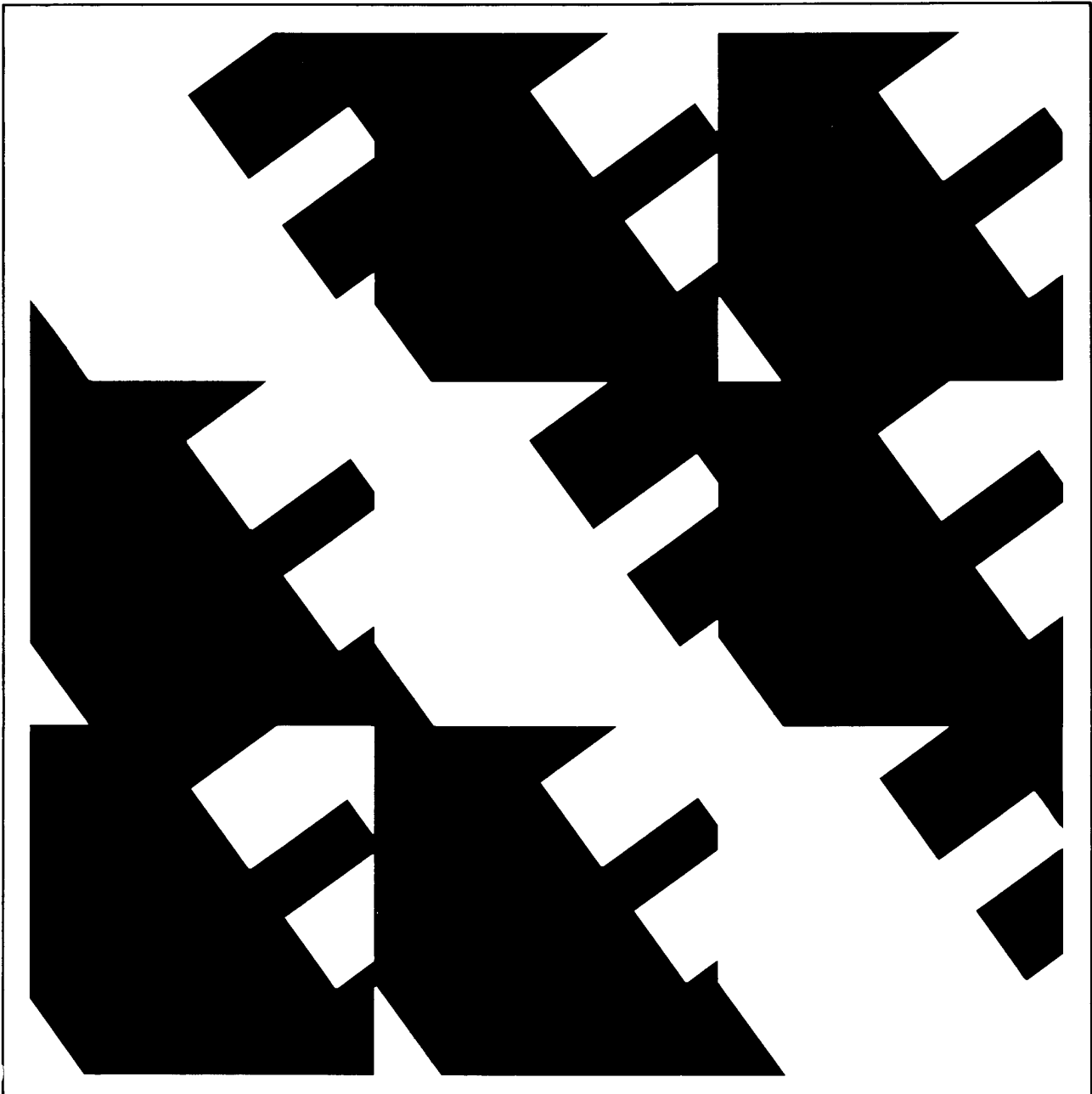


IEEE Guide for Design of Substation Rigid-Bus Structures

ANSI/IEEE Std 605-1987



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IEEE Guide for Design of Substation Rigid-Bus Structures

1. Purpose

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

Special considerations are given to short-circuit-current force calculations. These considerations take into account the decrement of the short-circuit current, the flexibility of supports, and the natural frequency of the bus. These factors are mentioned in ANSI C37.32-1972 [6]¹, but are not taken into consideration in the equation presented in that standard.

2. 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, short-circuit current, and thermal expansion are considered. Design criteria for conductor and insulator strength calculations are included. This guide does not consider

- (1) The electrical criteria for the selection of insulators
- (2) The seismic forces to which the substation may be subjected
- (3) The design of mounting structures.

3. Definitions

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

¹ The numbers in brackets correspond to the references listed in Section 4 of this guide.

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

bus support. An insulating support for a bus.

NOTE: It includes one or more insulator units with fittings for fastening to the mounting structure and for receiving the bus.

mounting structure. A structure for mounting an insulating support.

