

IEEE Guide for Design of Substation Rigid-Bus Structures

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**Substations Committee
of the
IEEE Power Engineering Society**

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Abstract: Rigid-bus structures for outdoor and indoor, air-insulated, and alternating-current substations are covered. Portions of this guide are also applicable to strain-bus structures or direct-current substations, or both. Ampacity, radio influence, vibration, and forces due to gravity, wind, fault current, and thermal expansion are considered. Design criteria for conductor and insulator strength calculations are included.

Keywords: ampacity, bus support, mounting structure, rigid-bus structures, strain-bus structure

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Introduction

(This introduction is not part of IEEE Std 605-1998, IEEE Guide for Design of Substation Rigid-Bus Structures.)

Substation rigid-bus structures are being applied by electrical utilities and other industries. Such structures usually reduce substation heights and have greater ampacity and lower corona than single-conductor strain-bus structures.

This guide presents an integrated design approach with methods for calculating the forces to which rigid-bus structures are subjected.

The data in this guide are taken from empirical and theoretical sources that can form the basis of a good design by a knowledgeable design engineer. The guide is not intended as a rigid procedural design guide for the inexperienced. Some of the empirical methods presented in this guide are based on experience.

Future work is required to give the design engineer a better understanding of certain portions of the design process, such as the flexibility of support structures and insulator overload factors.

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IEEE Guide for Design of Substation Rigid-Bus Structures

1. Overview

1.1 Scope

The information in this guide is applicable to rigid-bus structures for outdoor and indoor, air-insulated, and alternating-current substations. Portions of this guide are also applicable to strain-bus structures or direct-current substations, or both. Ampacity, radio influence, vibration, and forces due to gravity, wind, fault current, and thermal expansion are considered. Design criteria for conductor and insulator strength calculations are included. This guide does not consider

- a) The electrical criteria for the selection of insulators
- b) The seismic forces to which the substation may be subjected
- c) The design of mounting structures

1.2 Purpose

Substation rigid-bus structure design involves electrical, mechanical, and structural considerations. It is the purpose of this guide to integrate these considerations into one document.

Special consideration is given to fault current-force calculations. Factors considered include the decrement of the fault current, the flexibility of supports, and the natural frequency of the bus. These factors are mentioned in ANSI C37.32-1996, but are not taken into consideration in the equations presented in that standard.

2. References

This guide shall be used in conjunction with the following publications. If the following publications are superseded by an approved revision, the revision shall apply.

ANSI C29.1-1988 (R1996), American National Standard Test Methods for Electrical Power Insulators.¹

¹ANSI publications are available from the Sales Department, American National Standards Institute, 11 West 42nd Street, 13th Floor, New York, NY 10036, USA.

ANSI C29.9-1983 (R1996), American National Standard for Wet-Process Porcelain Insulators (Apparatus, Post Type).

ANSI C37.32-1996, American National Standard for High-Voltage Air Disconnect Switches Interrupter Switches, Fault Initiating Switches, Grounding Switches, Bus supports and Accessories Control Voltage Ranges—Schedule of Preferred Ratings, Construction Guidelines and Specifications.

ASCE 7-95, Minimum Design Loads for Buildings and Other Structures.²

ASTM B188-96, Standard Specification for Seamless Copper Bus Pipe and Tube.³

ASTM B241/B241M-96, Standard Specification for Aluminum and Aluminum-Alloy Seamless Pipe and Seamless Extruded Tube.

IEEE Std C2-1997, National Electrical Safety Code.⁴

IEEE Std C37.30-1997, IEEE Standard Requirements for High-Voltage Air Switches.

IEEE Std 100-1996, IEEE Standard Dictionary of Electrical and Electronics Terms.

IEEE Std 693-1997, IEEE Recommended Practice for Seismic Design of Substations.

NEMA CC 1-1993, Electric Power Connectors for Substations.⁵

NEMA 107-1988 (R1993), Methods of Measurement of Radio-Influence Voltage (RIV) of High-Voltage Apparatus.

NFPA 70-1996, National Electrical Code.⁶

3. Definitions

The following definitions apply specifically to the subject matter of this guide:

3.1 bus structure: An assembly of bus conductors, with associated connection joints and insulating supports.

3.2 bus support: An insulating support for a bus.

NOTE—A bus support includes one or more insulator units with fittings for fastening to the mounting structure and for receiving the bus.

3.3 mounting structure: A structure for mounting an insulating support.

3.4 rigid-bus structure: A bus structure comprised of rigid conductors supported by rigid insulators.

3.5 strain-bus structure: A bus structure comprised of flexible conductors supported by strain insulators.

²ASCE publications are available from the American Society of Civil Engineers, 1801 Alexander Bell Drive, Reston, VA 20191-4400, USA.

³ASTM publications are available from the American Society for Testing and Materials, 100 Barr Harbor Drive, West Conshohocken, PA 19428-2959, USA.

⁴IEEE publications are available from the Institute of Electrical and Electronics Engineers, 445 Hoes Lane, P.O. Box 1331, Piscataway, NJ 08855-1331, USA.

⁵NEMA publications are available from the National Electrical Manufacturers Association, 1300 N. 17th St., Ste. 1847, Rosslyn, VA 22209, USA.

⁶NFPA publications are available from Publications Sales, National Fire Protection Association, 1 Batterymarch Park, P.O. Box 9101, Quincy, MA 02269-9101, USA.

4. The design problem

The design problem considered in this guide is the selection of rigid-bus structure components and their arrangements. For a safe, reliable, and economic design, the components and their arrangements should be optimized to satisfy the design conditions.

The design conditions will establish minimum electrical and structural performance. These conditions are dependent upon the characteristics of the power system involved and the location of the substation. The design conditions specify the following:

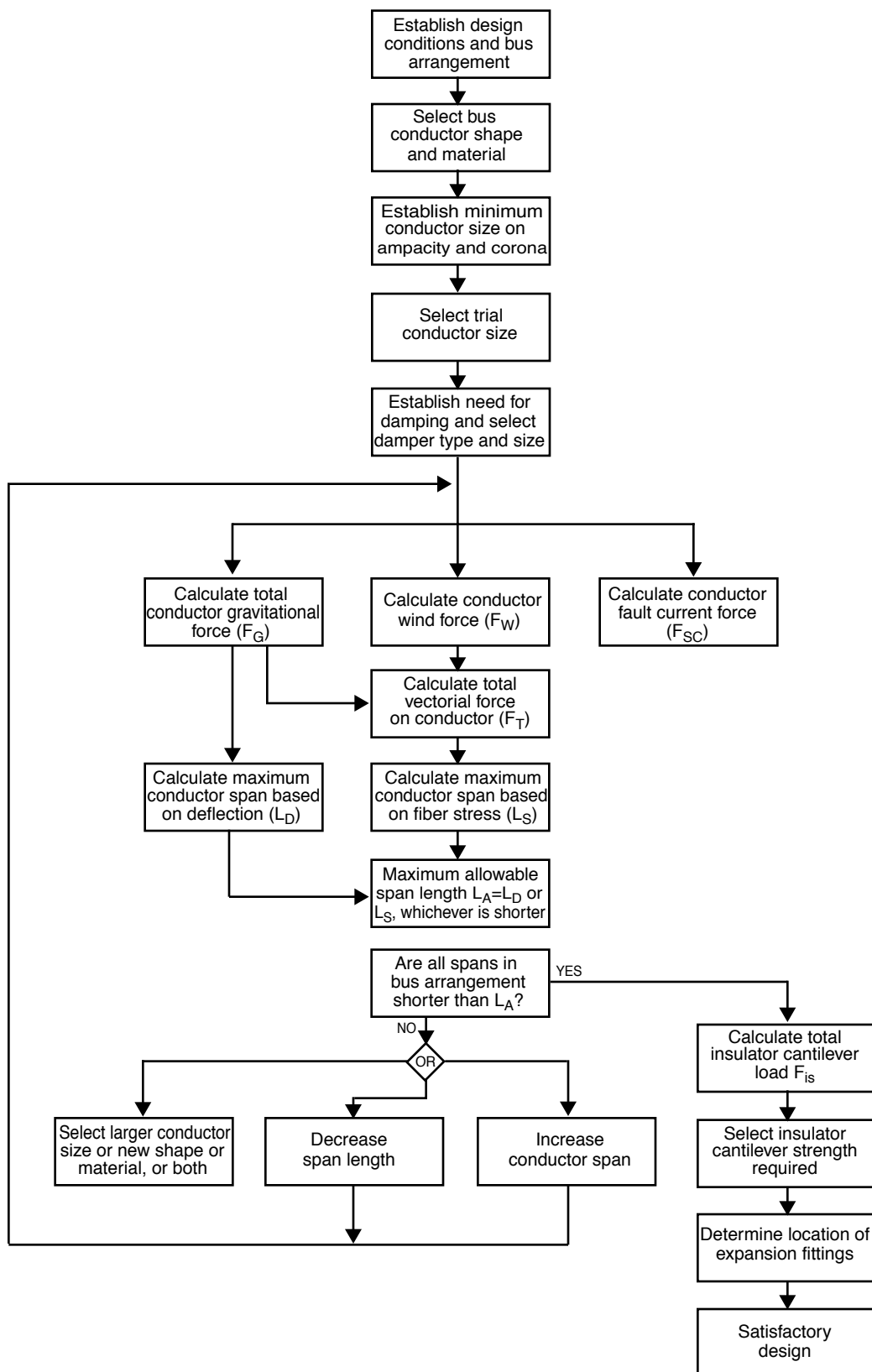
- a) Ampacity requirements
- b) Maximum anticipated fault current
- c) Maximum operating voltage
- d) Maximum anticipated wind speeds
- e) Maximum expected icing conditions combined with wind
- f) Altitude of the substation site
- g) Basic substation layout

The selection of conditions acting simultaneously on the bus structure (that is, fault current, extreme wind, combined wind and ice, or a combination of these) involves probability, and some risk is involved in their selection. The design engineer should consider the risks to life, property, and system operation when the design conditions are selected.

Design conditions should also be specified for the electrical performance of insulators. If the substation is located in an area of possible seismic activity, additional design conditions should be established. IEEE Std 693-1997 and the seismic zone maps in ASCE 7-95 may be used to establish these seismic design conditions.

The actual design can begin after the design conditions are firmly established. Because of the various bus-structure components available to the designer and their various possible physical arrangement, the design becomes an iterative process. This iterative process is interrelated by conductor ampacity, suppression of radio influence, elimination of conductor vibrations, and structural integrity (see Figure 1).

It should be noted that a guide is presently being developed by the ASCE that will address the structural aspects of rigid-bus design. When approved, this ASCE guide may be used to verify the structural aspects of this guide.



NOTE—This diagram assumes that maximum span length is not limited by aeolian vibration.

Figure 1—Design process for horizontal rigid bus

5. Ampacity

The ampacity requirement of the bus conductor is usually determined by either the electrical system requirements or the ampacity of the connected equipment. Conductor ampacity is limited by the conductor's maximum operating temperature. Excessive conductor temperatures may anneal the conductor, thereby reducing its strength, or may damage connected equipment by the transfer of heat. Excessive temperatures may also cause rapid oxidation of the copper conductor.

5.1 Heat balance

The temperature of a conductor depends upon the balance of heat input and output. For balance, the heat input due to I^2R and solar radiation equals the heat output due to convection, radiation, and conduction. The heat balance may be expressed as

$$I^2RF + q_s = q_c + q_r + q_{\text{cond}} \quad (1)$$

Solving the current for a given conductor temperature rise is

$$I = \sqrt{\frac{q_c + q_r + q_{\text{cond}} - q_s}{RF}} \quad (2)$$

where

I = current for the allowable temperature rise, A

R = direct-current resistance at the operating temperature, Ω/m [Ω/ft]

F = skin-effect coefficient

q_s = solar heat gain, W/m [W/ft]

q_c = convective heat loss, W/m [W/ft^*]

q_r = radiation heat loss, W/m [W/ft]

q_{cond} = conductive heat loss, W/m [W/ft^*]

* Values for convective or conductive heat gains on the right side of Equation (2) are entered as negative numbers.

5.1.1 Effective resistance, RF

A conductor's effective resistance at a given temperature and frequency is the direct-current resistance R modified by the skin-effect coefficient F . These values may be obtained from published data.

5.1.2 Solar heat gain, q_s

The amount of solar heat gained is a function of

- The total solar and sky radiation
- The coefficient of solar absorption for the conductor's surface
- The projected area of the conductor
- The altitude of the conductor above sea level
- The orientation of the conductor with respect to the sun's rays

5.1.3 Convective heat loss, q_c

A bus conductor loses heat through natural or forced convection.

5.1.3.1 Natural convective heat loss

Natural convective heat loss is a function of

- a) The temperature difference between the conductor surface and the ambient air temperature
- b) The orientation of the conductor's surface
- c) The width of the conductor's surface
- d) The conductor's surface area

5.1.3.2 Forced convective heat loss

Forced convective heat loss is a function of

- a) The temperature difference between the conductor's surface and the ambient air temperature
- b) The length of flow path over the conductor
- c) The wind speed
- d) The conductor's surface area

5.1.4 Radiation heat loss, q_r

A conductor loses heat through the emission of radiated heat. The heat lost is a function of

- a) The difference in the absolute temperature of the conductor and surrounding bodies
- b) The emissivity of the conductor's surface
- c) The conductor's surface area

5.1.5 Conductive heat loss, q_{cond}

Conduction is a minor method of heat transfer since the contact surface is usually very small. Conduction may cause an increase in the temperature of the equipment attached to the bus conductor. Conductive heat loss is usually neglected in bus-ampacity calculations.

5.2 Conductor temperature limits

5.2.1 Continuous (see IEEE Std C37.30-1997)

Aluminum alloy and copper conductors may be operated continuously at 90 °C without appreciable loss of strength. They may also be operated at 100 °C under emergency conditions with some annealing. Copper may, however, suffer excessive oxidation if operated at or above 80 °C. Conductors should not be operated at temperatures high enough to damage the connected equipment.

5.2.2 Fault conditions (see ANSI C37.32-1996)

A conductor's temperature will rise rapidly under fault conditions. This is due to the inability of the conductor to dissipate the heat as rapidly as it is generated. Annealing of conductor alloys may occur rapidly at these elevated temperatures. The maximum fault current that can be allowed for copper and aluminum alloy conductors may be calculated using Equations (3) and (4). In general, the final temperature of the conductor is limited to the maximum temperature considered for thermal expansion (see Clause 13).

For aluminum conductors [40% to 65% International Annealed Copper Standard (IACS) conductivity],

$$I = C \times 10^6 A \sqrt{\frac{1}{t} \log_{10} \frac{T_f - 20 + (15150/G)}{T_i - 20 + (15150/G)}} \quad (3)$$

where

$C = 92.9$ for Metric units [.144 for English units]

I = maximum allowable root-mean-square (rms) value of fault current, A

A = conductor cross-sectional area, mm² [in²]

G = conductivity in percent International Annealed Copper Standard (IACS)

t = duration of fault, s

T_f = allowable final conductor temperature, °C

T_i = conductor temperature at fault initiation, °C

And for copper conductors [95% to 100% International Annealed Copper Standard (IACS) conductivity],

$$I = C \times 10^6 A \sqrt{\frac{1}{t} \log_{10} \frac{T_f - 20 + (25400/G)}{T_i - 20 + (25400/G)}} \quad (4)$$

$C = 142$ for Metric units [0.22 for English units]

All other variables have been defined previously.

