreme wind loads.

The determination of design wind loads is more than just the computation of numbers. Most electric utility companies have internal design manuals and guidelines, and the methodologies and design equations recommended in these documents can differ markedly from one utility to another. As a result, different wind loads may be obtained by different companies for the same structure, despite the fact that the companies may operate in the same geographical area. Additionally, codes and standards always play important roles in engineering design practice. One of the reasons that companies use different approaches to determine wind loads for transmission line structures is the lack of a good national design standard. Reliability is a familiar term to most engineers. However, designing transmission lines for certain levels of reliability is not an easy task in practice. Section 6 discusses these important issues and their implications in conducting a meaningful wind loading assessment.

With reasonable effort, it is not difficult for engineers to apply concepts presented in this document to improve wind load procedures for designing new lines or evaluating existing lines for upgrade and maintenance. Section 7 provides the concluding remarks of this document.

2

WIND LOAD METHODS: AN OVERVIEW

2.1 ASCE Manual 74

American Society of Civil Engineers Manual 74 (ASCE 74) (8) is a design guide. It provides an approach for determining wind loads for transmission line design. The load and resistance factor design (LRFD) methodology is adopted by ASCE 74:

$$\gamma Q_{50} < \Phi R \qquad \text{(eq. 2-1)}$$

where

γ = Load factor (1.0 for 50-year return period, and 1.15 for 100-year return period)
Q_{50} = Load effect associated with the 50-year return period
Φ = Strength factor that accounts for the variability in strength
R = Nominal strength

The selection of Φ is not a straightforward process and some engineering judgment is required needed to achieve certain design objectives. ASCE 74 provides limited guidelines and a table for determining a proper Φ *value*.

ASCE 74 employs the same wind map used by ASCE 7-88 (7) (Figure 2-1). The map provides 50-year return period and fastest-mile wind speeds at 10 meters (33 ft.) above ground for exposure category C (open country or farmland terrain).

The ASCE 74 basic wind load equation is based on the fastest-mile basic wind speed and is written as follows:

$$F = Q(Z_v V_{fm})^2 G_w C_f dL \qquad \text{(eq. 2-2)}$$

where

F = Wind load on wire or conductor
Q = Air density factor (0.00256, at 60°F at sea level)

V_{fm} = Basic wind speed (fastest-mile at 33 ft.)
Gw = Gust response factor
C_f = Force coefficient/drag coefficient, 1.0 is typically used
d = Conductor diameter
L = Span length

$$Z_v = \text{Terrain factor} = 1.61\left(\frac{z}{z_g}\right)^{1/\alpha} \quad \text{for } 33\text{ ft} < z < z_g \qquad \text{(eq. 2-3)}$$

where

z = Height above ground (ft.)
z_g = Gradient height (ft.) (see Table 2-1)
α = Power law coefficient (see Table 2-1)

Table 2-1
Exposure Category Constants (1 ft = 0.3048 m)

Exposure Category	Power Law Coefficient α	Gradient Height (ft.) z_g	Surface Drag Coefficient κ	Turbulence Scale (ft.) L_s
B	4.5	1200	0.010	170
C	7.0	900	0.005	220
D	10.0	700	0.003	250

Three exposure categories, B, C, and D, are used in ASCE 74 to describe terrain types:

- Category B is for a suburban area
- Category C is for open country and farmland, and
- Category D is for a coastal area.

Both z_g and α values are listed in Table 2-1. Z_v is equal to 1.0 for a 33-ft. height and terrain type C. However, for the same 33-ft. height, Z_v is 0.72 and 1.18 for terrain types B and D, respectively. The different Z_v values mean that the basic design wind speed values given in the ASCE 74 wind map (terrain type C), which is shown in Figure 2-1, would be reduced by 28% for terrain type B and increased by 18% for terrain type D at the reference height of 33 ft. Engineers should exercise extra caution when using ASCE 74 to design power line structures for terrain types B and D because of the required significant modification of basic wind speeds.

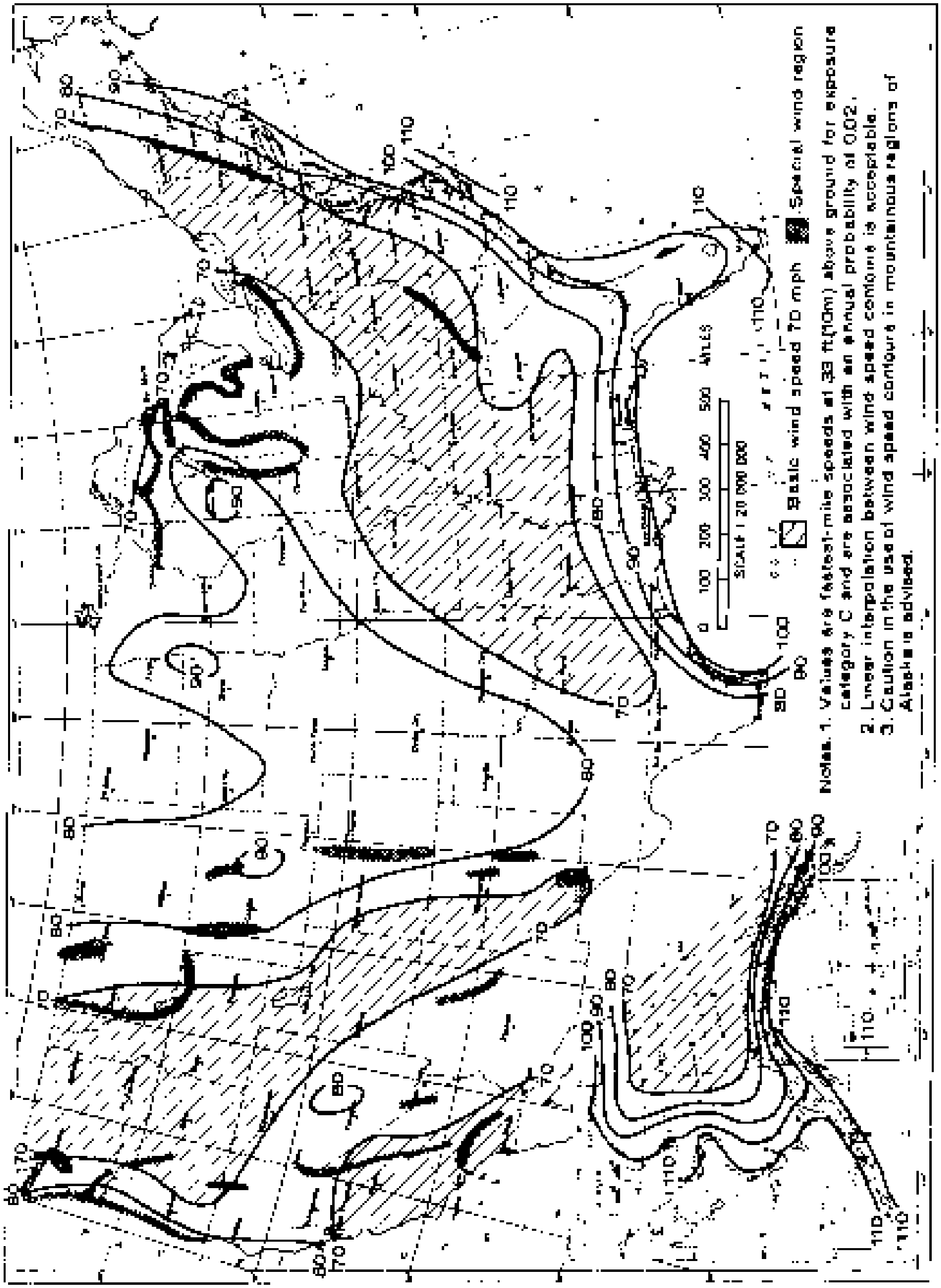

Figure 2-1
ASCE 74 Fastest-Mile Wind Speed Map (8), mph

The gust response factor G_w in Equation 2-2 is modified from the original Davenport model (9). In ASCE 74, there are two versions of G_w. One is simplified, which neglects the resonant response of the conductor. The other retains the full-form of the original Davenport model with only one exception: it uses the fastest-mile wind speed as the basic wind speed, while the Davenport model uses the 10-minute wind speed.

The following is a key to the notations used in Equations 2-4 through 2-12:

- G_w = Gust response factor for wind loading on conductor or ground wire;
- B_w = Dimensionless response term corresponding to the quasi-static background wind loading on the wire;
- R_w = Dimensionless resonant response term of the wire;
- E = Exposure factor evaluated at the effective height of the wire;
- C_f = Force coefficient for the wires;
- d = Diameter of the wire, in inches;
- f_w = Fundamental frequency for horizontal sway of the conductor, in hertz (Hz);
- g_s = Statistical peak factor dependent on the frequency characteristics of the response and sampling interval (for transmission line response and a 10-minute sampling interval of the wind), 3.5 to 4.0 (3.6 is a typical value);
- h = Total height of the structure above ground, in feet;
- K_v = Ratio of the fastest-mile wind speed to the 10-minute average wind speed in open country (Exposure C) at the 33-ft. (10-m) reference height;
- L = Design wind span, in feet;
- L_s = Transverse integral scale of turbulence, in feet (see Table 2-1 for suggested design values of various terrain types);
- S = Wire sag at midspan, in feet;
- V = Design wind speed, in mph;
- V_o = 10-minute average wind speed at the effective height of the wire, in feet per second (fps);
- Z_g = Gradient height, in feet;
- Z_o = Effective height above ground of the wires and/or structure;
- α = Power law coefficient;
- $\in$ = Approximate coefficient for separation of the conductor response terms in the general gust response factor equations (for typical transmission line systems, is approximately equal to 0.75);
- κ = Surface drag coefficient; and
- ζ_w = Wire aerodynamic damping to critical damping ratio.

Equations 2-4 and 2-5 are equations (as developed in ASCE 74) for calculating simplified and full-form gust response factors:

$$G_w(simplified) = 0.7 + 1.9\,E\sqrt{B_w} \qquad \text{(eq. 2-4)}$$

$$G_w(\textit{full-form}) = \frac{1 + g_s \in E\sqrt{B_w + R_w}}{K_v^{\,2}} \qquad \text{(eq. 2-5)}$$

where

$$B_w = \frac{1}{1 + 0.8\,L/L_s} \qquad \text{(eq. 2-6)}$$

$$E = 4.9\sqrt{k}\left(\frac{33}{Z_o}\right)^{1/\alpha} \qquad \text{(eq. 2-7)}$$

$$R_w = \frac{0.0113}{\zeta_w}\frac{Z_o}{L}\left(\frac{f_w Z_o}{V_o}\right)^{-5/3} \qquad \text{(eq. 2-8)}$$

$$K_v = 0.81\,V^{0.09}\ (20\,\text{mph} \le V \le 110\,\text{mph}) \qquad \text{(eq. 2-9)}$$

$$V_o = 1.605\left(\frac{Z_o}{Z_g}\right)^{1/\alpha}\left(\frac{88}{60}\right)\left(\frac{V}{K_v}\right) \qquad \text{(eq. 2-10)}$$

$$f_w \cong \sqrt{\frac{1}{S}} \qquad \text{(eq. 2-11)}$$

$$\zeta_w = 0.000048\frac{V_o}{f_w(d/12)}C_f \qquad \text{(eq. 2-12)}$$

Essentially, the ASCE 74 method is a derivative of the original Davenport model. However, the ASCE method does have a number of unique features. For example, ASCE uses the fastest-mile as the basic wind speed (which is consistent with current practice in the U.S.). ASCE 74 also allows for a simplified form of the gust response factor G_w in design by neglecting dynamic resonant responses of the conductor. Additionally, in attempting to adjust the blowout of the conductor, the ASCE 74 method raises the conductor height in the wind load calculation. The conductor height defined by the ASCE method, which can be significantly above the center of gravity, is equal to the height of the conductor attachment point minus one third the sum of the conductor sag and the insulator length. Such practice is likely to yield conservative results.