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

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

4. References

This guide shall be used in conjunction with the following publications:

- [1] ANSI/ASTM B241-80, Standard Specification for Aluminum-Alloy Seamless Pipe and Seamless Extruded Tube.²
- [2] ANSI A58.1-1982, American National Standard Minimum Design Loads for Buildings and Other Structures.
- [3] ANSI C2-1987, American National Standard National Electrical Safety Code.
- [4] ANSI C29.1-1982, American National Standard Testing Methods for Electrical Power Insulators.
- [5] ANSI C29.9-1983, American National Standard Wet-Process Porcelain Insulators (Apparatus, Post Type).

² ANSI publications are available from the Sales Department, American National Standards Institute, 1430 Broadway, New York, NY 10018.

- [6] ANSI C37.32-1972, American National Standard Guide for High-Voltage Air Switches, Bus Supports, and Switch Accessories, Schedules of Preferred Ratings, Manufacturing Specifications and Applications.
- [7] ANSI/IEEE C37.30-1971, IEEE Standard Definitions and Requirements for High-Voltage Air Switches, Insulators, and Bus Supports.³
- [8] ANSI/IEEE Std 100-1984, IEEE Standard Dictionary of Electrical and Electronics Terms.
- [9] ANSI/IEEE Std 693-1984, IEEE Recommended Practice for Seismic Design of Substations.
- [10] ANSI/NFPA 70-1981, National Electrical Code.⁴
- [11] ASTM B188-81, Standard Specification for Seamless Copper Bus Pipe and Tube.⁵
- [12] NEMA CC1-1984, Electric Power Connectors for Substations.⁶
- [13] NEMA 107-1964 (R 1981), Methods of Measurement of Radio-Influence Voltage (RIV) of High-Voltage Apparatus.
- [14] Wind Forces on Structures. *Transaction Paper* no 3269-1961, vol 126.⁷
- [15] *Aluminum Electrical Conductor Handbook*. Aluminum Company of America.
- [16] Transmission System Radio Influence. Radio Noise Subcommittee of the Transmission and Distribution Committee of the IEEE Power Group. *Transactions on Power Apparatus and Systems*, Aug 1965.

³ ANSI/IEEE publications are available from the Institute of Electrical and Electronics Engineers, IEEE Service Center, 445 Hoes Lane, PO Box 1331, Piscataway, NJ 08855-1331, or from the Sales Department, American National Standards Institute, 1430 Broadway, New York, NY 10018.

⁴ The National Electrical Code is published by the National Fire Protection Association, Batterymarch Park, Quincy, MA 02269. Copies are also available from the Sales Department, American National Standards Institute, 1430 Broadway, New York, NY 10018.

⁵ ASTM publications are available from the Sales Office, American Society for Testing Materials, 1916 Race Street, Philadelphia, PA 19103.

⁶ NEMA publications are available from the National Electrical Manufacturers Association, 2101 L Street, NW, Washington, DC 20037.

⁷ This publication is available from the American Society of Civil Engineers, 345 East 47th Street, New York, NY 10017.

- [17] CHAINE, P. M., VERGE, R. W., CASTONGUAY, G., and GARIEPY J. Wind and Ice Loading in Canada, Industrial Meteorology—Study II. Toronto: Environment Canada; 1974.