5.2.3 Attached equipment

Since heat generated in the bus conductor may be conducted to attached equipment, allowable conductor temperatures may be governed by the temperature limitations of attached equipment. Equipment temperature limitations should be obtained from the applicable specification or the manufacturer. High-voltage air switches and bus supports are described in IEEE Std C37.30-1997.

5.3 Ampacity tables

The ampacities for most aluminum-alloy and copper bus-conductor shapes are included in Annex B. These ampacities were calculated using the methods outlined in Annex C, which neglect conductive heat loss.

6. Corona and radio influence

Corona develops when the voltage gradient at the surface of a conductor exceeds the dielectric strength of the air surrounding the conductor and ionizes the air molecules. Radio influence (RI) is caused by corona. In practice, corona has not been a factor in rigid-bus design at 115 kV and below. However, the rigid-bus designer should be aware that radio influence can be produced at any voltage by arcing due to poor bonding between bus conductors and associated hardware.

The proximity and largeness of the equipment within a substation create multiple low-impedance paths to ground for radio-frequency current. The Radio Noise Subcommittee of the IEEE Transmission and Distribution Committee states that actual radio influence will be less than that calculated because of this effect [B15].⁷

The designer's problem is to select a bus conductor and specify bus hardware that is corona free during fair-weather conditions at the operating voltage, altitude, and temperature. It should be noted that corona may exist under wet or contaminated conditions.

⁷The numbers in brackets preceded by the letter B correspond to those of the bibliography in Clause 14.

6.1 Conductor selection

For corona-free operation, the maximum surface voltage gradient of the bus-conductor E_m should be less than the allowable surface voltage gradient E_o .

Four basic factors determine the maximum surface voltage gradient of a smooth bus-conductor E_m . They are

- 1) Conductor diameter or shape
- 2) Distance from ground
- 3) Phase spacing
- 4) Applied voltage

Circular bus shapes will generally give the best performance. A smooth surface condition is important if operating near the allowable surface voltage gradient.

Formulae are provided in Annex D for calculating the maximum surface voltage gradient for a smooth, circular bus-conductor E_m . The calculation should be 110% of the nominal line-to-ground voltage to provide for an operating margin.

The allowable surface voltage gradient for equal radio-influence generation E_o for smooth, circular bus conductors is a function of bus diameter, barometric pressure, and operating temperature. Annex D gives a method for determining the allowable surface voltage gradient.

6.2 Hardware specifications

Bus fittings and hardware for use in rigid-bus structures should be specified as being free of corona under fair-weather conditions at the intended operating voltage, altitude, and temperature.

It should be noted that the testing methods referred to in 6.2.1 do not require the control of air temperature and air pressure during testing. The specifier should refer to Annex D to determine the difference between the allowable voltage gradients under expected operating conditions and possible laboratory conditions. If the difference is significant, the designer may specify that the testing voltage be increased according to the methods of Annex D to compensate for the test pressure and temperature.

6.2.1 Testing methods

Bus fittings and hardware should be tested by the manufacturer in a laboratory under simulated field configuration. All bus fittings and hardware should be tested while attached to a section of the bus conductor for which they are to be used.

6.2.1.1 Visual corona

The visual corona extinction voltage should be tested according to NEMA CC 1-1993.

6.2.1.2 Radio-influence voltage (RIV) level

The radio-influence voltage (RIV) level should be tested according to NEMA 107-1988.

6.2.2 Acceptance criteria

The following performance should be specified for fittings and hardware under fair-weather conditions.

6.2.2.1 Visual corona

The extinction voltage for visual corona should be at least 110% of nominal operating voltage or at least 110% of the testing voltage adjusted to compensate for pressure and temperature.

6.2.2.2 Radio-influence voltage (RIV)

The specified radio-influence voltage (RIV) limits for various bus system components should match those given in the following standards:

- a) For fittings and connectors, see NEMA CC 1-1993.
- b) For insulators and hardware assemblies, see ANSI C29.9-1983.

7. Conductor vibration

A span of rigid conductor has its own natural frequency of vibration. If the conductor is displaced from its equilibrium position and released, it will begin to vibrate at this natural frequency. The magnitude of the oscillations will decay due to damping. If, however, the conductor is subjected to a periodic force whose frequency is near the natural frequency of the span, the bus may continue to vibrate and the amplitude will increase.

This vibration may cause damage to the bus conductor by fatigue or by excessive fiber stress.

7.1 Natural frequency

The natural frequency of a conductor span is dependent upon the manner in which the ends are supported and upon the conductor's length, mass, and stiffness. The natural frequency of a conductor span can be calculated using Equation (5).

$$f_b = \frac{\pi K^2}{CL^2} \sqrt{\frac{EJ}{m}} \quad (5)$$

where

$C = 20$ for Metric units [24 for English units]

f_b = natural frequency of conductor span, Hz

L = span length, m [ft]

E = modulus of elasticity, MPa [lbf/in²]

J = moment of inertia of cross-sectional area, cm⁴ [in⁴]

m = mass per unit length, kg/m [lbf/ft]

$K = 1.00$ for two pinned ends (dimensionless)

$K = 1.22$ for one pinned end and one fixed end (dimensionless)

$K = 1.51$ for two fixed ends (dimensionless)

End conditions can range between fixed and pinned. A fixed end is not free to rotate (moment resisting), whereas a pinned end is free to rotate (not moment resisting). Because of structure flexibility and connection friction, the end conditions are not truly fixed or pinned. However, the end conditions are generally closer to fixed than to pinned.

7.2 Driving functions

Either alternating current or wind may induce vibrations in a bus conductor with frequencies near the natural frequency of the bus conductor.

7.2.1 Current-induced vibrations

Currents flowing through parallel conductors create magnetic fields that interact and exert forces on the parallel conductors. This driving force oscillates at twice the power frequency.

If the calculated natural frequency of a bus span is found to be greater than half the current-force frequency (that is, greater than the power frequency), the bus spans' calculated natural frequency should be changed or a dynamic analysis should be made to determine stresses involved.

7.2.2 Wind-induced vibration

When a laminar (constant, nonturbulent) wind flows across a conductor, aeolian vibration may occur. This vibration may cause bus-conductor fatigue. Laminar flow does not usually occur at high wind speeds because of the ground effects created by terrain, trees, buildings, local thermal conditions, etc. Experience has shown that wind with speeds up to 15 mi/h can have laminar flow.

The maximum frequency of the aeolian force for circular conductors may be calculated from Equation (6), which is based on the Strohhal formula.

$$f_a = \frac{CV}{d} \quad (6)$$

where

$C = 5.15$ for Metric units [3.26 for English units]

f_a = maximum aeolian force frequency, Hz

V = maximum wind speed for laminar flow, km/h [mi/h]

d = conductor diameter in, [cm]

Formulae for calculating aeolian force frequency for bus cross-sectional shapes other than circular are not available.

If twice the calculated natural frequency of the bus span is greater than the aeolian force frequency, then the bus span length should be changed or the bus should be damped.