2.2 NESC

National Electrical Safety Code (NESC) (10), which is a code for safeguarding persons from hazards in various operating and loading conditions, is widely used in the structural design of transmission lines. In addition to employing Heavy, Medium, and Light district loadings, NESC uses this simple equation to calculate wind pressure to determine extreme wind loads on conductors:

$$p = 0.00256 V_{f-mile}^2 \qquad \text{(eq. 2-13)}$$

where

p = Wind pressure, lb/ft.^{2}
$V_{f\text{-}mile}$ = Fastest-mile wind speed, mph

Equation 2-13 assumes that the air density is equal to the value at 60°F at sea level. The wind load can be obtained by multiplying the projected area of a conductor or wire by the pressure computed from Equation 2-13.

NESC adopts the basic wind speed map from ASCE 74 for use with Equation 2-13, but because that map is based on the fastest-mile wind speed, the effect of wind gust on a line or structures is neglected when using Equation 2-13.

In NESC, overload capacity factors are used to obtain the factored loads in design, or:

$$F_{OLC} Q < R \qquad \text{(eq. 2-14)}$$

where

F_{OLC} = Overload capacity factor
Q = Load
R = Strength

The overload capacity factor F_{OLC} is related to a specific material or component that roughly represents the strength reduction of the structure. For example, in the NESC Extreme Wind load case, F_{OLC} is equal to 1.0 for steel and prestressed concrete structures. Because the overload capacity factors given by NESC are very specific, engineers can use them directly to design a line.

2.3 Companies A and B

Recognizing the inadequacies of the NESC code, companies A and B (names withheld to ensure anonymity) apply an overload factor of 1.5 instead of 1.0 to the NESC Extreme wind load case for steel and prestressed concrete structures. Accordingly, they achieve a higher level of reliability.

2.4 Company C

The method used by Company C (name withheld to ensure anonymity) to determine wind loads on conductors is a simple two-step process. First, a height factor (applied to wind pressure) is selected at the average conductor attachment point height as follows:

Table 2-2
Height Factors Used by Company C

Height h	Height Factor $(h/30)^{2/7}$
50	1.16
75	1.30
125	1.50

Then, the wind pressure on the conductor is determined by multiplying the extreme wind pressure value (obtained from a fastest-mile wind pressure map), by the height factor and an overload factor of 1.1.

2.5 Additional Wind Load Methods

2.5.1 IEC 826

The International Electrotechnical Commission (IEC) 826 is a document (11) prepared specifically for overhead transmission line design. The IEC 826 basic wind load equation is based on the 10-minute basic wind speed and is written as follows:

$$F = 1/2\ \rho\ L\ d\ C_d\ G_c\ V^2_{10min} \qquad \text{(eq. 2-15)}$$

where

F = Wind load on wire or conductor

ρ = Air density
L = Span length
d = Conductor diameter
C_d = Drag coefficient, 1.0 is often used
$V_{10\,min}$ = 10-minute average wind velocity at 33-ft. (10-meter) height, and
G_c = Combined wind factor.

In Equation 2-15, G_c – a combined wind factor that includes height, span length, and terrain adjustments – can be determined directly from the curves given in the IEC 826 document. G_c increases as ground roughness increases and also with height, but it decreases with the span length. The IEC 826 model appears simpler than the ASCE 74 method. However, due to the evolution process that took place during development of the IEC model, it cannot be determined how the terrain, span length, and height were combined to draw the combined wind factor curves in the document.

2.5.2 JEC 127

The Japanese Electrotechnical Committee (JEC) 127 (12) is the Japanese standard for transmission line structure design. Its design gust wind velocity is obtained by multiplying 10-minute basic wind speed by a gust factor:

$$V_g = g\, V_{10min} \qquad \text{(eq. 2-16)}$$

where

g = gust factor.

In Eq. 2-16, the gust factor can have three values. It is equal to:

- *1.45* for wind velocities less than 67 mph (30 m/s),
- *1.35* for wind velocities higher than 89 mph (40 m/s), and
- For wind velocity between 67 and 89 mph (30 and 40 m/s), g is determined by linear interpolation.

The design conductor wind load is calculated as follows:

$$F = \frac{1}{2}\rho C_d A V_g^2 a_1 a_2 K_1 K_2 \qquad \text{(eq. 2-17)}$$

where

F = Wind load on wire or conductor
ρ = Air density
C_d = Drag coefficient
A = Area normal to the wind direction
a_1 = Increment coefficient (height adjustment), if applicable
a_2 = "Span" reduction coefficient, if applicable
K_1 = Structure coefficient, if applicable
K_2 = Shield coefficient, if applicable

and

$$a_1 = \left(\frac{h}{h_0}\right)^{1/n} \quad \text{(eq. 2-18)}$$

where

h = Structure height
h_0 = Standard height, 33 ft. (10 m)
n = Height adjustment coefficient

and

$$a_2 = 0.5 + \frac{131.2}{S(foot)}, \text{ or } \left(0.5 + \frac{40}{S(meter)}\right) \quad \text{(eq. 2-19)}$$

where

S = Span length

The drag coefficient, C_d, for conductors covered with ice or snow is *0.95.* It is also *0.95* for ice-free conductors if *D/d* (overall diameter divided by strand diameter) is over eight, *1.05* if *D/d* is under six, and *1.0* if *D/d* is between six and eight.

3

RESULTS OF EPRI WIND LOADING RESEARCH

3.1 Vertical Wind Profile

The effective height of a conductor span normally differs from the height at which the reference velocity data were measured. Therefore, to determine the correct design wind velocity, the reference wind velocity must be adjusted to the height of the conductor.

The mean vertical wind profile describes the variation of wind velocity with height, i.e., wind velocity is zero at the surface and increases with elevation. This vertical wind profile pattern may be described by the power law of vertical wind profile, which is represented by the following equation:

$$V(z) = V_1 \left(\frac{z}{z_1} \right)^{1/\alpha} \qquad \text{(eq. 3-1)}$$

where:

z = Height above ground
$V(z)$ = Velocity at height z
z_1 = Reference height
V_1 = Velocity at the reference height z_1, and
α = Power law coefficient

The power law is an empirical equation widely adopted by various codes and standards. NESC, the only exception, does not require design wind velocity to be adjusted to the conductor height.

In general, terrain type is the sole factor in categorizing α values. In Equation 3-1, the nominal α values are as follows:

- 10 for coastal areas,
- 7 for open farmland,

- 4.5 for forest/suburban areas and
- 3 for city centers.

During the past several years, EPRI has conducted full-scale wind load experiments in Haslet, TX, and Rocky Flats, CO. Both sites are considered farmland with an α value of 7. However, the actual α values measured in the experiments cover a wide range of values. The measured α values ranged from 3.47 to 9.9 for the Haslet site, and 4.71 to 14.28 for the Rocky Flats site. The sources of wind at the Rocky Flats are winter mountain wind storms, while thunderstorm and cold front winds are the sources of wind at the Haslet site.

Although power law coefficients can vary considerably in short durations of a few minutes or seconds, the average of these values at a specific site tends to be less volatile over time. Because weather stations usually do not collect or supply power law coefficient values with yearly maximum velocity data, the coefficient values suggested by various design guides and standards must be used. The results of the full-scale experiments also indicate that if the actual field data are not available, the use of accepted nominal values of power law coefficients is adequate for making a height adjustment of the reference wind velocity in wind load calculations.

3.2 Gust Spectrum

In ASCE 74, the gust spectrum is used to derive the analytical method for predicting responses of transmission lines and structures to wind load. The form for the horizontal gust spectrum used in the ASCE 74 method is given as follows:

$$\frac{fS_u(f)}{u_*^2} = A\left|\frac{fh}{\overline{V}}\right|^{-n} \qquad \text{(eq. 3-2)}$$

where

f = Frequency
$S_u(f)$ = Spectral density of gusts at frequency f
u_* = Friction velocity
$\overline{V}$ = Mean wind speed at height h
h = Height above ground, and
A,n = Kamail's constants.

The constants, *A* and *n,* represent the amplitude and exponent value of the gust spectrum. In the ASCE 74 model, these values are approximately 0.28 for *A* and 0.67 for *n*. Estimated in another study by Kadaba (13), these values range from 0.009–0.591 for *A*, and 1.2–2.052 for *n*.

The average values of *A* measured at the Haslet site, at 33-ft., were between 0.5 and 0.6, and the average *n* values were approximately 1.0–1.25. Both numbers are higher than the nominal *A* and *n* values of 0.28 and 0.67, respectively. The average values of *A* measured at Rocky Flats, at 33-ft., were in the range of 0.8–1.2, and the average *n* values were approximately 0.7–0.9. Again, both values are greater than the nominal *A* and *n* values of 0.28 and 0.67. In both cases this is a significant discrepancy. Not only are the measured *A* values significantly higher than the values used by the ASCE 74 model, they are not constant, increasing with height. This large deviation of nominal *A* values from actual values presents one difficulty in using the ASCE 74 method to predict wind loads accurately.

3.3 Turbulence Scale

The scale of turbulence is another unique parameter used by the ASCE 74 model to account for the impact of wind gust on a transmission line. The transverse scale of turbulence measures the size of an eddy perpendicular to the wind and is expressed as follows:

$$L_y = \int_0^\infty R_{v_a, v_b}(y)\,dy \quad \text{(eq. 3-3)}$$

where

$R_{v_a, v_b}(y)$ = Cross-correlation function of fluctuation components v_a and v_b in the transverse direction and

y = Distance in the direction perpendicular to the wind.

Theoretically, if L_y is significantly shorter than the span length of a line, the effect of span gust reduction will be significant. The nominal values of L_y are 170, 220, and 250 ft., for suburban, farmland, and coastal area terrain types, respectively. The measured values of L_y at the Haslet and Rocky Flats sites varied over a wide range, from near zero to over 1000 ft. On average, L_y values for non-stationary data are longer than L_y values for quasi-stationary data. This phenomenon is expected because the correlation between two wind velocities is likely to be more significant for non-stationary data than for quasi-stationary data. (Note: A set of wind data is said to be stationary if all data points oscillate randomly about its mean value, i.e., all observations are time-independent. Strictly speaking, most wind load models are only accurate for stationary winds; however, extreme wind events in nature are non-stationary winds). Based on the large variation exhibited in the field data, using L_y of 170 to 250 ft. to account for span effect in wind load calculations is not only inadequate, but also highly questionable.

3.4 Gust Factor and Span Effect

The gust factor, *g*, is a widely used wind characteristic. If a 3-second gust wind speed and a 1-minute wind speed are of interest, the gust factor can be written as follows:

$$g = V_{3\text{-}sec} / V_{1\text{-}min} \qquad \text{(eq. 3-4)}$$

Gust factors based on the Haslet and Rocky Flats field data were estimated using Equation 3-4. The field data show that the maximum gust factors were as high as

1.7–1.9, though typically were below 1.4. The average was approximately 1.2. According to the Durst curve (Figure 3-1) adopted by ASCE 7 and ASCE 74 (7, 8), the gust factor defined by Equation 3-4 (3-second wind speed over 1-minute wind speed) for farmland terrain is approximately 1.2. This implies that the gust factor provided by ASCE 74 can be used to estimate average gust speed, not the maximum. Therefore, if a wind speed of 1-minute or other average time is known, then the average gust wind speed can be estimated by multiplying by an appropriate gust factor determined using the wind speed conversion curve in Figure 3-1.