5. The Design Problem

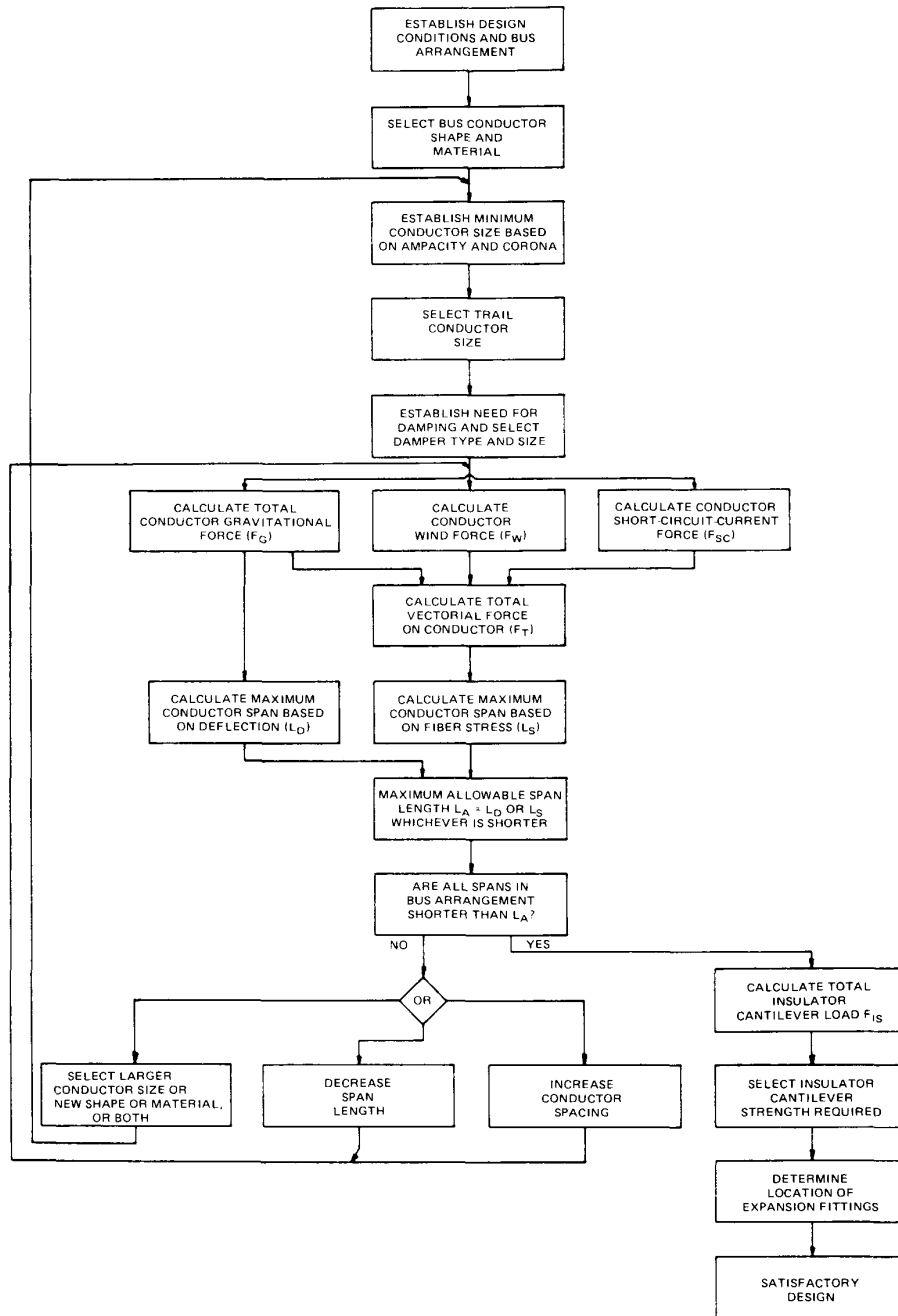
The design problem considered in this guide is the selection of rigid-bus structure components and their arrangements. For a safe, reliable, and economic design, the components and their arrangements should be optimized to satisfy the design conditions. The design conditions will establish minimum electrical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

- (1) The minimum ampacity requirements
- (2) Maximum anticipated short-circuit current
- (3) Maximum operating voltage
- (4) Maximum anticipated wind speeds
- (5) Maximum expected icing conditions combined with wind
- (6) The altitude of the substation site
- (7) Basic substation layout

The selection of conditions acting simultaneously on the bus structure (that is, short circuit, extreme wind, or 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, which is involved with a bus failure when the design conditions are selected.

Design conditions should also be specified for the electrical performance of insulators. Also, if the substation is located in an area of possible seismic activity, additional design conditions should be established. ANSI/IEEE Std 693-1984 [9] and the seismic zone maps in ANSI A 58.1-1982 [2] 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 Fig 1).



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

Fig 1
Design Process for Horizontal Bus

6. 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 copper conductor.

6.1 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:

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

where

- I = current for the allowable temperature rise, A
- R = direct-current resistance at the operating temperature, Ω/ft
- F = skin-effect coefficient
- q_s = solar heat gain, W/ft
- q_c = convective heat loss, W/ft^*
- q_r = radiation heat loss, W/ft
- q_{cond} = conductive heat loss, W/ft^*

* Values for convective or conductive heat gains on the right side of Eq 1 is entered as negative numbers.

The current for a given conductor temperature rise is

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

where

- I = current for the allowable temperature rise, A
- R = direct-current resistance at the operating temperature, Ω/ft
- F = skin-effect coefficient
- q_s = solar heat gain, W/ft
- q_c = convective heat loss, W/ft^*
- q_r = radiation heat loss, W/ft
- q_{cond} = conductive heat loss, W/ft^*

* Values for convective or conductive heat gains on the right side of Eq 2 is entered as negative numbers.

6.1.1 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.

6.1.2 Solar Heat Gain, q_s . The amount of solar heat gained is a function of

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

6.1.3 Convective Heat Loss, q_c . A bus-conductor loses heat through natural or forced convection.

6.1.3.1. Natural convective heat loss is a function of

- (1) The temperature difference between the conductor surface and the ambient air temperature
- (2) The orientation of the conductor's surface
- (3) The width of the conductor's surface
- (4) The conductor's surface area

6.1.3.2. Forced convective heat loss is a function of

- (1) The temperature difference between the conductor's surface and the ambient air temperature
- (2) The length of flow path over the conductor
- (3) The wind speed
- (4) The conductor's surface area

6.1.4 Radiation Heat Loss, q_r . A conductor loses heat through the emission of radiated heat. The heat lost is a function of

- (1) The difference in the absolute temperature of the conductor and surrounding bodies
- (2) The emissivity of the conductor's surface
- (3) The conductor's surface area

6.1.5 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.

6.2 Conductor Temperature Limits

6.2.1 Continuous. (See ANSI/IEEE C37.30-1971 [7].) 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

6.2.2 Short Circuit. (See ANSI C37.32-1972 [6].) 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 Eqs 3 and 4. In general, the final temperature of the conductor is limited to the maximum temperature considered for thermal expansion (see Section 14).