7.3 Damping

Bus spans may be damped to reduce aeolian vibration. For tubular bus conductors, damping may be accomplished by installing stranded bare cable inside the bus conductor to dissipate vibrational energy. The cable should be of the same material as the bus conductor to prevent corrosion, and the weight of the cable should be from 10% to 33% of the bus-conductor weight, although some designers have found that from 3% to 5% of the bus-conductor weight is adequate. In some locations, the audible noise generated by stranded cable dampers may be unacceptable.

Commercially available vibration dampers may be used for both tubular and nontubular conductors. Commercial vibration dampers should be sized and placed according to the manufacturer's recommendations.

8. Conductor gravitational forces

Gravitational forces determine the vertical deflection of bus conductors and are a component of the total force, which the conductor must withstand. Gravitational forces consist of the weights of the conductor, damping material, ice, and concentrated masses.

8.1 Conductor

Conductor weight should be obtained from applicable specifications or from the manufacturer.

8.2 Damping material

The weight of the material used to damp vibration should be included in computing gravitational forces. If commercial dampers are used, these should be considered as concentrated masses.

8.3 Ice

The minimum radial ice thickness used for design should be determined from IEEE Std C2-1997. See Figure 2 or [B3].

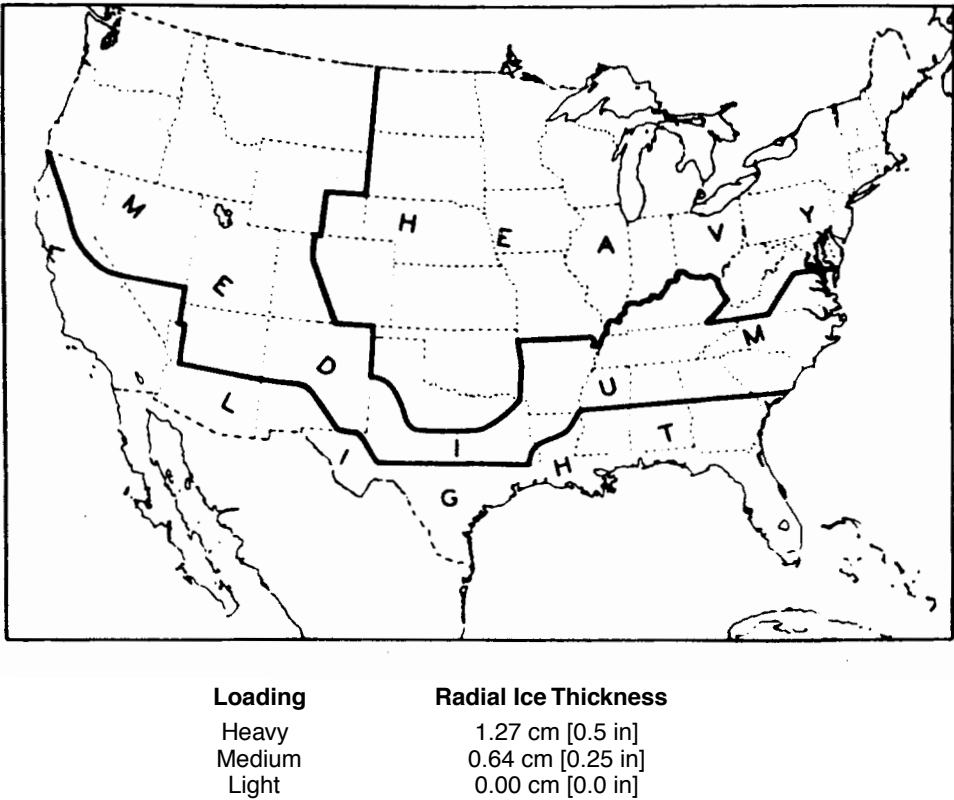


Figure 2—General loading map showing territorial division of the United States with respect to loading of overhead lines

Consideration should be given to special local conditions where greater ice thicknesses may occur, such as near a cooling-tower installation. The ice weight on a circular conductor is given as

$$F_I = C\pi W_I r_I (d + r_I) \quad (7)$$

where

$C = 0.0001$ for Metric units [12 for English units]

F_I = ice unit weight, N/m [lbf/ft]

W_I = ice weight = 7.18, N/m³ [0.0330, lbf/in³]

r_I = radial ice thickness, cm [in]

d = outside conductor diameter, cm [in]

Equation (7) may be simplified to

$$F_I = Cr_I(d + r_I) \quad (8)$$

where

$C = 2.26 \times 10^{-3}$ for Metric units [1.24 for English units]

Similar equations may be derived for other conductor shapes.

8.4 Concentrated masses

Gravitational forces due to concentrated masses (vibration dampers, equipment attachments, cross conductors, etc.) should be determined and included in the summation of gravitational forces.

9. Conductor wind forces

The bus structure should be capable of withstanding the mechanical forces due to expected winds. The maximum force due to wind may occur either during extreme wind conditions with no ice or high wind conditions with ice. In general, the maximum wind speed with ice is less than the extreme wind speed.

The annual extreme fastest-mile wind speeds for design without ice should be determined from ASCE 7-95. See Figure 3 or [B3]. The choice of the 50- or 100-year recurrence map depends upon the degree of hazard to life or property. Local or state codes should be followed if their wind-force requirements exceed those determined by reference to ASCE 7-95.

The fastest-mile wind speed with ice should be determined from the ice/wind history at the substation site. In general, the wind speed that occurs after icing conditions is lower than the annual extreme fastest-mile wind speed.

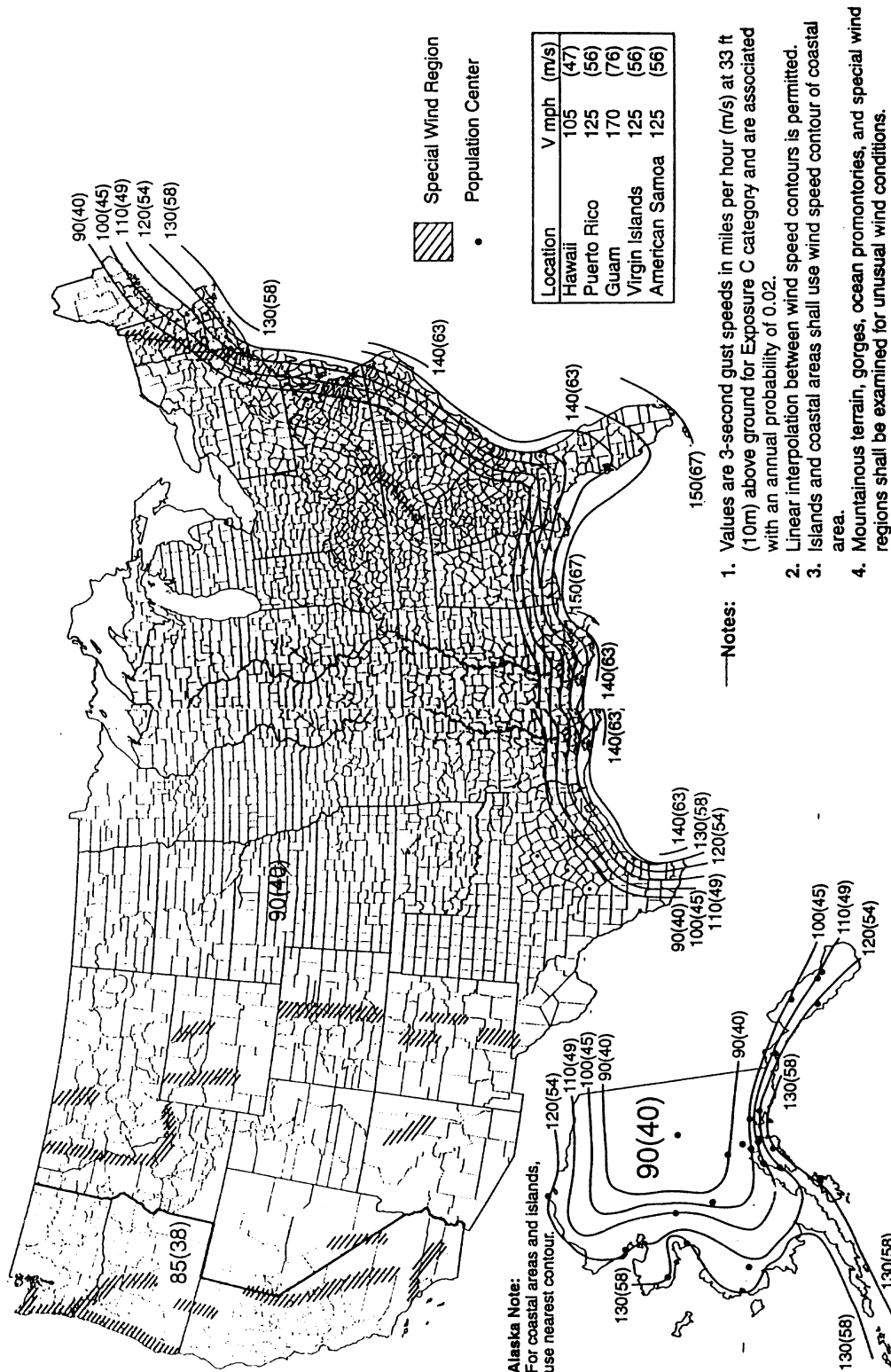
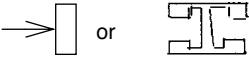
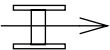
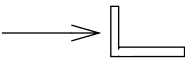
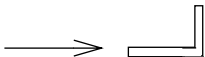