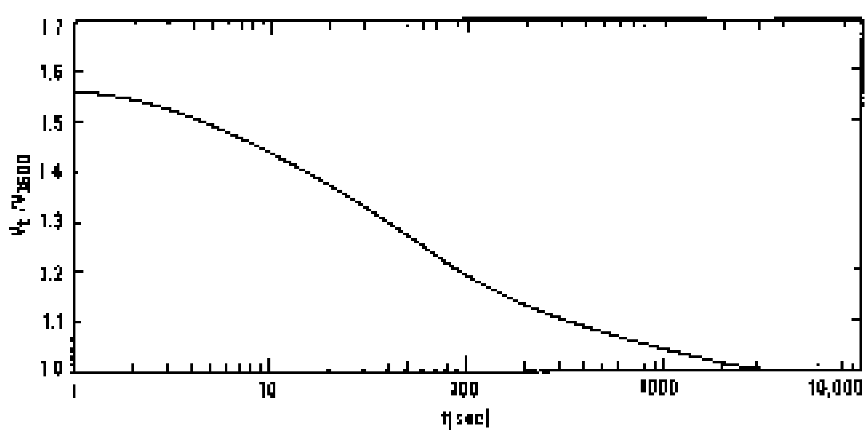

Figure 3-1
Ratio of Probable Maximum Speed Averaged over t Seconds to Hourly Mean Speed (7)

For short durations of 2 or 3 seconds, the gust wind speed at a single location along a transmission line is not likely to be the same as gust wind speeds at other locations.

Furthermore, the gust wind speed at a single point usually does not represent the average or effective gust wind speed over an entire span. In general, the effective gust speed for a span is below the gust speed at a single location. The longer the span length, the lower the effective span gust speed. This phenomenon, called "span effect," was evidenced in the Haslet and Rocky Flats data.

The expression, $0.5\rho V^2$, represents the wind pressure for a known wind speed V. Replacing V with the mean span gust wind speed (see Equation 3-8) derived from the Haslet and Rocky Flats data, the effective gust wind pressure on a conductor span can be written as follows:

$$p_{g-span}^{mean} = 0.5\rho\left(\frac{1}{1+2.13\times10^{-5}S^{1.2340}}\right)^2 V_{3-\sec}^2 = 0.5\rho S_p V_{3-\sec}^2 \qquad \text{(eq. 3-5)}$$

where

p_{g-span}^{mean} = Effective gust wind pressure,
ρ = Air density,
S = Span length,
$V_{3\text{-}sec}$ = Gust wind speed at a single location, and
S_p = Span gust wind pressure reduction factor (span reduction factor).

And S_p, the span reduction factor, is equal to:

$$S_p = \left(\frac{1}{1+2.13\times10^{-5}S^{1.2340}}\right)^2 \qquad \text{(eq. 3-6)}$$

Figure 3-2 plots two span reduction curves that are based on:

- Equation 3-6, which in turn, was derived from the field data obtained at the Haslet and Rocky Flats sites and
- Equation 2-19, which is taken from JEC 127.

From the curve based on Equation 3-6, one can see that the span reduction factor:

- Is 1.0 if the span length is zero,
- Decreases as the span length increases and
- Is about 0.81 at 1,000 ft.

From the curve based on Equation 2-19, one can see that the span reduction factor:

- Is 1.0 if the span length is 262.4 ft.,
- Decreases rapidly as the span length increases and
- At 1,000 ft, is about 0.63, a value significantly lower than the value of 0.81 given by Equation 3-6.

Additionally, a constant span reduction factor of 0.85 has been cited in literature.

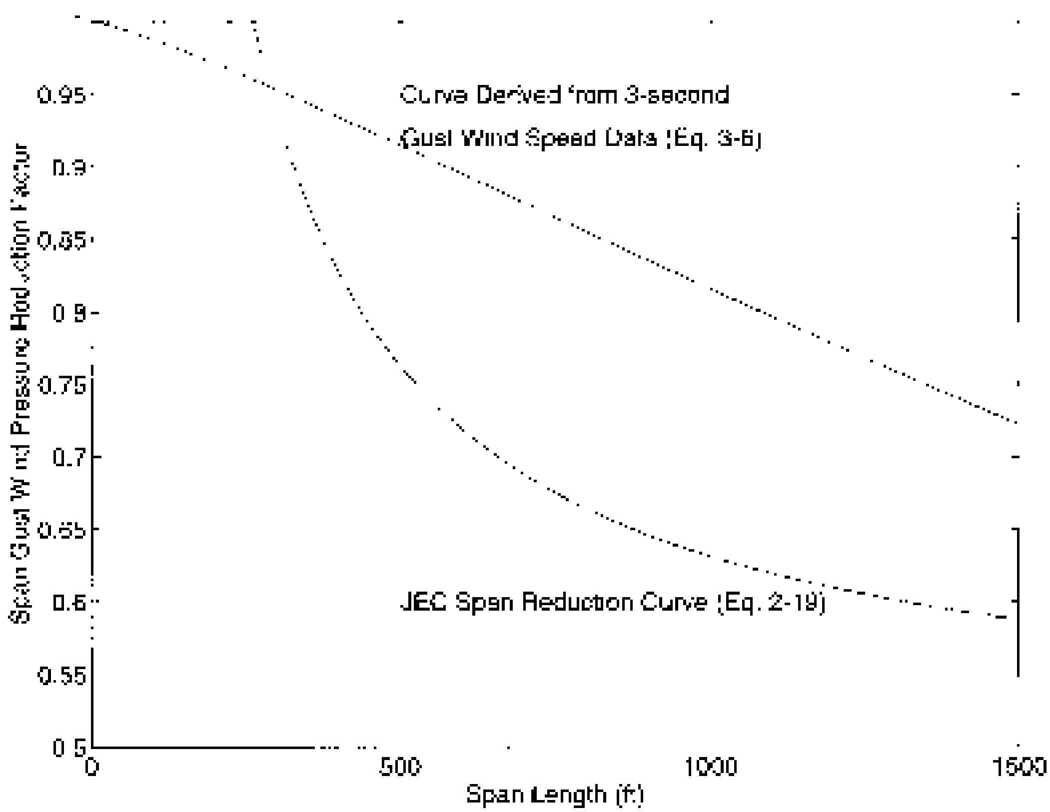

Figure 3-2
Reduction of Gust Wind Pressure on a Span

3.5 Drag Coefficient

In practice, it is common for a drag coefficient of 1.0 to be assumed for all types of conductors. However, the conductor drag coefficient is a function of wind velocity, conductor diameter, and surface characteristics of the conductor, and it varies with the Reynolds number.

Conductor drag coefficients typically are determined by wind tunnel testing. In the past, there were a number of unresolved issues regarding the use of wind tunnel drag coefficients in wind load calculations; however, a previous EPRI study (2) verified that drag coefficients measured in wind tunnels are comparable to the results obtained in field conditions. Additionally, to assess the effect of drag coefficients on wind loads, measured wind loads from the Haslet and Rocky Flats field experiments were compared to the calculated wind loads, which included wind tunnel drag coefficients in the calculations. The results indicated that the inclusion of drag coefficients in wind load calculations noticeably improved the correlation between the calculated loads and the field data.

Figure 3-3 shows the wind tunnel drag coefficient data for a Chukar conductor (14), which is smaller in diameter than the Bluebird conductor used in the Haslet and Rocky Flats field experiments but has the same surface characteristics. To help improve wind load calculations in design, it is important for engineers to have access to a wind tunnel drag coefficient data base covering various types of conductors.

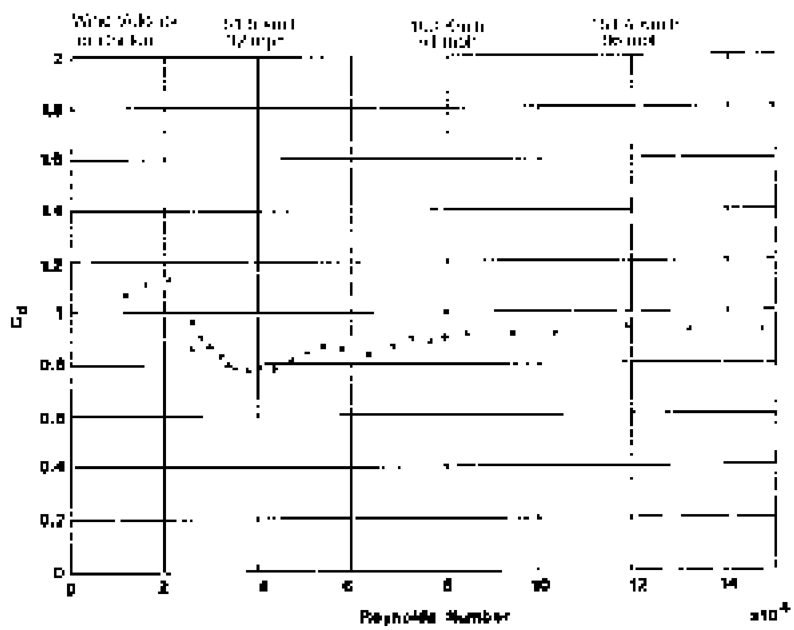

Figure 3-3
Drag Coefficients of Chukar Conductor—Alcoa Wind Tunnel Data (14)

3.6 Air Density

The calculated wind load is a linear function of air density: If air density varies by 10%, the wind load will change by 10%. For example, during the wind load experiment at the Rocky Flats site, the actual air density at its relatively high elevation was often 20% lower than the nominal air density at sea level at 60°F. If all other factors were equal, the wind load calculated for Rocky Flats would be 20% lower if actual air density was used in the wind load calculation.

Air density changes with temperature and elevation, and these variations can be significant from area to area. Accordingly, an adjustment in air density for the line route is appropriate. If the normal temperature during high wind seasons is obtainable and because the elevation of a site is always known, the appropriate air density value for computing design wind loads can be selected from Table 3-1 (converted from Table

D-1, Appendix D, ASCE 74). As long as it is coupled with sound engineering judgment, such a practice should be encouraged.

Table 3-1
Air Density (lb./ft.3) (1 lb/ft3 = 16.02 kg/m3, 1 ft = 0.3048 m)

		Elevation Above Sea Level (ft)					
Air Temp.		0	2000	4000	6000	8000	10000
-40°F,	#°C	0.09486	0.08798	0.08170	0.07601	0.07092	0.06584
-20°F,	#°C	0.08768	0.08409	0.07811	0.07272	0.06763	0.06284
0°F,	#°C	0.08649	0.08020	0.07451	0.06943	0.06464	0.06015
20°F,	-7°C	0.08289	0.07691	0.07152	0.06673	0.06195	0.05746
40°F,	4°C	0.07960	0.07392	0.06883	0.06404	0.05955	0.05536
60°F,	16°C	0.07661*	0.07092	0.06614	0.06135	0.05716	0.05327
80°F,	27°C	0.07362	0.06853	0.06374	0.05925	0.05506	0.05117
100°F,	38°C	0.07122	0.06614	0.06135	0.05716	0.05297	0.04938

* Nominal value

3.7 Basic Wind Speed

The averaging times associated with wind speeds—i.e., 2 seconds, 3 seconds, 1 minute, 10 minutes, hourly, or fastest mile—should always be specified. (Note: Wind speeds that are averaged over 2 or 3 seconds are referred to as gust wind speeds.)

In the U.S., the basic wind speeds most commonly used for design are the fastest-mile wind speeds. The averaging time of a fastest-mile wind speed varies with its magnitude, e.g., the averaging time is 1 minute at 60 mph, and decreases to 30 seconds at 120 mph.

The basic wind speeds given in ASCE 74 are fastest-mile wind speeds. However, it was demonstrated by the Haslet and Rocky Flats field data that gust wind speeds are more closely related to the peak conductor loads than either the fastest-mile wind speeds or other wind speeds with long averaging periods. In predicting peak conductor loads, the results based on the 3-second reference wind speeds were superior to the results based on the 1-minute reference wind speeds. Statistically, a 3-second reference wind speed is more closely related to the effective span gust speed than a 1-minute reference wind speed.