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

$$I = 0.144 \cdot 10^6 A$$

$$\left[\frac{1}{t} \log_{10} \frac{T_f - 20 + (15150/G)}{T_i - 20 + (15150/G)} \right]^{\frac{1}{2}} \quad (\text{Eq 3})$$

where

- I = the maximum allowable root-mean-square (rms) value of fault current, A
- A = conductor cross-sectional area, 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),

$$I = 0.22 \cdot 10^6 A$$

$$\left[\frac{1}{t} \log_{10} \frac{T_f - 20 + (25400/G)}{T_i - 20 + (25400/G)} \right]^{\frac{1}{2}} \quad (\text{Eq 4})$$

where

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

A = conductor cross-sectional area, in²

G = conductivity in percent IACS

t = duration of fault, s

T_f = allowable final conductor temperature, °C

T_i = conductor temperature at fault initiation, °C

6.2.3 Attached Equipment. Since heat generated in the bus-conductor may be conducted to attached equipment, allowable bus-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 ANSI/IEEE C37.30-1971 [7].

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

7. 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 (RI) 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 (RI) will be less than that calculated because of this effect [16].

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.

7.1 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

- (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 Appendix D for calculating the maximum surface voltage gradient for smooth, circular bus-conductors E_m . The calculations 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 (RI) generation E_o for smooth, circular bus-conductors is a function of bus diameter, barometric pressure, and operating temperature. Appendix D gives a method for determining the allowable surface voltage gradient.

7.2 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 7.2.1 do not require the control of air temperature and air pressure during testing. The specifier should refer to Appendix 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 Appendix D to compensate for the test pressure and temperature.

7.2.1 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.

7.2.1.1 Visual Corona. The visual corona extinction voltage should be tested according to NEMA CC1-1984 [12].

7.2.1.2 Radio-Influence Voltage (RIV) Level. The radio-influence voltage (RIV) level should be tested according to NEMA 107-1964 (R1981) [13].

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

7.2.2.1 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.

7.2.2.2 Radio-Influence Voltage (RIV). The specified radio-influence voltage (RIV) limits for various bus system components should be those given by the following standards:

- (1) *For fittings and connectors* see NEMA CC1-1984 [12].
- (2) *For insulators and hardware assemblies* see ANSI C29.9-1984 [5].

8. 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 increases.

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

8.1 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 Eq 5.

$$f_b = \frac{K^2}{24L^2} \left(\frac{EJ}{M} \right)^{\frac{1}{2}} \quad (\text{Eq 5})$$

where

- f_b = natural frequency of conductor span, Hz
- L = span length, ft
- E = modulus of elasticity, lbf/in²
- J = moment of inertia of cross-sectional area, in⁴

m = mass per unit length (pound-mass per linear foot = $\frac{1}{32.2} \cdot \text{weight}$), lbf/ft

K = 1.00 for two pinned ends (dimensionless)
 = 1.22 for one pinned end and one fixed end (dimensionless)
 = 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.

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

8.2.1 Current Induced Vibrations. Current 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.

8.2.2 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 using the Von Karmen formula.

$$f_a = \frac{3.26 V}{d} \quad (\text{Eq 6})$$

where

f_a = maximum aeolian force frequency, Hz
 V = maximum wind speed for laminar flow, mi/h
 d = conductor diameter, in

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

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

8.3 Damping. Bus spans may be damped to reduce aeolian vibration. For tubular bus-conductor, 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 non-tubular conductors. Commercial vibration dampers should be sized and placed according to the manufacturer's recommendations.

9. Conductor Gravitational Forces

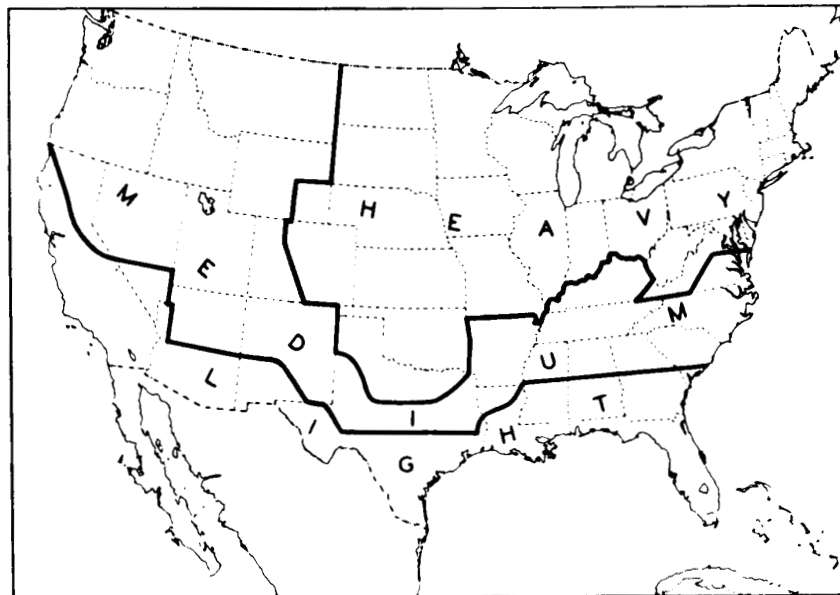
Gravitational forces determine the vertical deflection of bus-conductors and are a component of the total force, which the conductor must withstand. Gravitational forces consist of the weights of the conductor, damping material, ice, and concentrated masses.