Figure 3—Basic wind speed—miles per hour (mi/h) annual extreme fastest-mile speed
33 ft (10 m) above ground, 50 yr mean recurrence interval

From ASCE 7-95
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Table 1 displays the drag coefficients for structural shapes in relation to profile and wind direction.

Table 1—Drag coefficients for structural shapes

Profile and Wind Direction	C_D
	2.03
	1.00
	2.00
	2.04
	2.00
	1.83
	1.99

Factors that will affect wind forces are the speed and gust of the wind, radial ice thickness, and the shape, diameter, height, and exposure of the conductors.

The unit wind force for bus is given as

$$F_W = C C_D K_Z G_F V^2 I(d + 2r_I) \tag{9}$$

where

$C = 6.13 \times 10^{-3}$ for Metric unit [2.132×10^{-4} for English units]

F_W = wind unit force on bus, N/m t [lbf/f]

d = outside conductor diameter, cm [in]

r_I = radial ice thickness, cm [in]

- C_D = drag coefficient, (see 9.1)
 K_Z = height and exposure factor, (see 9.2)
 G_F = gust factor, (see 9.3)
 V = wind speed at 9.1 m (30 ft) above ground, km/h [mi/h]
 I = importance factor (see 9.4)

9.1 Drag coefficient, C_D

The wind force exerted on a conductor varies with the shape of the conductor. This variation is reflected in the drag coefficient C_D . The drag coefficient for smooth tubular conductors is 1.0. Coefficients for other shapes are given in Table 1.

9.2 Height and exposure factor, K_Z

In the height zone from 0 m (0 ft) to 9.1 m (30 ft) and for exposure category A, B, C, the height and exposure factor $K_Z = 1.0$, and the wind speed at 9.1 m (30 ft) should be used. For exposure category, $K_Z = 1.16$. ASCE 7-95 has a detailed definition of each of these exposure categories. Summarized definitions are as follows:

- *Exposure A:* Large city centers with at least 50% of the buildings having a height in excess of 21.3 m (70 ft).
- *Exposure B:* Urban and suburban areas, wooded areas, or other terrain with numerous closely spaced obstructions having the size of single-family dwellings or larger.
- *Exposure C:* Open terrain with scattered obstructions having heights generally less than 9.1 m (30 ft). This category includes flat open country and grassland.
- *Exposure D:* Flat, unobstructed areas exposed to wind flowing over open water for a distance of at least 1.61 km (1 mi).

9.3 Gust factors, G_F

A gust factor G_F of 0.8 shall be used for exposure A and B, and 0.85 shall be used for exposure C and D.

9.4 Importance factor, I

The importance factor I for electric substations shall be 1.15 as classified by ASCE 7-95.

10. Conductor fault current forces

The magnetic fields produced by fault current cause forces on the bus conductors. The bus conductors and bus supports must be strong enough to withstand these forces.

The force imparted to the bus structure by fault current is dependent on conductor spacing, magnitude of fault current, type of short circuit, and degree of short-circuit asymmetry. Other factors to be considered are support flexibility, and corner and end effects.

10.1 Classical equation

The classical equation for the force between parallel, infinitely long conductors in a flat configuration due to an asymmetrical short-circuit current is as follows:

For Metric units:

$$F_{SC} = \frac{5.4\Gamma(2\sqrt{2}I_{SC})^2}{10^7(D)} = \frac{43.2\Gamma I_{SC}^2}{10^7(D)} \tag{10a}$$

For English units:

$$F_{SC} = \frac{2\Gamma(2\sqrt{2}I_{SC})^2}{10^4(D)} = \frac{1.6\Gamma I_{SC}^2}{10^4(D)} \tag{10b}$$

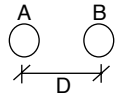
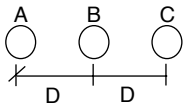
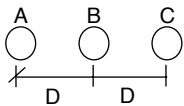
where

- F_{sc} = Fault current unit force, N/m [lbf/ft]
- I_{sc} = symmetrical rms fault current, A
- D = conductor spacing center-to-center, cm [in]
- Γ = constant based on type of fault and conductor location (see Table 2)

Equation (10) assumes that the fault is initiated to produce the maximum current offset. The magnitudes of the fault current I_{SC} for each type of fault (three-phase, phase-to-phase, etc.) are not equal to each other and will depend upon the electrical system parameters.

Unless data on the present and future available fault currents are known, it is suggested that the interrupting capability of the substation interrupting equipment (circuit breakers, circuit switchers, etc.) be considered as the maximum I_{SC} .

Table 2—Constant Γ for calculating short-circuit current forces

Type of short circuit	Configuration	Force on conductor	Γ
Phase-to-Phase		A or B	1.00
Three-Phase		B	0.866
Three-Phase		A or C	0.808

10.2 Decrement factor

Due to the presence of system impedance, there is a decrement of the asymmetrical wave in the first half-cycle of the fault. Therefore, it is practical to assume a lower value of peak fault current. Using a value of 1.6 as the assumed current offset, Equation (10) becomes

$$F_{sc} = \frac{C\Gamma(D_f\sqrt{2I_{sc}})^2}{(D)} \quad (11)$$

where

$C = 0.2 \times 10^{-4}$ for Metric units [5.4×10^{-7} for English units]

F_{sc} = short-circuit current unit force, N/mt [lbf/f]

I_{sc} = symmetrical short-circuit current, A, rms

D = conductor spacing center-to-center, cm [in]

Γ = constant based on type of short circuit and conductor location (see Table 2)

D_f = decrement factor is given by the following equation:

$$D_f = \sqrt{1 + \frac{T_a}{t_f} \left(1 - \exp^{-\frac{2t_f}{T_a}}\right)} \quad (11a)$$

where

$$T_a = \frac{X}{R} \frac{1}{2\pi f} \quad (X = \text{System Reactance}, R = \text{System Resistance}, \text{ and } f = 60\text{Hz})$$

t_f = fault current duration in seconds

If a system's maximum current offset is less than the assumed value of 1.6, the force will be further reduced.