Gust speeds may be obtained by multiplying gust factors by reference wind speeds. However, the Haslet and Rocky Flats field data indicated that using gust factors to convert wind speeds of one averaging time to wind speeds of another averaging time may not provide the best results, especially when non-stationary wind events are considered. Additionally, using the 3-second gust speed as the basic wind speed reduces the need for gust factors.

Recognizing the drawbacks of using the fastest-mile wind speed as the basic wind speed, the committee on “ASCE 7-95 Minimum Loads for Buildings and other Structures” recently adopted the 3-second wind speed for its basic wind speed map. The results of the EPRI wind load research support the use of the 3-second gust speed as the basic wind speed in design.

3.8 Conductor Response

One factor that needs clarification is the averaging time of a gust load. An often-asked, but difficult to answer question is, “How much time must pass before a structure responds to gust loads and incurs irreversible damage?” The proper averaging time may be related to the response characteristics of the conductor span as well as the structure.

The analysis of the field wind load data showed that the quasi-static wind loads based on 3-second effective span gust wind speeds correlated well with the 3-second measured gust loads, while the dynamic resonant responses of the conductor appeared to be insignificant. On the other hand, if the averaging factor is defined as the ratio of a 1-second load divided by loads of different averaging times, this factor can be used to convert gust loads from one averaging time to another. On average, the 1-second gust load was 1.03 times greater than the 3-second gust load and 1.054 times greater than the 5-second gust load. The differences in the measured gust loads using different gust load averaging times were noticeable but small. In general, the ratios increased as the averaging time increased. To calculate gust loads for different averaging times, one can use the conversion curve in Figure 3-4 to determine the appropriate averaging factors. This curve was generated using the Haslet and Rocky Flats field data.

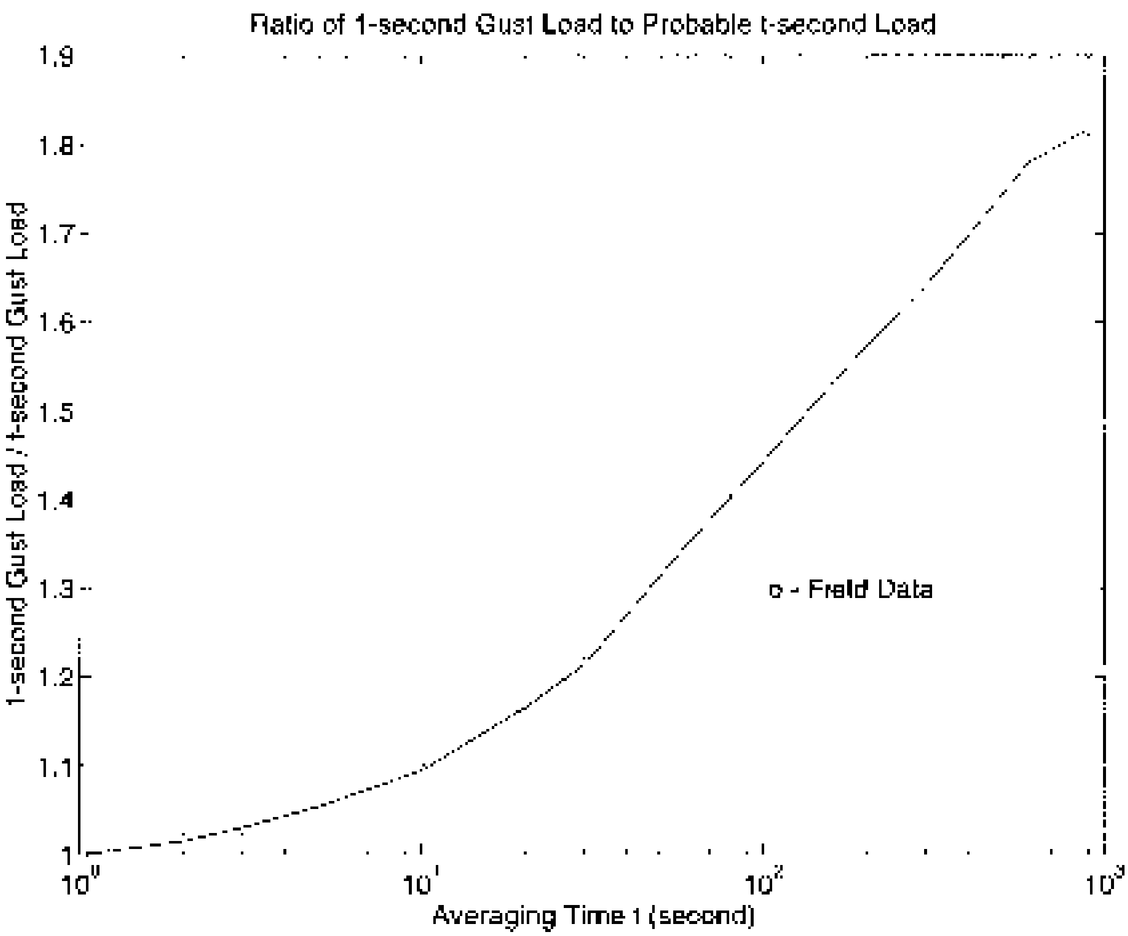

Figure 3-4
Ratio of 1-second Gust Load to Probable t-second Load

3.9 Span Gust Load Equation Based on EPRI Field Experiments

One of the most useful outcomes of studying the span effect of the Haslet and Rocky Flats data was the establishment of quantitative relationships between the reference wind speed and the effective span gust speeds. For the purposes of this report, the wind load equation based on these relationships is referred to as the span gust load equation. The purpose in presenting this approach is to demonstrate how the outcome of the recent EPRI research can be included in wind load calculations to improve the accuracy of wind loads on power lines. In many respects this approach is primarily a method to estimate mean gust wind speeds over different span lengths. The equation for calculating mean span gust loads is:

$$P_c = \frac{1}{2} f_a \rho L d (V_{g-span}^{mean})^2 \quad \text{(eq. 3-7)}$$

where

P_c = Mean gust load for a given conductor or wire span
f_a = Conductor response averaging factor (f_a = 1.0 for a 3-second gust load)
ρ = Actual air density
L = Span length
d = Conductor diameter
C_d = Wind tunnel drag coefficient, and
V_{g-span}^{mean} = 3-second mean span gust velocity estimated from reference velocity (using the following power law and equations).

The following two equations for estimating 3-second mean span gust wind speeds were derived using the Haslet and Rocky Flats field data. One equation is based on the

1-minute reference wind speed, and the other is based on the 3-second wind speed.

$$V_{g-span}^{mean} = \frac{1.1773}{1 + 3.02\text{x}^{-6} S^{1.4858}} V_{1-\min} + 2\text{mph} \quad \text{(eq. 3-8)}$$

$$V_{g-span}^{mean} = \frac{1}{1 + 2.13\text{x}^{-5} S^{1.2340}} V_{3-\sec} \quad \text{(eq. 3-9)}$$

where

S = Span length,
$V_{1\text{-}min}$ = 1-minute reference wind speed and

$V_{3\text{-}sec}$ = 3-second reference wind speed.

Equations 3-8 and 3-9 are functions of span length. As the span length increases, the effective span gust speeds decrease. Using Equations 3-8 and 3-9, we are now able to estimate span gust speeds for various span lengths from 3-second and 1-minute reference wind speeds.

4

PROCEDURE FOR THE ASSESSMENT OF WIND LOADS

4.1 Selection of Design Wind Speeds

4.1.1 Source of Design Wind Speeds

The wind velocity used by an engineer to design a transmission line can come from a variety of sources. Often a utility employs a velocity value that has been derived from years of experience (e.g., 100 mph plus an overload factor). These customized velocity values may work well for the particular utility, but they cannot be used by utilities located in other areas.

The National Climatic Data Center (NCDC) periodically publishes a summary report of climatic averages and extremes, including the historical maximum wind speed, for more than 200 U.S. cities (15). With sound engineering judgment, these values can be converted into design wind speeds. NCDC also can provide, on tape or hard copy, weather data that have been gathered from various stations all over the U.S., but engineers have to perform their own data analyses to obtain the extreme values for their service areas.

The wind map used by ASCE 7-88 (7) and ASCE 74 (8) is probably the most widely cited source of design wind speed values in the U.S. (Figure 2-1). It is based on the extreme value analysis of annual fastest-mile wind speeds from 129 stations in the U.S. and a Monte Carlo simulation of hurricane data. The map provides 50-year return period, fastest-mile wind speeds at 33 ft. above ground for exposure C category and covers the entire U.S. based on a very limited amount of wind data. Because of its large scale, however, it cannot show local variations of the annual maximum wind speeds. In general, the ASCE map may not be used when localized effects must be considered. Although basic wind speeds for hurricane regions are also shown on the map, caution should be exercised when using these values in hurricane-prone regions due to the limited amount of hurricane data used in generating this map.

A utility's service area may extend over hundreds, even thousands, of square miles, and the climatic and topographical conditions within that service area can vary drastically. As such, it can be very difficult to determine the most cost effective design wind speeds for that service area using the ASCE wind map or wind data from a distant station. However, if local wind data are available for a specific site or area, the maximum wind speed associated with a predefined return period (e.g., 50 years) can be estimated using certain statistical techniques (16). In the past, a number of utilities have conducted various climatic condition studies (17, 18, 19, 20, 21, 22, 23) to establish loading criteria for a particular site or even an entire service area.

4.1.2 Evaluation and Development of Design Wind Speeds

When assessing the wind loads for a particular transmission line, one of the primary concerns is the selection of an appropriate design wind speed. Typically, utilities have internal design manuals that specify extreme wind speed values. However, before these values are used in line assessment, it is important that engineers know the origin of these extreme wind speed values and the averaging times of the design wind speeds.

If an averaging time cannot be determined, it is likely that the available design wind speeds are empirical values not directly derived from historic wind speed data. For example, a utility may use the design wind speed of 100 mph plus an overload factor of 1.1 for its service territory without any direct relation to the local wind history. However, it is recommended that engineers search for local wind maps or equivalent design wind values developed for the territory serviced by the utility. If this type of information cannot be found, the ASCE 74 wind map (Figure 2-1) can be consulted with caution.

Additionally, if the design values used by a utility are based solely on the ASCE 74 fastest-mile wind map, the engineers should search for local wind maps or other equivalent design wind values applicable to the utility's service area. When approached properly, design values based on local wind data may be more credible than values taken from the ASCE 74 map.

When both the empirical design wind speeds and the values given by the ASCE 74 wind map do not appear realistic, and there is no readily available data to prove or disprove them, it is recommended that a local area wind study be conducted to determine the proper wind speed for design. A simple approach would include browsing weather reports published by NCDC and contacting local weather stations. A comprehensive approach would include performing extreme value analyses of the historic wind data and developing local area wind maps.

If the design wind speeds used by a utility were derived from historic wind data, they are most likely fastest-mile, 1-minute, or 10-minute wind speeds, i.e., they are not based on peak wind speed data. However, the results of EPRI wind load research show that the gust load is closely related to the gust wind speed, and the use of 3-second reference wind speeds can improve wind load calculations. Therefore, to improve their wind load predictions, it is advisable for utilities to generate design wind speeds based on local peak wind speed data.

Note: The ASCE 7 committee has recently published a new wind map for the U.S. that is based on 3-second gust wind speeds. In the new map, a gust wind speed of 90 mph covers most of the country, except for the hurricane-prone regions. However, due to some limitations in the approach and also the data used in developing this new 3-second gust map, the values given in the map do not reflect wind speed variations at local levels. Using a 3-second averaging time to define wind speeds is the correct approach, but using a single 90-mph gust wind speed value for transmission line design over most of the U.S. may not lead to the most cost effective designs and upgrades. Therefore, it is recommended that a utility wanting to adopt 3-second design wind speeds for the design of transmission lines use local area gust wind maps, not simply the new ASCE 7 gust wind map.