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

9.2 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.

9.3 Ice. The minimum radial ice thickness used for design should be determined from ANSI C2-1987 [3] (see Fig 2), or [17].

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 circular conductor is given as



Loading	Radial Ice Thickness (in)
Heavy	0.50
Medium	0.25
Light	0.00

Fig 2
General Loading Map Showing Territorial Division of the United States With Respect to Loading of Overhead Lines

$$F_I = \pi W_I r_I (d + r_I), 12 \text{ in/ft} \quad (\text{Eq 7})$$

where

F_I = ice unit weight, lbf/ft
 W_I = ice weight = 0.0330, lbf/in³
 r_I = radial ice thickness, in
 d = outside conductor diameter, in

Equation 7 may be simplified to

$$F_I = 1.244 r_I (d + r_I) \quad (\text{Eq 8})$$

Similar equations may be derived for other conductor shapes.

9.4 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.

10. 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.

Annual extreme fastest-mile wind speeds for design without ice should be determined from ANSI A58.1-1982 [2] (see Fig 3), or [17]. 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 ANSI A58.1-1982 [2].

The fastest-mile wind speed with ice should

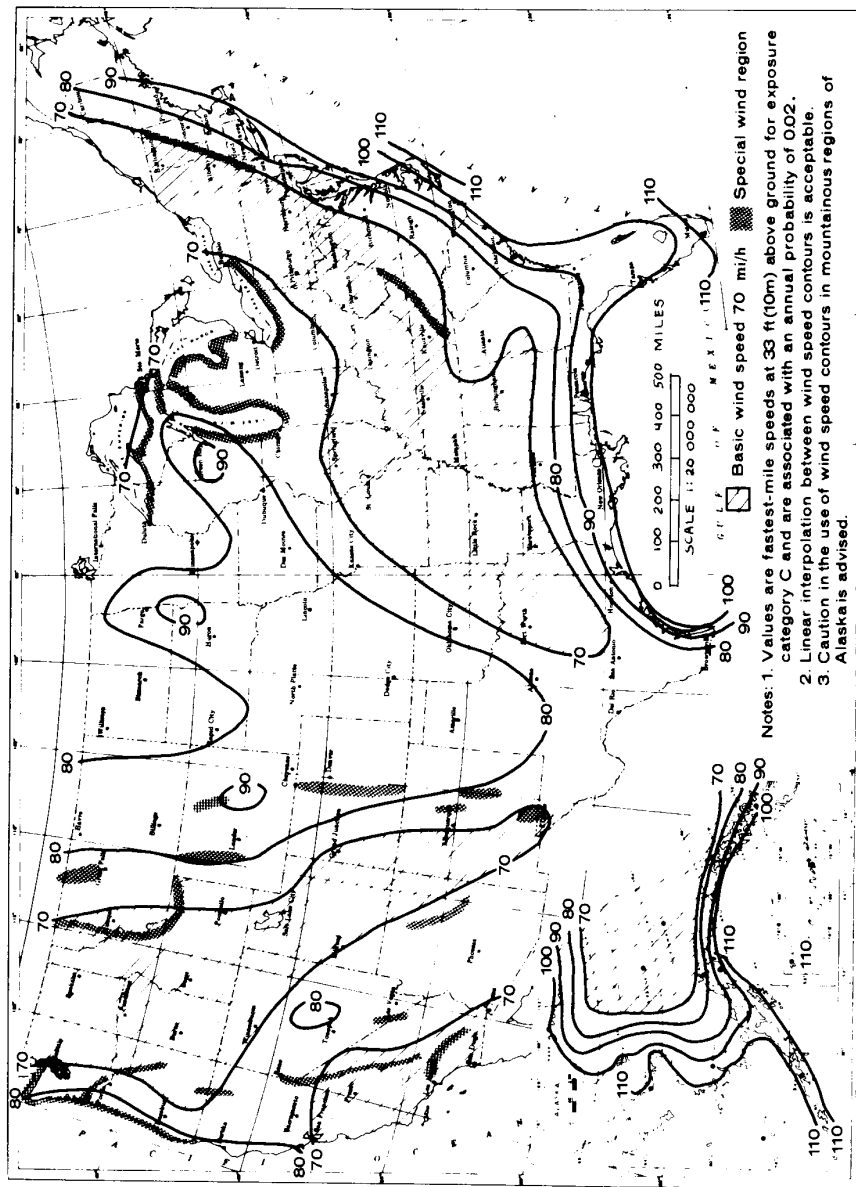
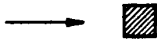
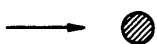
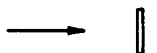
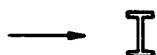
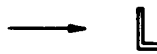
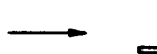
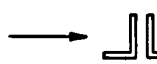


Fig 3*
**Basic Wind Speed—Miles Per Hour (mi/h) Annual Extreme Fastest-Mile
 Speed 30 ft Above Ground, 50 yr Mean Recurrence Interval**

*From ANSI A58.1-1982. Reprinted with permission.