Equation (11) gives the maximum force in the first half-cycle of the fault. The actual force present when maximum conductor span deflection occurs is usually less because

- Most conductor spans will not reach maximum deflection until after the first quarter-cycle, and
- Additional current decrement occurs as the fault continues.

The combination of these two factors results in lower maximum deflection than the deflection caused by a steady-state force equal to the maximum force in the first quarter-cycle.

Tests have shown that conductor spans with natural frequencies of 1/10 of the power frequency or less, and in a system with an X/R ratio of 13 or less, will have fault current forces of less than one half the calculated first quarter-cycle force when the conductor span reaches full deflection.

In practice, a static force equal to the first quarter-cycle force is generally used to calculate rigid-bus structure deflections and stresses. This practice has given a margin of safety to the rigid-bus structure design for fault current forces.

10.3 Mounting-structure flexibility

Because of their flexibility, the bus and mounting structures are capable of absorbing energy during a fault. Thus, depending on the type of mounting structures and their heights, the effective fault current forces can be further reduced by using Equation (12).

$$F_{SC} = K_f \frac{C\Gamma(D_f\sqrt{2I_{SC}})^2}{(D)} \quad (12)$$

K_f = mounting-structure flexibility factor

Values of K_f , as suggested by Working Group D3 for single-phase mounting structures, are given in Figure 4. K_f is usually assumed to be unity for three-phase mounting structures.

All other variables have been defined previously.

There have been fault current tests conducted on specific combinations of rigid-bus structures with mounting structures that indicate lower values of K_f than those shown in Figure 4. Where the structures are similar to those tested, the lower values of K_f may apply. Future work is expected to produce methods for determining values of K_f for specific mounting structures.

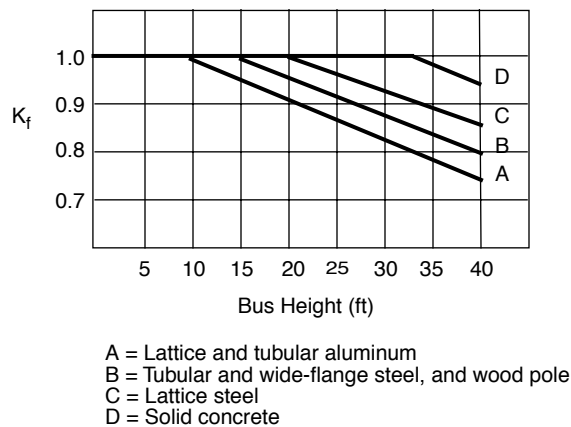


Figure 4— K_f for various types of single-phase mounting structures

10.4 Corner and end effects

The values for the short-circuit current force calculated by Equations (10), (11), and (12) are for parallel and infinitely long conductors. The results for short bus lengths will be conservative because of end effects. The equations cannot be used for special cases, such as corners and nonparallel conductors. Annex E provides methods for determining the forces for special bus configurations.

11. Conductor strength considerations

Any span of a bus conductor must have enough stiffness and strength to withstand the expected forces of gravity, wind, and short circuits, and maintain its mechanical and electrical integrity. The span should also not sag excessively under normal conditions.

This clause only includes equations for single-level, single-span bus conductors supported at both ends, and for continuous bus conductors supported at equal spans without concentrated loads. Annex F of this guide covers analysis for other forms. The simple static method given in Annex F can be used for analyzing distributed loads and concentrated loads on continuous bus conductors supported at equal or unequal spans.

This method is particularly valuable for analyzing a two-level bus arrangement, where one bus at the lower level supports the other bus at upper level using an A-frame form. In this case, the forces acting on the upper bus are transmitted to the lower bus as concentrated loads at each base of the A-frame. Such loading can impose severe stress on the bus conductors and the supporting insulators. A full static analysis could be performed to determine the stresses at various points using the method described in Annex F or other methods obtained from structural design handbooks.

11.1 Vertical deflection

11.1.1 Vertical deflection limits

The allowable vertical deflection of a bus conductor is usually limited by appearance. Commonly used limits are based either on the ratio of conductor deflection to span length (1 : 300 to 1 : 150), or the vertical dimension of the conductor (0.5% to 1% times the vertical dimension). Vertical deflection depends upon the total gravitational force. In practice, since appearance is usually not considered during icing conditions, the ice weight is usually not considered for vertical deflection. However, if the vertical deflection during icing conditions is important, then ice weight should be considered.

11.1.2 Total gravitational force

The total gravitational force on a conductor is the sum of the weights of the conductor, ice, damping material, and any concentrated loads. Without concentrated loads,

$$F_G = F_c + F_I + F_D \quad (13)$$

where

F_G = total bus unit weight, N/m [lbf/ft]

F_c = conductor unit weight, N/m [lbf/ft]

F_I = ice unit weight, N/m [lbf/ft]

F_D = clamping material unit weight, N/m [lbf/ft]

If the bus span is subjected to concentrated loads, the force distribution on that span should be analyzed more thoroughly.

11.1.3 Allowable span length for vertical deflection

The maximum allowable bus span length may be calculated with a given vertical deflection limit, end conditions, and total vertical force distribution.

The deflection may be based on either the vertical conductor dimension or a fraction of the span length.

End conditions for a single span range between fixed and pinned—A fixed end is not free to rotate (moment resisting), whereas a pinned end is free to rotate (not moment resisting). In reality, because of supporting structure flexibility and connection friction, the end conditions are not truly fixed or pinned.

If the end conditions of the single bus span are unknown, then Equation (14) for two pinned ends should be used. For a continuous bus, end conditions are assumed to be pinned and mid-supports are fixed.

11.1.3.1 Single-span bus, two pinned ends

For a single span with two pinned ends, the allowable span length based on vertical deflection may be calculated by one of the equations given in Table 3:

Table 3—Modulus of elasticity E for common conductor alloys

Bus-Conductor Alloy	E	
	kPa	lbf/in ²
Aluminum 6061-T6	6.895×10^7	10×10^6
Aluminum 6063-T6	6.895×10^7	10×10^6
Aluminum 6101-T61	6.895×10^7	10×10^6
Copper	11.03×10^7	16×10^6

$$L_D = C \sqrt[4]{\frac{384(E)(J)(Y_A)}{5F_G}} \text{ or } L_D = C \left[\frac{384(E)(J)(Y_A)}{5F_G} \right]^{\frac{1}{4}} \quad (14)$$

where

$C = 1.78$ for Metric units [1.86 for English units]

L_D = allowable span length, cm [in]

Y_A = allowable deflection, cm [in]

E = modulus of elasticity, kPa [lbf/in²] (see Table 3)

J = cross-sectional moment of inertia, cm⁴ [in⁴] (see [B1], chapter 13)

F_G = total bus unit weight, N/m [lbf/ft]

or

$$L_D = C \sqrt[3]{\frac{384(E)(J)(Y_B)}{5F_G}} \text{ or } L_D = C \left[\frac{384(E)(J)(Y_B)}{5F_G} \right]^{\frac{1}{3}} \quad (15)$$

where

Y_B = allowable deflection as a fraction of span length

All other variables have been defined previously.