Utilities that decide to generate wind maps that are specific to their operating area should consult experts for assistance. However, in 1996, EPRI will prepare a guideline document for generating local area wind maps, and utilities may want to use this as a guide to generating their own local area wind maps.

4.2 Selection of Other Design Parameters

In addition to design wind speeds, a number of other design parameters must be defined before wind load calculations can be performed. The following is a summary of some of those parameters:

Power law coefficient α: Unless the α value was determined from actual field data, the nominal α values should be used (10 for coastal areas, 7 for open farmland, 4.5 for forest/suburban areas, and 3 for city centers).

Effective conductor height: The effective conductor height is located at the center of gravity of a conductor span under a no-wind condition and is given by the following equation:

$$H_{cg} = T_{height} - I_{length} - \frac{2}{3} C_{sag} \qquad \text{(eq. 4-1)}$$

where

T_{height} = Structure height at insulator to structure attachment point,

I_{length} = Insulator length, and
C_{sag} = Conductor sag.

Equation 4-1 does not account for the effect of blowout of the conductor as the wind speed increases. For wind speeds of less than 100 mph, the effect is fairly small and can be neglected in wind load calculations. However, for wind speeds over 100 mph, it is prudent to properly adjust C_{sag} and I_{length} to raise the effective height for wind load calculations.

Conductor drag coefficient: In practice, a drag coefficient of 1.0 is assumed for all types of conductors; however, most design procedures allow the use of actual drag coefficients in wind load calculations. For many round-strand conductors, actual drag coefficients often differ from 1.0 by a noticeable amount in the design wind speed range, and the actual drag coefficients for trapezoidal conductors can change even more dramatically than for round-strand conductors.

Using the actual drag coefficient in wind load calculations can improve the wind load prediction. Unfortunately, the consistent, comprehensive conductor drag coefficient data base necessary for design does not exist.

If available, the actual drag coefficients obtained from quality wind tunnel testing are recommended for use in wind load calculations. If they are not available, a drag coefficient of 1.0 may continue to be used with round-strand conductors. However, EPRI is conducting wind tunnel testing to generate drag coefficient curves for families of round-strand conductors. Once this data is available, it may be used to improve wind load prediction for round-strand conductors. For trapezoidal-strand conductors, individual wind tunnel testing is highly recommended to obtain drag coefficients over the design wind speed range.

Air density: Air density is a function of temperature and elevation. Although some design codes permit the use of the actual air density of the area under consideration, few engineers do so because they typically do not know either the seasons in which extreme wind events are likely to occur or the average temperature during the extreme wind events. However, because such information is easily obtained by contacting NCDC or at local libraries, it is recommended that design engineers include a realistic air density value in their wind load calculations, provided that the location of the line is known.

Table 3-1 can be used to determine the air density value if temperature and elevation information is available. The nominal air density in ASCE 74, and other sources, is typically about 0.0766 lb./ft.^{3}, sea level at 60°F.

Others: In addition to the parameters discussed previously, other parameters may be required by some wind load methods. For example, the ASCE 74 method is a comprehensive approach for predicting the peak response of a conductor during a steady wind event that has certain characteristics. Wind parameters, such as gust spectrum coefficients, scales of turbulence and surface drag coefficients, are necessary ingredients for this model to be able to predict wind loads.

Most of the codes, or design procedures, either provide guidance on how to determine these parameters or simply list their nominal values. However, from the discussion in Sections 3.2 and 3.3, not only are the actual values of some parameters difficult to obtain, they also can be very different from the nominal values. Engineers need to understand that a large variation in these parameters can diminish or negate the intended benefits of including them in wind load calculation.

One difficulty in determining wind parameters is that terrain is the only measure for categorizing the wind. Undoubtedly, terrain can modify the characteristics of the wind traveling over it, however, the sources of traveling winds can be very different and can possess unique characteristics independent of terrain. Depending on the source (thunderstorms, cold fronts, hurricanes, etc.), non-stationary high winds with very different turbulence characteristics can occur over the same parcel of land. The conventional assumption is that the same terrain characteristics will have the same turbulence characteristics. This assumption may not be appropriate under these circumstances. To better determine wind loads in design, engineers may want to study known localized conditions that could have an effect on the characteristics of wind and select proper values for some of the parameters accordingly.

4.3 Wind Load Calculations

4.3.1 Wind Speed Conversion

The wind speeds selected by a utility for power line design can come from different sources, and the averaging times of the design wind speeds can also vary. The wind speeds of one averaging time may need to be converted to the wind speeds of another averaging time for each of the respective wind load methods. Figure 3-1 is the wind speed conversion curve used by ASCE 7 and ASCE 74. The equation representing this curve is given as follows:

$$\begin{aligned}\frac{V_t}{V_{3600}} &= 6.68326\times10^{-6}(\ln t)^7 - 1.83894\times10^{-4}(\ln t)^6 + 1.89848\times10^{-3}(\ln t)^5 \\ &- 9.06946\times10^{-3}(\ln t)^4 + 2.21314\times10^{-2}(\ln t)^3 - 4.26399\times10^{-2}(\ln t)^2 \\ &- 3.53686\times10^{-3}(\ln t) + 1.55968\end{aligned} \quad \text{(eq. 4-2)}$$

where

t = Averaging time (seconds),
V_{3600} = Hourly wind speed, and
V_t = t-second wind speed.

Equation 4-2 was produced by curving-fitting based on Figure 3-1. It can be added to a computer program or used in a spreadsheet.

Another useful equation for wind speed conversion is the equation for computing the averaging time of fastest-mile wind speed. This equation is as follows:

$$t_{f\text{-}mile} = 3600/V_{f\text{-}mile} \quad \text{(eq. 4-3)}$$

where $t_{f\text{-}mile}$ is the averaging time (seconds) and $V_{f\text{-}mile}$ is the fastest-mile wind speed (mph).

Three examples, listed below, illustrate the use of these two equations in wind speed conversions:

Example 1: Converting fastest-mile wind speed to 1-minute wind speed

$V_{f\text{-}mile} = 90$ mph; $t_{f\text{-}mile} = 3600/90 = 40$ seconds;

$V_{40}/V_{3600} = 1.2935$; $V_{60}/V_{3600} = 1.2477$

$V_{60} = 90\times1.2477/1.2935 = 86.8$ mph

Example 2: Converting 3-second gust speed to 1-minute wind speed

$V_3 = 90$ mph;

$V_3/V_{3600} = 1.5232$; $V_{60}/V_{3600} = 1.2477$

$V_{60} = 90\times1.2477/1.5232 = 73.7$ mph

Example 3: Converting to 1-minute wind speed to fastest-mile wind speed

$V_{60} = 90$ mph; $V_{60}/V_{3600} = 1.2477$

Select an averaging time of 38.45 seconds using the trial-and-error method,

$V_{f\text{-}mile1} = 3600/38.45 = 93.6$ mph;

$V_{38.45}/V_{3600} = 1.2980$; $V_{f\text{-}mile2} = 90\times1.2980/1.2477 = 93.6$ mph;

$V_{f\text{-}mile1} = V_{f\text{-}mile2}$; $V_{f\text{-}mile}$ = 93.6 mph.

4.3.2 Selection of Wind Load Methods

Company Methods: If a utility has in-house wind load design procedures, these procedures should be used to calculate wind loads for line assessment and design. However, the loads determined with these procedures should be compared to the loads computed with other methods to better understand how different methods predict wind loads. It is also recommended that the company make an earnest effort to verify its existing wind load design procedure. If it is determined that the current procedure provides unfavorable results, the company may want to adopt elements of the span gust approach described in Section 3.9.

NESC: Although NESC is simply a safety code, many companies are required to design transmission lines to meet NESC specifications as a minimum requirement. For some companies, NESC might be the only required loading criteria. For these companies, the NESC wind load method should be among the methods selected for determining wind loads. However, it is highly recommended that power lines not be designed according to NESC specifications alone.

For companies not required to comply with NESC, it is recommended that the NESC method be ignored for wind load calculations because power lines should be designed for gust loads, and the NESC method (actually only a wind pressure equation) is incapable of determining gust loads.

ASCE 74: Since publication of the latest edition in 1991, some utilities have tried to use ASCE 74 in the design of power lines. However, because ASCE 74 is only a guideline, the majority of utilities have opted not to use it in design. Several reasons that may have prevented companies from adopting the ASCE 74 guidelines include:

- The methodology used by ASCE 74 can be very difficult to understand, and the theory behind the design equations is complicated and not yet verified by full-scale field wind load experiments,
- ASCE 74 offers two versions of the method for wind load calculations, yet the wind loads computed using the simplified version in the main section can be significantly different from those using the full-form version in the appendix,
- The full-form equations are very complicated and difficult to use in design and
- ASCE 74 is not a design standard, and companies have no obligation to use it.

Nevertheless, ASCE 74 is the only national loading guideline available for transmission lines. Engineers may wish to use it in conjunction with other methods.

***Span Gust Load Equation**:* The span gust load equation (Eq. 3-7), based on recent EPRI research, is a modified version of the basic wind pressure equation. It estimates the mean gust load on a conductor span by accounting for mean wind gusts and spatial effects in wind load calculations. The mean span gust speeds are estimated from the reference wind speeds using equations developed from field data.

If wind speed and a few other design parameters are well-defined, this approach based on field wind data comparisons provides the very reliable and accurate wind load estimates. In addition to the summary provided in Section 3.9 of this document, the details on the development of this approach and the related field verification of the approach can be found in Ref. (6).

4.4 Estimation of Equivalent Return Periods

4.4.1 Gumbel Distribution for Annual Maximum Wind Speeds

Design wind speeds of various reliability levels can be determined directly from annual maximum wind speed data. Typically, a Gumbel (Extreme Type I) distribution is assumed to describe annual maximum wind speeds. For annual maximum wind speeds V, with mean wind speed $\overline{V}$, and standard deviation σ_V, the cumulative distribution function is:

$$F(V) = \exp\left\{-\exp\left[-\frac{C_1}{\sigma_V}\left(V - \overline{V} + \frac{C_2}{C_1}\sigma_V\right)\right]\right\} \qquad \text{(eq. 4-4)}$$

where C_1 and C_2 are constants based on the number of observations. Table 4-1 lists C_1 and C_2 values starting at 10 observations. As the number of observations goes to infinity, C_1 and C_2 are equal to 1.2826 and 0.5772, respectively.

Table 4-1
Constants C1 and C2

Observations	C1	C2
10	0.9497	0.4952
15	1.0206	0.5128
20	1.0628	0.5236
25	1.0915	0.5309
30	1.1124	0.5362
40	1.1413	0.5436
50	1.1607	0.5485
∞	1.2826	0.5772

The cumulative probability $F(V_{RP})$ for an extreme wind speed with a return period of *RP*, V_{RP}, can be expressed as:

$$F(V_{RP}) = 1 - \frac{1}{RP} \qquad \text{(eq. 4-5)}$$

Combining Equations 4-4 and 4-5:

$$V_{RP} = \overline{V} + \left\{ -\ln\left[-\ln\left(1 - \frac{1}{RP} \right) \right] - C_2 \right\} \frac{\sigma_V}{C_1} \qquad \text{(eq. 4-6)}$$

If local wind data is available, Equation 4-6 can be used to generate the design wind values for a local area wind map. For meteorological data, *RP* can be either years or months.

4.4.2 Equivalent Return Periods

One approach to measuring the reliability of lines in resisting wind loads is to use the return periods of the design wind speeds (a 50-year wind speed means that, on average, the extreme wind speed of this magnitude will occur once every 50 years). However, for various reasons, different methods may compute different wind loads, even if the same design wind speeds are used. Therefore, if wind loads are computed using the 50-year return period wind speeds and Method A, we can only say they are 50-year wind loads based on Method A.