Table 1
Drag Coefficients for Structural Shapes
($\lambda \rightarrow \infty$)*

PROFILE AND WIND DIRECTION	C_D
	2.03
	1.00
 OR 	2.00
	2.04
	2.00
	1.83
 OR 	1.99

* λ = Ratio of span length to vertical dimension of bus-conductor

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.

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

$$F_w = 2.132 \cdot 10^{-4} C_D K_z G_F V^2 (d + 2r_i)$$

where

F_w = wind unit force on bus, lbf/ft

d = outside conductor diameter, in

r_i = radial ice thickness, in

C_D = drag coefficient, (see 10.1)

K_z = height and exposure factor, (see 10.2)

G_F = gust factor, (see 10.3)

V = wind speed at 30 ft above ground, mi/h

10.1 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.

10.2 Height and Exposure Factor, K_z . In the height zone from 0 ft to 30 ft, the height and exposure factor $K_z = 1.0$, and the wind speed at 30 ft should be used. If the height of the bus structure exceeds 30 ft or the terrain surrounding the substation is such that ground resistance effects to the wind are diminished, the height and exposure factor K_z should be increased according to ANSI A58.1-1982 [2].

10.3 Gust Factors, G_F . A gust factor G_F of 1.3 for small structures and 1.1 for structures having a horizontal dimension, transverse to the wind, of at least 125 ft, is recommended by [14]. Depending on the span length of the bus conductor under consideration, a gust factor G_F of 1.1 to 1.3 should be applied to the wind force.

11. Conductor Short-Circuit-Current Forces

The magnetic fields produced by short-circuit 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 short-circuit current is dependent on conductor spacing, magnitude of short-circuit current, type of short circuit, and degree of short-circuit asymmetry. Other factors to be considered are support flexibility, and corner and end effects.

11.1 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

$$F_{sc} = \frac{5.4\Gamma (2\sqrt{2} I_{sc})^2}{10^7(D)} = \frac{43.2\Gamma I_{sc}^2}{10^7(D)} \quad (\text{Eq 9})$$

where

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

Equation 9 assumes that the fault is initiated when the voltage is zero and consequently the current offset is maximum. The magnitudes of the short-circuit current I_{sc} for each type of fault (three phase, phase-to-phase, etc) are not equal

to each other and will depend on the electrical system parameters.

Unless data on the present and future available short-circuit current 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} .

11.2 Decrement Factor. Due to the presence of system impedance, there is a decrement of the asymmetrical wave in the first quarter-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, Eq 9 becomes

$$F_{sc} = \frac{5.4\Gamma (1.6\sqrt{2} I_{sc})^2}{10^7(D)} = \frac{27.6\Gamma I_{sc}^2}{10^7(D)} \quad (\text{Eq 10})$$

where

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

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

Equation 10 gives the maximum force in the first quarter-cycle of the fault. The actual force present when maximum conductor span deflection occurs is usually less because:

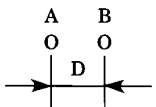
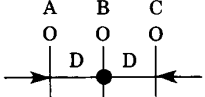
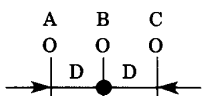
- (1) Most conductor spans will not reach maximum deflection until after the first quarter-cycle
- (2) Additional current decrement occurs as the fault continues

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 $\frac{1}{10}$ of the power frequency or less, and in a system with an X/R ratio of 13 or less, will have short-circuit-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-

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	1.000
Three phase		B	0.866
Three phase		A or C	0.808

bus structure design for short-circuit-current forces.

11.3 Mounting Structure Flexibility. Because of their flexibility, the bus structure and mounting structures are capable of absorbing energy during a fault. Thus, depending on the type of mounting structures and their heights, the effective short-circuit-current forces can be further reduced by using Eq 11.

$$F_{sc} = K_f \left[\frac{27.6\Gamma I_{sc}}{10^7(D)} \right]^2 \quad (\text{Eq 11})$$

where

F_{sc} = short-circuit-current unit force in the first quarter-cycle recognizing decrement and support flexibility factors, lbf/ft

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

D = conductor spacing center-to-center, in

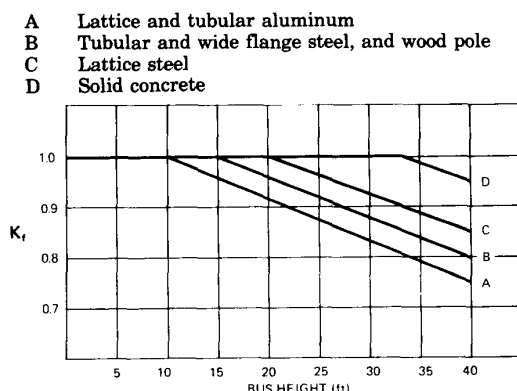
Γ = constant based on type of short circuit and conductor location (see Table 2)

K_f = mounting structure flexibility factor

Values of K_f , as suggested by Working Group 69.1 for single-phase mounting structures, are given in Fig 4. K_f is usually assumed to be unity for three-phase mounting structures.