11.1.3.2 Single-span bus, two fixed ends

For a span with two fixed ends, the allowable span length based on vertical deflection may be calculated by Equations (16) or (17).

$$L_D = C \sqrt[4]{\frac{384(E)(J)(Y_A)}{F_G}} \text{ or } L_D = C \left[\frac{384(E)(J)(Y_A)}{F_G} \right]^{\frac{1}{4}} \quad (16)$$

or

$$L_D = C \sqrt[3]{\frac{384(E)(J)(Y_B)}{F_G}} \text{ or } L_D = C \left[\frac{384(E)(J)(Y_B)}{F_G} \right]^{\frac{1}{3}} \quad (17)$$

where

$C = 1.78$ for Metric units [1.86 for English units]

L_D = allowable span length, cm [in]

Y_A = allowable deflection, cm [in]

Y_B = allowable deflection as a fraction of span length

E = modulus of elasticity, kPa [lbf/in²] (see Table 3)

J = cross-sectional moment of inertia, cm⁴ [in⁴] (see [B1], chapter 13)

F_G = total bus unit weight, N/m [lbf/ft]

11.1.3.3 Single-span bus, one pinned end, one fixed end

For a single span with one pinned end and one fixed end, Equations (18) and (19) may be used to calculate the maximum allowable span length based on vertical deflection.

$$L_D = C \sqrt[4]{\frac{185(E)(J)(Y_A)}{F_G}} \text{ or } L_D = C \left[\frac{185(E)(J)(Y_A)}{F_G} \right]^{\frac{1}{4}} \quad (18)$$

or

$$L_D = C \sqrt[3]{\frac{185(E)(J)(Y_B)}{F_G}} \text{ or } L_D = C \left[\frac{185(E)(J)(Y_B)}{F_G} \right]^{\frac{1}{3}} \quad (19)$$

where

$C = 1.78$ for Metric units [1.86 for English units]

All other variables have been defined previously.

11.1.3.4 Continuous bus

For a continuous bus, Equations (20) or (21) may be used to calculate the maximum allowable span length based on vertical deflection.

$$L_D = C \sqrt[4]{\frac{185(E)(J)(Y_A)}{F_G}} \text{ or } L_D = C \left[\frac{185(E)(J)(Y_A)}{F_G} \right]^{\frac{1}{4}} \quad (20)$$

$$L_D = C \sqrt[3]{\frac{185(E)(J)(Y_B)}{F_G}} \text{ or } L_D = C \left[\frac{185(E)(J)(Y_B)}{F_G} \right]^{\frac{1}{3}} \quad (21)$$

where

$C = 1.78$ for Metric units [1.86 for English units]

All other variables have been defined previously.

NOTE—The above equations are for two-span buses. For continuous bus of more than two spans, the maximum deflection occurs in the end spans and is slightly less than that of the two-span bus. The allowable span will be slightly longer.

11.2 Conductor fiber stress

In some cases, span lengths may be limited by the fiber stress of the bus-conductor material. The elastic limit and minimum yield stresses for common conductor materials are tabulated in Table 4. In practice, when wind and gravitational forces are combined, the elastic limit stress is commonly used as the maximum allowable stress. When wind, gravitational, and fault current forces F_{SC} are combined, the minimum yield stress is commonly used as the maximum allowable stress, since F_{SC} is conservative.

11.2.1 Effects of welding

Where welded fittings are used for bus, the allowable stress for the bus should be reduced to allow for annealing due to welding. Tests have shown that the reduction in allowable stress is approximately 50% for aluminum. The reduction in allowable stress for copper is dependent on the welding method (brazing, exothermic, etc.) and should be discussed with the manufacturers. Locating the weld in a region of moderate stress is a usual method of offsetting the effect of weld annealing. Where welded splices are used with a tubular bus, the reduction in allowable stress may not be required if a reinforcing insert is incorporated.

11.2.2 Summation of conductor forces

The maximum bending stresses a conductor withstands are a function of the total vectorial force on the conductor. The total force on a conductor in a horizontal configuration is

$$F_T = \sqrt{[(F_w + F_{SC})^2 + (F_G)^2]} \quad (22)$$

where

F_T = total unit force, N/m [lbf/ft]

F_w = wind unit force, N/m [lbf/ft]

F_{SC} = fault unit force, N/m [lbf/ft]

F_G = total bus unit weight, N/m [lbf/ft]

Table 4—Allowable stress for common conductor materials

Bus-Conductor Material	Stress (lbf/in ²)		Stress (kPa)	
	Elastic Limit	Minimum Yield	Elastic Limit	Minimum Yield
Aluminum alloy—6063-T6 or 6101-T6	20 500	25 000 ^a	141 348	172 375 ^a
Aluminum alloy— 6061-T6	29 500	35 000 ^a	203 403	241 325 ^a
Aluminum alloy— 6061-T61	11 000	15 000 ^a	75 845	103 452 ^a
Copper No. 110 hard drawn	—	24 000 ^b	—	275 800 ^b

^aWith 0.2 offset per ASTM B241/B241M-96.^bWith 0.5% offset per ASTM B188-96.

The angle of the total force below horizontal is

$$\theta = \tan^{-1} \left[\frac{F_G}{F_w + F_{SC}} \right] \quad (23)$$

The total force on a conductor in a vertical configuration is

$$F_T = \sqrt{(F_w)^2 + (F_G + F_{SC})^2} \quad (24)$$

where

F_T = total unit force, lbf/ft [N/m]

F_W = wind unit force, N/m [lbf/ft]

F_G = total bus unit weight, N/m [lbf/ft]

F_{SC} = short-circuit unit force, N/m [lbf/ft]

The angle of the force below horizontal is

$$\theta = \tan^{-1} \left[\frac{F_G + F_{SC}}{F_w} \right] \quad (25)$$

11.2.3 Allowable span length for fiber stress

The maximum allowable span length for fiber stress may be calculated for any given conductor, total force, and allowable stress. If the conductor cross section is not symmetrical about the direction of the total force, calculations should be made for the conductor section modulus in the direction of the total force.

If the end conditions of the bus span are unknown, then Equation (26) should be used.

11.2.3.1 Two pinned ends

For a single span with two pinned ends, the allowable span length is calculated with Equation 26.

$$L_S = C \sqrt{\frac{8F_A S}{F_T}} \quad (26)$$

where

L_S = maximum allowable length, cm [in]
 $C = 3.16$ for Metric units [3.46 for English units]
 F_A = maximum allowable stress, kPa² [lbf/in]
 S = section modulus, cm³ [in³]
 F_T = total force, N/m [lbf/ft]

The maximum bending moment will occur at the middle of the span.

11.2.3.2 Single-span bus, two fixed ends

For a span with two fixed ends, the allowable span-length equation based on fiber stress is:

$$L_S = C \sqrt{\frac{12(F_A)(S)}{F_T}} \quad (27)$$

where

$C = 3.16$ for Metric units [3.46 for English units]

All other variables have been defined previously.

11.2.3.3 Single-span bus, one pinned end, one fixed end

For a single span with one pinned end and one fixed end, the maximum allowable span based on fiber stress may be calculated as follows:

$$L_S = C \sqrt{\frac{8(F_A)(S)}{F_T}} \quad (28)$$

where

$C = 3.16$ for Metric units [3.46 for English units]

All other variables have been defined previously.

The maximum bending moment will occur at the fixed end of the span.

11.2.3.4 Continuous-span bus

Equation (29a), Equation (29b), and Equation (29c), as follows, may be used to calculate the maximum allowable span length based on fiber stress for a different number of spans.