The span gust load equation discussed in Section 3.9 was largely developed with field data, and EPRI research has demonstrated its effectiveness. This approach can produce more accurate results than other methods if design parameters are reasonably defined. Therefore, the wind loads computed using the span gust load equation can be used as a basis, or reference, for comparing results computed by other methods. Because wind load is primarily a function of the square of the wind speed, the RP_1-year wind loads based on the span gust load equation and another method called Method A may be simplified as follows:

$$L_{RP_1,span-gust}(V_{RP_1}) = aV_{RP_1}^2 \quad \text{(eq. 4-7)}$$

$$L_{RP_1,Method-A}(V_{RP_1}) = bV_{RP_1}^2 \quad \text{(eq. 4-8)}$$

where *a* and *b* underline the difference between the span gust load equation and Method A. Since the Method A wind loads are different from the results obtained using the span gust load equation, the equivalent return period (RP_2) of the Method A wind loads based on the span gust load equation can be estimated by first establishing the following equation:

$$L_{RP_1,Method-A}(V_{RP_1}) = L_{RP_2,span-gust}(V_{RP_2}) = aV_{RP_2}^2 \quad \text{(eq. 4-9)}$$

then, divide Equation 4-9 by Equation 4-7 and define the wind load difference ratio β as:

$$\beta = \frac{L_{RP_1,Method-A}}{L_{RP_1,span-gust}} = \frac{V_{RP_2}^2}{V_{RP_1}^2} \quad \text{(eq. 4-10)}$$

and let:

$$\sigma_V = C_3\overline{V} \quad \text{(eq. 4-11)}$$

where C_3 reflects the variation of annual maximum wind speeds (a value of 0.2 may be used if the actual data is not available).

Equation 4-10 can be rewritten as follows:

$$\beta = \frac{V_{RP_2}^2}{V_{RP_1}^2} = \left(\frac{1 + \frac{C_3}{C_1}\left\{ -\ln\left[-\ln\left(1 - \frac{1}{RP_2}\right)\right] - C_2 \right\}}{1 + \frac{C_3}{C_1}\left\{ -\ln\left[-\ln\left(1 - \frac{1}{RP_1}\right)\right] - C_2 \right\}} \right)^2 \qquad \text{(eq. 4-12)}$$

solving for RP_2, the following equation is obtained:

$$RP_2 = \frac{1}{1 - \exp\left\{ -\exp\left[-\left(\frac{C_1}{C_3}\left(C_4\sqrt{\beta} - 1\right) + C_2 \right)\right]\right\}} \qquad \text{(eq. 4-13)}$$

where

$$C_4 = 1 + \frac{C_3}{C_1}\left\{ -\ln\left[-\ln\left(1 - \frac{1}{RP_1}\right)\right] - C_2 \right\} \qquad \text{(eq. 4-14)}$$

4.5 Evaluation of Results

Once equivalent return periods are obtained, it may be determined that the reliability levels of the original design loads for existing power lines are significantly different from the target level. If the reliability levels are below the target level, the following steps should be taken:

- Check the design wind speed—it may not be correct if it was not derived from actual wind data;
- Reevaluate other design parameters—if nominal values were used in the wind-load calculation, additional investigations should be conducted to determine the actual values;
- Re-compute wind loads—a change in design parameters can result in loads significantly different from those obtained in the initial wind-load calculation.

If these steps result in reliability levels that are still below the target level, the engineer should take actions to strengthen the lines in question to ensure reliable operation. In addition, the company should consider revising its wind load design procedure.

If the results are above the target level and the engineer wishes to upgrade the line, the additional wind loads above the current design loads can be estimated for the redesign of the line by using the procedure outlined in this document. To achieve better results, the engineer may wish to evaluate further the various design parameters used in the initial calculation. If a lower wind load estimate than the original design wind load is achieved following the wind load procedure recommended in this document, the utility may also want to make some change in its current design procedure to allow for the utilization of the extra capacity in the existing lines.

5

EXAMPLES

5.1 Introduction

For a better understanding of the implications of using different methods to compute extreme wind loads, four such methods and the span gust load equation were selected for use in four examples that are presented later in this section. Fifty-year return period has been selected as the reference value for wind loads. The five approaches considered are:

1. **American Society of Civil Engineers (ASCE) Manual 74:** Both simplified and full-form versions of the ASCE 74 method are used to compute wind loads. The simplified version is in the main body of the document and the full-form version is an option found in one of the appendices. Most utility trial applications have been based on the simplified method because it is not only recommended by ASCE 74 but is also relatively “simple” to use. However, because the full-form version can yield results different from those computed using the simplified version, both versions are included in the first three examples, and the differences in these two methods are discussed.

2. **National Electrical Safety Code (NESC):** In addition to Extreme Wind loads, NESC divides the U.S. into three loading districts, Light, Medium, and Heavy. NESC Light District loading specifies a 9 lb./ft.^{2} wind pressure. Medium and Heavy District loads are wind-on-ice loads and cannot be compared directly to Extreme Wind loads. Therefore, only NESC Light and Extreme wind loads are included in the first three examples. NESC Medium and Heavy loads are discussed in the fourth example.

   NESC specifies different overload capacity factors for different structural materials. So, to simplify the comparison of wind loads computed by the various methods, all structures in these examples are assumed to be steel. The NESC overload capacity factor for Extreme Wind loads on steel and prestressed concrete structures is 1.0. For wind loading portions of NESC district load cases for Grade B steel and prestressed concrete structures, the overload capacity factor is 2.5.

3. **Companies A and B:** The only difference between the NESC Extreme Wind load case and Companies A and B's method (mentioned in Section 2.3) is that Companies A and B use an overload capacity factor of 1.5 for extreme wind loads on steel and prestressed concrete structures, while NESC specifies 1.0. The method used by Companies A and B is included in the first three examples to show whether the increased level of reliability resulting from a large overload capacity factor is sufficient for power line design.

4. **Company C**: Company C's method (Section 2.4), which is also used by some other utilities, employs height factors to adjust the wind pressure for any given conductor height. Except for the use of a small overload factor (1.1) and the wind speed adjustment for height, this method is very similar to that used by companies A and B. Company C's method is used in the first three examples to demonstrate the differences in wind load calculations done by each of the three companies.

5. **Span Gust Load Equation**: Since this relationship is based on the field data taken during the EPRI field experiments, the values are used as the reference values and assumed best to extrapolate the field measured data. A unique feature of this approach is the calculation of span gust wind speed (or span reduction of gust wind). This calculation is done with a simple equation, derived from field data, that relates reference winds to span gust winds. To use this approach effectively, it is important that engineers use appropriate values for design parameters such as drag coefficients and air density.

In addition to Companies A, B, and C methods, there are other company methods that could be used to compute wind loads for the examples presented in this section. Some of the other company methods may allow the adjustments of span factor, air density, drag coefficient, and other factors in wind load calculations. They are not presented here because of the lack of specific information.

5.2 Example 1—Wind Loads on a 500-ft. Span

5.2.1 Description

Span length:	500 ft.
Line sag:	15 ft.
Structure support height:	80 ft.
Insulator length:	5 ft.
Effective conductor heights:	73.3 ft. (ASCE 74)
	75 ft. (Company C)
	65 ft. (Span gust load equation)
Structure type:	Steel
Conductor type:	Chukar

Conductor diameter:	1.602 in.
Conductor drag coefficient:	Actual (0.93) used by the Span gust load equation and ASCE methods; Nominal (1.0) used by other three methods and again the ASCE method
Site elevation:	Sea level—0 ft.
Air temperature:	60 °F
Weight of air:	0.0764 lb./ft.^{3} at sea level (0-ft. elevation) at 60 °F
Terrain exposure:	C (Open country, farms, or grass lands)
Power law coefficient α:	7.0

For ASCE 74 Method:

Gradient height:	900 ft.
Surface drag coefficient:	0.005
Turbulence scale:	220 ft.

5.2.2 Results

The wind loads and corresponding return periods predicted by each of the four methods and referenced to the span gust load equation for Example 1 are presented in Table 5-1.

Table 5-1
Wind Loads and Their Return Periods—Example 1

	1				2		3	4	5
Fastest-Mile Wind Speed (50-Year)	ASCE 74 (Simplified)		ASCE 74 (Full-form)		NESC Light (w/ LF=2.5)	NESC Extreme Wind	Companies A & B NESC Extreme Wind (w/ LF=1.5)	Company C (High Wind w/ HF & LF=1.1)	Span Gust Approach-Reference (50-Year)
	(Cd=1.0)	(Cd=0.925)	(Cd=1.0)	(Cd=0.925)					
	Predicted Wind Loads (lb.)								
70 mph	1113	1030	1214	1129	1502	837	1256	1197	1245
90 mph	1840	1702	1939	1804	1502	1384	2076	1978	1950
110 mph	2748	2543	2820	2625	1502	2068	3101	2955	2796
	Equivalent Return Periods of Wind Loads (year)								
70 mph	30	21	44	32	130	9	52	41	50
90 mph	38	27	49	35	16	11	68	54	50
110 mph	46	32	52	37	4	13	84	66	50

The effective conductor height defined by the ASCE 74 method is 8.3 ft. above that defined by the span gust approach. The wind loads predicted by the simplified version of the ASCE 74 method are lower than the loads predicted by the span gust approach, with corresponding return periods of about 21-46 years. If a drag coefficient of 1.0 is used, the wind loads predicted by the full-form ASCE 74 method appear similar to the loads predicted by the span gust approach. However, when the actual drag coefficient is used, the wind loads are reduced, and the corresponding return periods are about 32-37 years.

In Table 5-1, the NESC Light District loads exceeded the NESC Extreme Wind loads for wind speeds of 70 and 90 mph. Therefore, if wind speed is less than 90 mph, the NESC Extreme Wind loads can be ignored in the NESC Light loading district. Except for one NESC Light District load case (extreme wind speed of 70 mph), the return periods for all other NESC Light and Extreme Wind load cases are significantly shorter than the 50 year reference (4-16 years).

The wind loads predicted by Method 3 (Companies A and B) were higher than the loads predicted by the span gust approach. The return periods for wind load cases of 70, 90, and 110 mph were 52, 68, and 84 years, respectively.

The wind load predicted by Method 4 (Company C) was close to the load predicted by the span gust approach at 90 mph, lower than the span gust approach at 70 mph, and higher than the span gust approach at 110 mph. The return periods were 41, 54, and 66 years, respectively, for wind load cases of 70, 90, and 110 mph.

5.3 Example 2—Wind Loads on a 1250-ft. Span

5.3.1 Description

Span length:	1250 ft.
Line sag:	40 ft.
Structure support height:	74 ft.
Insulator length:	6 ft.
Effective conductor heights:	58.7 ft. (ASCE 74)
	68 ft. (Company C)
	41 ft. (Span gust equation)
Structure type:	Steel
Conductor type:	Rail
Conductor diameter:	1.165 in.
Conductor drag coefficient:	Nominal (1.0) used by all methods
Site elevation:	Sea level—0 ft.
Air temperature:	60 °F
Weight of air:	0.0764 lb./ft.^{3} at sea level (0-ft. elevation) at 60 °F

Terrain exposure: C (open country, farms, or grass lands)
Power law coefficient α: 7.0
For ASCE 74 Method:
- Gradient height: 900 ft.
- Surface drag coefficient: 0.005
- Turbulence scale: 220 ft.

5.3.2 Results

The wind loads and corresponding return periods predicted by each of the four methods and referenced to the span gust load equation for Example 2 are presented in Table 5-2.