There have been short-circuit tests conducted on specific combinations of rigid-bus structures with mounting structures that indicate lower values of K_f than those shown on Fig 4. Where the structures are similar to those tested, the lower values of K_f may apply. Future work is

Fig 4
 K_f For Various Types of
Single-Phase Mounting Structures



expected to produce methods for determining values of K_f for specific mounting structures.

11.4 Corner and End Effects. The values for the short-circuit-current force calculated by Eqs 9, 10, and 11 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. Appendix E provides methods for determining the forces for special bus configurations.

12. Conductor Strength Considerations

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

Although this section includes only bus-conductors supported at both ends without concentrated loads, equations for other configurations and for analyzing concentrated loads may be obtained from structural design handbooks.

12.1 Vertical Deflection

12.1.1 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 (.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.

12.1.2 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,

$$F_G = F_c + F_i + F_d \quad (\text{Eq 12})$$

where

F_G = total bus unit weight, lbf/ft
 F_c = conductor unit weight, lbf/ft
 F_D = damping material unit weight, lbf/ft
 F_I = ice unit weight lbf/ft

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

12.1.3 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 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 bus span are unknown, then Eq 13 for two pinned ends should be used.

12.1.3.1 Two Pinned Ends. For a span with two pinned ends, the allowable span length based on vertical deflection may be calculated by one of the following equations. Equations 13, 14, 15, 16, 17, or 18.

Table 3
Modulus of Elasticity E for
Common-Conductor Alloys

Bus-Conductor Alloy	E , lbf/in ²
Aluminum 6061-T6	$10 \cdot 10^6$
Aluminum 6063-T6	$10 \cdot 10^6$
Aluminum 6101-T61	$10 \cdot 10^6$
Copper	$16 \cdot 10^6$

$$L_D = \left[\frac{384(E)(J)(Y_A)}{5(F_G/12)} \right]^{\frac{1}{4}} \quad (\text{Eq 13})$$

where

L_D = allowable span length, in
 Y_A = allowable deflection, in
 E = modulus of elasticity, lbf/in²
 (see Table 3)
 J = cross-sectional moment of inertia, in⁴
 (see [15], ch 13)
 F_G = total bus unit weight, lbf/ft

or,

$$L_D = \left[\frac{384(E)(J)(Y_B)}{5(F_G/12)} \right]^{\frac{1}{3}} \quad (\text{Eq 14})$$

where

L_D = allowable span length, in
 Y_B = allowable deflection as a fraction of span length
 E = modulus of elasticity, lbf/in²,
 (see Table 3)
 J = cross-sectional moment of inertia, in⁴
 (see [15], ch 13)
 F_G = total bus unit weight, lbf/ft

12.1.3.2 Two Fixed Ends. For a span with two fixed ends, the allowable span length based on vertical deflection may be calculated by Eqs 15 or 16.

$$L_D = \left[\frac{384(E)(J)(Y_A)}{F_G/12} \right]^{\frac{1}{4}} \quad (\text{Eq 15})$$

or,

$$L_D = \left[\frac{384(E)(J)(Y_B)}{F_G/12} \right]^{\frac{1}{3}} \quad (\text{Eq 16})$$

where

L_D = allowable span length, in
 Y_A = allowable deflection, in
 Y_B = allowable deflection as a fraction of span length
 E = modulus of elasticity, lbf/in²
 (see Table 3)
 J = cross-sectional moment of inertia, in⁴
 (see [15], ch 13)
 F_G = total bus unit weight, lbf/ft

12.1.3.3 One Pinned End, One Fixed End. For spans with one pinned end and one fixed end, Eqs 17 and 18 may be used to calculate the maximum allowable span length based on vertical deflection.

$$L_D = \left[\frac{185(E)(J)(Y_A)}{F_G/12} \right]^{\frac{1}{4}} \quad (\text{Eq 17})$$

or,

$$L_D = \left[\frac{185(E)(J)(Y_B)}{F_G/12} \right]^{\frac{1}{3}} \quad (\text{Eq 18})$$

where

L_D = allowable span length, in
 Y_A = allowable deflection, in
 Y_B = allowable deflection as a fraction of span length
 E = modulus of elasticity, lbf/in²
 (see Table 3)
 J = cross-sectional moment of inertia, in⁴
 (see [15], ch 13)
 F_G = total bus unit weight, lbf/ft

12.2 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 short-circuit-current forces F_{SC} are combined, the minimum yield stress is commonly used as the maximum allowable stress, since F_{SC} is conservative.

12.2.1 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 tubular bus, the reduction in allowable stress may not be required if a reinforcing insert is incorporated.