Number of Spans	Equation	Equation Number
Two-Span Bus	$L_S = C \sqrt{\frac{8(F_A)(S)}{F_T}}$ $C = 3.16 \text{ Metric units [3.46 for English units]}$	(29a)
Three-Span Bus	$L_S = C \sqrt{\frac{10(F_A)(S)}{F_T}}$ $C = 3.16 \text{ Metric units [3.46 for English units]}$	(29b)
Four-Span Bus	$L_S = C \sqrt{\frac{28(F_A)(S)}{F_T}}$ $C = 3.16 \text{ Metric units [3.46 for English units]}$	(29c)

NOTE—The allowable span length is limited by the maximum fiber stress that occurs at the second support from each end. Equation (29c) can be used conservatively for continuous bus with more than a four-span length. L_S , F_A , F_T , and S are as defined earlier.

11.3 Maximum allowable span length

The maximum allowable span length L_A is equal to L_S or L_D , whichever is shorter.

12. Insulator strength considerations

Since the forces on the bus conductors are transmitted to the insulators, the strength of the insulators must be considered. With various bus configurations, insulators may be required to withstand cantilever, compressive, tensile, and torsional forces. Only cantilever forces have been considered in this guide. However, other forces (tension, torsion, and compression) may be critical, requiring consideration in the design.

12.1 Insulator cantilever forces

The insulator cantilever force for some common bus arrangements can be given as a function of the effective conductor span length supported by the insulator and the external forces on the bus and insulator. The external forces are

- a) The fault current force on the bus
- b) The wind force on the bus and insulator
- c) The gravitational forces on the bus, insulator or concentrated masses, or both

The effective conductor span length L_E depends on the span length and the bus-support conditions. Use Table 5 to find L_E for each particular support condition and the number of spans. If the support conditions are not known, then take the support condition that yields the maximum span length L_S calculated in Clause 11.

Table 5—Maximum effective bus span length L_E supported by insulator for common bus arrangements^a

Bus Configuration	Support Conditions					Maximum Span Length L_E
	S1	S2	S3	S4	S5	
Single-Span	P	P				$(1/2)L$
Single-Span	P	F				$(5/8)L$ (Max at S2)
Single-Span	F	F				$(1/2)L$
Two Cont.-Span	P	C	P			$(5/4)L$ (Max at S2)
Two Cont.-Span	P	F	F			$(9/8)L$ (Max at S2)
Two Cont.-Span	F	F	F			L (Max at S2)
Three Cont.-Span	P	C	C	P		$11/10 L$ (Max at S2)
Four Cont.-Span	P	C	C	C	P	$32/28 L$ (Max at S2)

^a L = Bus Span Length - Equal Spans for two or more spans. L_E = Maximum Effective Span Length.

P = Pinned Support

F = Fixed Support

C = Mid-Support of Continuous Span

NOTE—This table is applicable only to equal span bus arrangement. The mid-support of a continuous bus has only reaction force, but no moment although the continuous bus conductor has a moment at the support point. See Annex F for the method of calculating insulator cantilever forces for individual support of all continuous-bus arrangements. For continuous spans of more than the spans shown, use the equation for the largest span shown for the same end conditions.

12.1.1 Bus short-circuit current force

The short-circuit current force transmitted to the bus-support fitting can be calculated using Equation (30).

$$F_{SB} = L_E F_{SC} \quad (30)$$

where

F_{SB} = bus fault current force transmitted to bus-support fitting, N [lbf]

L_E = effective bus span length, m [ft] (See Table 5)

F_{SC} = fault current unit force as calculated in Clause 10, N/m [lbf/ft]

If the end conditions are unknown, then the fixed end conditions at the bus-support fitting in question and pinned end conditions at the opposite ends of the adjacent spans will yield the maximum effective bus span length. The adjacent bus span lengths L_1 and L_2 should be equal to or less than the maximum allowable span length L_D calculated in Clause 11.

12.1.2 Bus wind force

The unit wind force associated with the bus span is the same as that described in Clause 9. The wind force transmitted to the bus-support fitting can be calculated using Equation (31).

$$F_{WB} = L_E F_W \quad (31)$$

where

F_{WB} = bus wind force transmitted to bus-support fitting, N [lbf]

L_E = effective bus span length, m [ft] (see Table 5)

F_W = wind unit force on the bus, N/m [lbf/ft]

12.1.3 Insulator wind force

The wind force on the bus-support insulator is a function of

- a) The insulator dimensions
- b) The wind speed
- c) The gust factor
- d) The radial ice thickness
- e) The mounting height
- f) Exposure to wind

The wind force acting on the center of an insulator can be calculated using Equation (32).

$$F_{WI} = C C_D K_Z G_F V^2 (D_i + 2 r_1) H_i \quad (32)$$

where

F_{WI} = wind force on insulator, N [lbf]

$C = 6.13 \times 10^{-3}$ for Metric units [2.132×10^{-4} for English]

C_D = drag coefficient

K_Z = height and exposure factor

G_F = gust factor

V = wind speed at 30 ft [9.1 m] above ground, km/h [mi/h]

D_i = effective insulator diameter, cm [in]

r_1 = radial ice thickness, cm [in]

H_i = insulator height, cm [in] (see Fig 5)

r_1 , K_Z , G_F , and V are the same factors used for the wind force on the bus conductor (see Clause 9). C_D is usually considered as unity.

The effective insulator diameter D_i is usually considered as the insulator diameter over the skirts. For tapered insulators the effective diameter is the average diameter and can be calculated using Equation (33).

$$D_i = \frac{D_1 + D_2 + \dots + D_n}{n} \quad (33)$$

where

D_1 , D_2 , and D_n = outside diameters of each subassembly for the 1st, 2nd, and nth sections of the insulator (see Figure 5).

The total wind force F_{WI} on a uniform-diameter insulator acts at the center of the insulator (see Figure 5). For a tapered insulator, the total wind force is usually considered acting at the center $H_i/2$ since the resulting error is of small magnitude and is conservative.

12.1.4 Gravitational forces

In some rigid-bus structure configurations, the insulator may be subjected to cantilever gravitational forces. These forces should be added vectorially to the fault current and wind forces. These gravitational forces will be due to the mass of the supported rigid bus, the mass of the insulator itself or other concentrated masses, or both.

The effective weight of the bus mass transmitted to the bus-support fitting can be determined using Equation (34).

$$F_{GB} = L_E F_G \quad (34)$$

where

F_{GB} = effective weight of bus transmitted to bus-support fitting, N [lbf]

L_E = effective bus span length, m [ft] (see Table 5)

F_G = total bus unit weight, N/m [lbf/ft]

If the bus span is subjected to concentrated loads, the force transmitted to the bus-support fitting should be analyzed more thoroughly.

The weight of the insulator F_{GI} should be included in the total cantilever force if the insulator is not mounted vertically.

12.1.5 Total insulator cantilever load

The total cantilever load on an insulator is the summation of the cantilever forces acting on the insulator multiplied by their overload factors.

The total cantilever load on a vertically-mounted insulator supporting a horizontal bus (see Figure 5) can be calculated using Equation (35).

$$F_{IS} = K_1 \left[\frac{F_{WI}}{2} + \frac{(H_i + H_f)F_{WB}}{H_i} \right] + K_2 \left[\frac{(H_i + H_f)F_{SB}}{H_i} \right] \quad (35)$$

where

F_{IS} = total cantilever load acting at end of insulator, N [lbf]

F_{WI} = wind force on the insulator, N [lbf]

F_{SB} = short-circuit current force transmitted to bus-support fitting, N [lbf]

F_{WB} = bus wind force transmitted to the bus-support fitting, N [lbf]

H_i = insulator height, cm [in]

H_f = bus centerline height above the insulator, cm [in]

K_1 = overload factor applied to wind forces

K_2 = overload factor applied to short-circuit current forces