Table 5-2
Wind Loads and Their Return Periods—Example 2

	1		2		3	4	5
Fastest-Mile Wind Speed (50-Year)	**ASCE 74 (Simplified)**	**ASCE 74 (Full-form)**	**NESC Light (w/ LF=2.5)**	**NESC Extreme Wind**	**Companies A & B NESC Extreme Wind (w/ LF=1.5)**	**Company C (High Wind w/ HF & LF=1.1)**	**Span Gust Approach-Reference (50-Year)**
	Predicted Wind Loads (lb.)						
70 mph	1732	1853	2730	1522	2283	2116	1832
90 mph	2863	2951	2730	2516	3775	3497	2866
110 mph	4276	4283	2730	3759	5639	5224	4106
	Equivalent Return Periods of Wind Loads (year)						
70 mph	38	53	425	21	154	103	50
90 mph	50	58	40	27	209	138	50
110 mph	61	61	9	33	264	173	50

The wind load predicted by the simplified version of the ASCE 74 method was equal to the load predicted by the span gust approach at 90 mph, lower than the span gust approach at 70 mph, and higher than the span gust approach at 110 mph. The corresponding return periods increased to 38-61 years versus 21-46 years in Example 1. The wind loads predicted by the ASCE 74 full-form method showed improvement over the loads predicted by the simplified method at the low wind speed. The effective conductor height defined by the ASCE 74 method was 17.7 feet above that used by the span gust approach. In general, the increased effective conductor height leads to high wind load estimates.

As in Example 1, for wind speeds of 70, and 90 mph, the NESC Light District loads exceeded the NESC Extreme Wind loads. In Table 5-2, except for one NESC Light District load case (extreme wind speed of 70 mph), all other NESC Light District and Extreme Wind loads had shorter return periods (9-40 years) than 50 years.

The wind loads predicted by Method 3 (Companies A and B) were considerably higher than the loads predicted by the span gust approach. The return periods were 154, 209, and 264 years, respectively, for wind load cases of 70, 90, and 110 mph. The wind loads predicted by Method 4 (Company C) were also higher than the loads predicted by the span gust approach. The return periods were 103, 138, and 173 years, respectively, for wind load cases of 70, 90, and 110 mph.

Because Methods 3 and 4 do not account for a span gust reduction factor (or span factor), these methods predict high wind loads. Typically, the longer the span, the less the effective gust wind speed on the span. The span length used in Example 1 was 500 ft., and the span length used in this example was 1250 feet. Figure 3-2 shows that the span factor for a 500-ft. span is about 0.92 while the span factor for a 1250-ft. span can be as low as 0.77.

5.4 Example 3—Wind Loads for Lines at High Elevation (5280 ft.)

5.4.1 Description

Line 1: All design parameters are the same as in Example 1 except that the site is at a higher elevation.
Site Elevation of Line 1: 5280 ft.

Line 2: All design parameters are the same as in Example 2 except that the site is at a higher elevation.
Site Elevation of Line 2: 5280 ft.

Weight of Air: 0.0631 lb./ft.^{3} at elevation of 5280 ft. at 60 °F
ASCE 74 method: (0.0631 lb./ft.^{3} used by the span gust load equation and 0.0764 lb./ft.^{3} used by other three methods and again the ASCE 74 method)

5.4.2 Results

Line 1:

The wind loads and corresponding return periods predicted by each of the four methods and reference values using the span gust load equation for Line 1 are presented in Table 5-3.

Table 5-3
Wind Loads and Their Return Periods—Line 1, Example 3

	1				2		3	4	5
Fastest-Mile Wind Speed (50-Year)	ASCE 74 (Simplified) (Nominal Air Density)	ASCE 74 (Simplified) (Actual Air Density)	ASCE 74 (Full-form) (Nominal Air Density)	ASCE 74 (Full-form) (Actual Air Density)	NESC Light (w/ LF=2.5)	NESC Extreme Wind	Companies A & B NESC Extreme Wind (w/ LF=1.5)	Company C (High Wind w/ HF & LF=1.1)	Span Gust Approach-Reference (50-Year)
	Predicted Wind Loads (lb.)								
70 mph	1030	848	1123	930	1502	837	1256	1197	1027
90 mph	1702	1401	1793	1485	1502	1384	2076	1978	1609
110 mph	2543	2093	2608	2161	1502	2068	3101	2955	2307
	Equivalent Return Periods of Wind Loads (year)								
70 mph	51	21	78	31	380	20	139	108	50
90 mph	66	26	86	34	36	25	186	143	50
110 mph	81	32	92	37	8	30	234	179	50

The wind loads predicted by the span gust approach decreased somewhat because of the lower air density value at the elevation of 5280 ft. When the nominal air density was used, the wind loads predicted by the ASCE 74 simplified method were slightly higher than the loads predicted by the span gust approach. The return periods were 51, 66, and 81 years, respectively, for wind load cases of the 70, 90, and 110 mph. The wind loads predicted by the ASCE 74 full-form method were also higher than the loads predicted by the span gust approach. The return periods were 78, 86, and 92 years, respectively, for wind load cases of 70, 90, and 110 mph. However, when actual air density was used, the loads predicted by the ASCE 74 methods decreased, and the return periods were the same as those in Example 1.

Except for one NESC Light District load case (extreme wind speed of 70 mph), all other NESC Light District and Extreme Wind loads had shorter return periods than 50 years (8-36 years).

The wind loads predicted by Method 3 (Companies A and B) were significantly greater than the loads predicted by the span gust approach. The return periods were 139, 186, and 234 years, respectively, for wind load cases of 70, 90, and 110 mph.

The wind loads predicted by Method 4 (Company C) also exceeded the loads predicted by the span gust approach. The return periods were 108, 143, and 179 years, respectively, for wind load cases of 70, 90, and 110 mph.

Line 2:

The wind loads and corresponding return periods predicted by each of the four methods and reference values for Line 2 using the span gust load equation are presented in Table 5-4.

Table 5-4
Wind Loads and Their Return Periods—Line 2, Example 3

	1				2		3	4	5
Fastest-Mile Wind Speed (50-Year)	ASCE 74 (Simplified)		ASCE 74 (Full-form)		NESC Light (w/ LF=2.5)	NESC Extreme Wind	Companies A & B NESC Extreme Wind (w/ LF=1.5)	Company C (High Wind w/ HF & LF=1.1)	Span Gust Approach-Reference (50-Year)
	(Nominal Air Density)	(Actual Air Density)	(Nominal Air Density)	(Actual Air Density)					
	Predicted Wind Loads (lb.)								
70 mph	1732	1426	1853	1532	2730	1522	2283	2116	1512
90 mph	2863	2357	2951	2441	2730	2516	3775	3497	2365
110 mph	4276	3521	4283	3544	2730	3759	5639	5224	3389
	Equivalent Return Periods of Wind Loads (year)								
70 mph	98	38	141	53	1407	52	460	294	50
90 mph	132	49	155	58	103	68	643	406	50
110 mph	165	60	166	62	19	84	834	521	50

Again, the wind loads predicted by the span gust approach decreased because of the low air density value. When the nominal air density was used, the wind loads predicted by the ASCE 74 simplified method were significantly greater than the loads predicted by the span gust approach. The return periods were 98, 132, and 165 years, respectively, for wind load cases of 70, 90, and 110 mph. The wind loads predicted by the full-form method were higher than the loads predicted by the simplified method. The return periods were 141, 155, and 166 years, respectively, for wind load cases of 70, 90, and 110 mph. However, when actual air density was used, the loads predicted by the ASCE 74 methods decreased, and the return periods were the same as those in Example 2.

All three NESC Extreme Wind load cases had return periods of 52-84 years, which exceed 50 years. Only one NESC Light District load case (extreme wind speed of 110 mph) had a return period shorter than 50 years (19 years).

The wind loads predicted by Method 3 (Companies A and B) far exceed the loads predicted by the span gust approach. Their corresponding return periods were approximately 460-834 years.

The wind loads predicted by Method 4 (Company C) were also significantly above the loads predicted by the span gust approach. Their corresponding return periods were approximately 294-521 years.

Because Methods 3 and 4 neglect the span factor and do not use actual air density values, these methods produced the excessive wind loads shown in Table 5-4.

5.5 Example 4—NESC District Loads vs. NESC Extreme Wind Loads

5.5.1 Description

In the previous examples, it was demonstrated that NESC Extreme Wind loads can be ignored in the NESC Light loading district if the extreme wind speed is less than 90 mph. For most areas in the Medium and Heavy loading districts, the 50-year fastest-mile wind speeds likely are below 90 mph. As was mentioned in Section 5.1, Medium and Heavy District loads are wind-on-ice loads and cannot be compared directly to wind loads. To investigate whether the NESC Extreme Wind load cases can also be ignored in the NESC Medium and Heavy loading districts, a study was conducted to compare the different structural weights required by various NESC load cases. The weight of a structure was obtained from MINIDES (24) (an EPRI program for preliminary design of various types of transmission line structures that provides a quick estimate of structural weights) using the line parameters specified in Example 2. The results are not intended to represent the actual structural weights but provide reasonable relative measurements so the effect of the various loads can be evaluated.

5.5.2 Results

Table 5-5 lists the weights of five different types of structures under the NESC Medium District and Extreme Wind loads. The NESC Extreme Wind load cases can be ignored if wind speed is equal to 70 mph. However, it may not be ignored if wind speed is 90 mph or above. Because only a small portion of the area in the NESC Medium loading district has a 50-year fastest-mile wind above 90 mph, the NESC Extreme Wind loads seldom control design.

Table 5-5
Comparison of NESC Medium District Loading and Extreme Wind Loading Based on Structural Weights

	Weight of Structure (lb)		
Structure Type	**70 mph NESC Extreme Wind**	**90 mph NESC Extreme Wind**	**NESC Medium Loading District**
Single Circuit Flat Self-Supporting Steel Latticed Tower	4397 <	5323 >	4803
Double Circuit Self-Supporting Steel Latticed Tower	5972 <	7077 <	7218
Single Circuit Delta Self-Supporting Steel Latticed Tower	9065 <	11389 >	10127
Single Circuit Rotated Delta Self-Supporting Steel Latticed Tower	8738 <	10007 <	10139
Single Shaft Unguyed Steel Pole	5000 <	6000 >	5900

< NESC Medium District Loading Controls
> NESC Extreme Wind Loading Controls

Note: These weights may not be accurate absolute structure weights but are used here as the only effective method of demonstrating the relative change in structure required for the various combination of load cases.

Table 5-6 lists the weights of five different types of structures under the NESC Heavy District and Extreme Wind loads. The results in Table 5-6 indicate that the NESC Extreme Wind load case can also be ignored if wind speed is 90 mph or less.

Table 5-6
Comparison of NESC Heavy District Loading and Extreme Wind Loading Based on Structural Weights

	Weight of Structure (lb)		
Structure Type	**70 mph NESC Extreme Wind**	**90 mph NESC Extreme Wind**	**NESC Heavy Loading District**
Single Circuit Flat Self-Supporting Steel Latticed Tower	4397 <	5323 <	5586
Double Circuit Self-Supporting Steel Latticed Tower	5972 <	7077 <	7947
Single Circuit Delta Self-Supporting Steel Latticed Tower	9065 <	11389 <	11410
Single Circuit Rotated Delta Self-Supporting Steel Latticed Tower	8738 <	10007 <	10954
Single Shaft Unguyed Steel Pole	5000 <	6000 <	6800

< NESC Heavy District Loading Controls
> NESC Extreme Wind Loading Controls

Note: These weights may not be accurate absolute structure weights but are used here as the only effective method of demonstrating the relative change in structure required for the various combination of load cases.

Because most structures are effective against certain types of loads and may not effective against others, many load cases need to be considered before the final design of a power line is complete. Because only wind-related loads are considered in Tables 5-5 and 5-6, the large variation in weights in these two tables does not indicate that one structure type is superior to the other. Once all load cases are carefully considered, such variations should become minimal.