12.2.2 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

$$F_T = \left[(F_W + F_{SC})^2 + (F_G)^2 \right]^{1/2} \quad (\text{Eq 19})$$

where

F_T = total unit force, lbf/ft
 F_W = wind unit force, lbf/ft
 F_{SC} = short-circuit unit force, lbf/ft
 F_G = total bus unit weight, lbf/ft

The angle of the total force below horizontal is

$$\theta = \tan^{-1} \left(\frac{F_G}{F_W + F_{SC}} \right) \quad (\text{Eq 20})$$

The total force on a conductor in a vertical configuration is

$$F_T = \left[(F_W)^2 + (F_G + F_{SC})^2 \right]^{1/2} \quad (\text{Eq 21})$$

where

F_T = total unit force, lbf/ft
 F_W = wind unit force, lbf/ft
 F_{SC} = short-circuit unit force, lbf/ft
 F_G = total bus unit weight, lbf/ft

The angle of the force below horizontal is

$$\theta = \tan^{-1} \left(\frac{F_G + F_{SC}}{F_W} \right)^{1/2} \quad (\text{Eq 22})$$

12.2.3 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 Eq 23 should be used.

12.2.3.1 Two Pinned Ends. For a span with two pinned ends, the allowable span length is calculated with Eq 23.

$$L_S = \left[\frac{8 (F_A) (S)}{F_T / 12} \right]^{1/2} \quad (\text{Eq 23})$$

where

L_S = maximum allowable length, in
 F_A = maximum allowable stress, lbf/in²
 S = section modulus, in³
 F_T = total force, lbf/ft

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

Table 4
Allowable Stresses for
Common-Conductor Materials

Bus-Conductor Material	Stress (lbf/in ²)	
	Elastic Limit	Minimum Yield
Aluminum alloy 6063-T6 or 6101-T6	20 500	25 000*
Aluminum alloy 6061-T6	29 500	35 000*
Aluminum alloy 6101-T61	11 000	15 000*
Copper No 110 hard drawn	—	40 000†

*With 0.2% offset per ANSI/ASTM-B241-80 [1]

† With 0.5% offset per ASTM B188-81 [11]

12.2.3.2 Two Fixed Ends. For a span with two fixed ends, the allowable span length equation is

$$L_s = \left[\frac{12 (F_A) (S)}{F_T / 12} \right]^{1/2} \quad (\text{Eq 24})$$

where

L_s = maximum allowable length, in
 F_A = maximum allowable stress, lbf/in²
 S = section modulus, in³
 F_T = total force, lbf/ft

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

12.2.3.3 One Pinned End, One Fixed End.

For a span with one pinned end and one fixed end, the maximum allowable span may be calculated as follows:

$$L_s = \left[\frac{8 (F_A) (S)}{F_T / 12} \right]^{1/2} \quad (\text{Eq 25})$$

where

L_s = maximum allowable length, in
 F_A = maximum allowable stress, lbf/in²
 S = section modulus, in³
 F_T = total force, lbf/ft

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

12.3 Maximum Allowable Span Length. The maximum allowable span length L_A is equal to L_s or L_D , whichever is shorter.

13. 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.

13.1 Insulator Cantilever Forces. The insulator cantilever force is a function of the effective conductor span length supported by the insulator, and is caused by

- (1) The short-circuit-current force on the bus

Table 5
Effective Bus Span Length L_E Supported by Insulator

End Conditions			
Adjacent Span L_1	Insulator Connector	Adjacent Span L_2	Effective Supported Span L_1
F	F	F	$\frac{1}{2} (L_1 + L_2)$
P	F	P	$\frac{5}{8} (L_1 + L_2)$
F	F	P	$\frac{1}{8} (4L_1 + 5L_2)$
P	F	F	$\frac{1}{8} (5L_1 + 4L_2)$
P	P	P	$\frac{1}{2} (L_1 + L_2)$
P	P	F	$\frac{1}{8} (4L_1 + 3L_2)$
F	P	P	$\frac{1}{8} (3L_1 + 4L_2)$
F	P	F	$\frac{3}{8} (L_1 + L_2)$

*maximum effective supported span

F = Fixed end condition

P = Pinned end condition

L_1 and L_2 = adjacent bus span lengths, ft

- (2) The wind force on the bus and insulator
- (3) The gravitational forces on the bus, insulator or concentrated masses, or both.

13.1.1 Bus Short-Circuit-Current Force. The short-circuit-current force transmitted to the bus support fitting can be calculated using Eq 26.

$$F_{SB} = L_E F_{SC} \quad (\text{Eq 26})$$

where

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

L_E = effective bus span length, ft

F_{SC} = short-circuit-current unit force as calculated in Section 11, lbf/ft

The effective bus span length L_E is determined from the length of bus on each side of the bus support fitting and the end conditions (see Table 5).

If the end conditions are unknown, then fixed end condition 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_A calculated in Section 12.

13.1.2 Bus Wind Force. The unit wind force associated with the bus span is the same as that described in Section 10. The wind force transmitted to the bus support fitting can be calculated using Eq 27.

$$F_{WB} = L_E F_W \quad (\text{Eq 27})$$

where