5.6 Example 5—Estimation of Local Extreme Wind Speeds

5.6.1 Description

In the previous examples, the 50-year fastest-mile wind speeds were taken from the ASCE wind map (Figure 2-1) (7, 8). However, there are limitations and problems associated with this map. Not only is this wind speed data base small for a national map but also some of the wind data are questionable. It is known that the map provides unrealistic wind speed values in some geographical areas, and because of the large scale of the map, it cannot provide local variations in wind speeds.

To establish a reliable design wind speed for a specific line or area, the wind speed data collected at local weather stations (including the high-quality data collected in the last 20 years) should be used. A usable service area wind map can be generated if sufficient wind data from a network of weather stations are available (one of the planned tasks in the EPRI wind research project is to write a guideline for generating local area wind maps). Example 5 estimates design wind speeds using the wind data from one weather station.

Table 5-7 lists the maximum monthly peak gust wind speeds from a weather station in the Midwest.

Table 5-7
Maximum Monthly Peak Gust Wind Velocity (mph)

Year	Jan.	Feb.	Mar.	Apr.	May	Jun.	Jul.	Aug.	Sep.	Oct.	Nov.	Dec.	MAX	
1970	40	45	35	60	50	53	75	31	44	40	46	56	75	(Jul.)
1971	47	47	50	67	43	51	59	30	41	48	44	36	67	(Apr.)
1972	51	54	50	44	56	47	37	59	43	36	39	48	59	(Aug.)
1973	43	41	58	62	53	67	44	37	32	43	38	38	67	(Jun.)
1974	47	47	45	50	56	53	40	43	33	36	35	37	56	(May)
1975	59	50	56	45	44	53	33	56	35	38	48	50	59	(Jan.)
1976	44	52	53	52	46	63	39	48	40	45	38	39	63	(Jun.)
1977	48	50	51	45	53	45	39	43	40	41	51	47	53	(May)
1978	47	37	41	52	59	76	48	52	48	46	35	44	76	(Jun.)
1979	39	46	48	48	45	59	61	73	47	61	37	44	73	(Aug.)
1980	55	43	38	43	46	40	53	30	48	48	45	38	55	(Dec.)
1981	40	52	56	48	40	56	39	43	38	50	40	44	56	(Mar./Jun.)
1982	54	32	54	63	41	38	36	35	36	46	59	53	63	(Apr.)
1983	52	40	39	43	58	43	39	50	40	38	44	45	58	(May)
1984	47	62	44	58	43	44	46	50	51	45	46	53	62	(Feb.)
1985	54	40	58	41	43	40	35	47	54	60	38	55	60	(Oct.)
1986	54	39	48	54	47	52	67	37	39	35	62	43	67	(Jul.)
1987	47	59	52	37	38	36	41	39	37	45	37	40	59	(Feb.)
1988	48	45	54	48	54	47	38	43	50	50	52	51	54	(Mar./May)
1989	48	39	48	66	50	56	43	63	47	38	45	52	66	(Apr.)
1990	55	51	43	50	53	58	37	39	43	46	40	43	58	(Jun.)
1991	35	50	48	47	48	43	37	38	43	36	50	48	50	(Feb./Nov.)
1992	48	43	40	33	45	40	56	39	53	37	47	46	56	(Jul.)
1993	37	30	46	60	44	43	83	33	35	38	38	43	83	(Jul.)
1994	37	40	36	48	32	50	45	46	29	48	46	36	50	(Jun.)
AVG	47	45	48	51	47	50	47	44	42	44	44	45	62	
STD	6	8	7	9	7	10	13	11	7	7	7	6	8	

5.6.2 Results

Table 5-8 shows the results of the extreme value analysis of the data in Table 5-7. The Gumbel Extreme Type I distribution was assumed in the data analysis.

In Table 5-8, the 50-year gust wind speed is 85 mph, which is equivalent to a 71-mph fastest-mile wind speed at this wind speed range. According to the ASCE wind map, the 50-year fastest-mile wind speed for the area near that particular weather station is 83 mph—considerably higher than 71 mph determined by this study.

Table 5-8
Design Gust Wind Speeds Based on Data in Table 5-7

Average of Maximum Yearly Gust Wind Speeds	62 mph
Standard Deviation of Maximum Yearly Gust Wind Speeds	8 mph
25-year Design Gust Wind Speed	80.2 mph
50-year Design Gust Wind Speed	84.9 mph
100-year Design Gust Wind Speed	89.5 mph

Table 5-7 contains 25 years of data, which is considered sufficient for determining 50-year design wind speed. For those places where long term records are not available, EPRI has a method (25) for determining design wind speeds using short term records.

6

ISSUES

6.1 Utility Wind Loading Design Criteria

Previous sections of this document discussed methods that utilities use to determine design wind loads. This section will continue that discussion and will explore some of the issues important to improving current utility wind loading design criteria.

Utilities commonly have their own in-house manuals for structural design of their power lines, and engineers are required to follow the wind loading design criteria in these manuals. The approaches adopted in these design manuals vary from utility to utility, but one typical approach is to use NESC load cases as the basis for the initial design. Large overload capacity factors are then applied to increase the basic NESC loads to levels the utility feels appropriate for given power line structures. Another approach used by some utilities completely ignores NESC load cases and, instead, specifies the loads they consider appropriate for their power line systems. Although not common, some companies design lines solely on the basis of NESC load cases. Finally, a small number of utilities follow ASCE 74 to determine design wind loads.

The process of selecting design wind speed or pressure also varies from company to company. A small number of utilities have local area wind speed or pressure maps that reflect local variations of extreme wind speeds and can be used for their service territories. Most utilities, however, do not have local wind maps. Instead, they have developed design wind speed values that are based on past experience in their service territories. For those utilities that operate in hurricane-prone regions or high wind areas, these values can be quite high. Today, most utilities still use design wind speeds in their in-house manuals, but a small number now use the ASCE fastest-mile wind map for design.

There are a number of problems with current practices for the selection of design wind loads. These include:

- There are no clear requirements for selecting design wind speeds. However, if a design wind speed is improperly selected, all other efforts to improve wind load prediction will be futile.

- Because most utilities use approaches similar to the NESC method for determining wind loads, the span gust effect is neglected in the calculation. However, the inclusion of a span gust reduction factor improves wind load prediction, typically resulting in low wind loads for long conductor spans.

- Most utility design manuals are very rigid, and use of design parameter values other than those specified in the manuals typically is not done. However, the use of actual parameters such as air density and drag coefficients, instead of nominal values, will in most cases, significantly improve wind load prediction.

Because the majority of utilities have had in-house design manuals for decades, it is important that they reevaluate these manuals and improve them by conducting a study to determine appropriate local design wind speeds, including span gust reduction effect in wind load equations, and allowing the option to use actual values for some design parameters. With effort, a method, both practical and capable of accurately predicting wind loads, can be obtained.

6.2 Codes and Standards

Utilities have their own in-house wind loading design criteria. It is not surprising that some power lines are designed to carry different loads even when conditions for those lines are the same. One reason utilities have their own wind loading criteria is that there are no loading standards that are directly applicable to power line design in the U.S. To have consistent wind loading design criteria across the U.S., a national code or standard specifically applicable to power lines is needed.

NESC, however, is only a safety code, and while utilities may need to meet NESC requirements for safety reasons, the code is not intended for power line design. ASCE 74 is only a design guideline, and recent EPRI research has revealed some problems associated with the wind load methods provided in that document. While some of those issues may be solved easily, others could be difficult to overcome without a change in the fundamentals upon which the ASCE 74 methods are based. Additionally, while many countries have codes and standards for power line design, the methods employed by some of them to calculate wind loads are no better than current methods available in the U.S., and others may not be appropriate for U.S. applications because of their country-specific provisions.

While the lack of a national code or standard prevents adoption of consistent wind loading design criteria across the U.S., a more important issue is the lack of sufficient experimental validation of most of the current wind load methods. EPRI wind load research has shown that utilities can improve their ability to determine wind loads for power line evaluation and design by using wind load procedures that have been validated by field data. Utility engineers are encouraged to become involved with the committees working on the codes, standards, and design guidelines related to wind loading. A consistent wind load design procedure will emerge for the U.S. that would be beneficial.

6.3 Reliability of Lines—Theory vs. Practice

A transmission line is an integrated system with many components, and the reliability of such systems is an increasingly important issue to utilities. If the behavior of each component is known or can be well predicted, it is possible to use probability theory to determine the reliability of the line or to vary the composition of the components to control the reliability of the line.

Because annual maximum wind speeds for a given area vary from year to year, the maximum wind speed for the entire service life of a line should be used for design. A 50-year return period wind speed means that, on average, the wind speed of the specified magnitude likely will occur once every 50 years. The longer the return periods of design wind speeds, the higher the wind loads, and the higher the wind loads a line is designed for, the higher the reliability of the line. When an engineer designs a transmission line, that line is expected to be operational during its entire service life. Therefore, for efficient design, the return periods of maximum wind speeds should be related to the service life of the line.

Once the design wind speeds are determined, the next question is how accurate are the calculated wind loads. Utilities may use wind speeds with certain return periods, say 50 years, in design. However, while a line may have been designed for a 50-year wind speed, it may have not been designed for the 50-year gust load because the wind load model used may not be able to effectively convert the reference wind speeds into proper gust loads. To achieve this, a wind load model that is able to predict span gust loads accurately is necessary. One issue related to the reliability assessment of power lines is the consistency with which models can predict accurate span gust loads over an appropriate design wind speed range. The span gust load prediction made by a wind load model should be compared with the field data, especially for the design wind speed range. One model may predict wind loads accurately at the low wind speed range and poorly at the high wind speed range. Another model might do just the opposite. In EPRI wind load research, it was obvious that for the load range in which data were available, some methods of calculating wind loads provided consistent results while other methods did not perform consistently over the wind speed range given by the field data.

In addition to wind load models, materials also play an important part in predicting the overall reliability of a line. For instance, because the behavior of a wood-pole structure is less predictable than that of a steel structure, it is far more difficult to assess the reliability of a line with wood-pole structures than one with steel structures.

To assess the reliability of a line, we need to know the statistical distributions of all the major parameters required to define the reliability of the line. This requires a great deal of full-scale testing, component testing, analytical model evaluation, and data collection of various types (such as wind and ice), a process that is both difficult and time-consuming.

Because of the obvious difficulty of obtaining the necessary data, a full systematic reliability assessment of a power line is seldom performed. Utilities must rely on simple approaches such as the use of overload factors, strength reduction factors, or overload capacity factors to account for the uncertainty in materials and wind load calculations. Few of these factors are determined from actual test data, however. Instead, most are based on engineers' experience. Therefore, it is difficult to judge the reliability of a line when these factors are used in design. Often, you can hear statements such as: "...this line is designed for 100 mph winds with an overload factor of 1.2." This does not give any indication of the reliability of the line. The combination of wind speed and overload factor is not a measure of the reliability of the line.

Instead of attempting to estimate the overall reliability of a power line system, we may use wind loads or other design parameters to partially define reliability of the line. For example, using the procedure outlined in this document, we can provide wind loads with certain return periods without directly involving the supporting structures themselves. This provides some indication of how reliable the line is if only wind loads are considered. Of course, there are many other factors affecting the reliability of the line that should be dealt with separately.

7

CONCLUDING REMARKS

The goal of this document is to help engineers accurately determine wind loads on wires and conductors. The procedure outlined in this document can be used for designing new lines or evaluating existing power lines for upgrade or maintenance. The document also provides a useful tool, based on wind loading, for assessing the reliability of power line systems. Additionally, guidance is provided to help utilities assess and modify their current wind loading design criteria for efficient design in future applications.

Information presented in this document and previous EPRI publications can help governing bodies of design codes, standards, and guidelines in making necessary changes to their respective codes and standards.

8

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