PDHonline Course E470 (3 PDH)

Substations – Volume III – Conductors & Bus

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2020

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Substation Design
Volume III
Conductors & Bus Design

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This series of courses are based on the "Design Guide for Rural Substations", published by the Rural Utilities Service of the United States Department of Agriculture, RUS Bulletin 1724E-300, June 2001.

Preface

This course is one of a series of thirteen courses on the design of electrical substations. The courses do not necessarily have to be taken in order and, for the most part, are stand-alone courses. The following is a brief description of each course.

Volume I, Design Parameters. Covers the general design considerations, documents and drawings related to designing a substation.

Volume II, Physical Layout. Covers the layout considerations, bus configurations, and electrical clearances.

Volume III, Conductors and Bus Design. Covers bare conductors, rigid and strain bus design.

Volume IV, Power Transformers. Covers the application and relevant specifications related to power transformers and mobile transformers.

Volume V, Circuit Interrupting Devices. Covers the specifications and application of power circuit breakers, metal-clad switchgear and electronic reclosers.

Volume VI, Voltage Regulators and Capacitors. Covers the general operation and specification of voltage regulators and capacitors.

Volume VII, Other Major Equipment. Covers switch, arrestor, and instrument transformer specification and application.

Volume VIII, Site and Foundation Design. Covers general issues related to site design, foundation design and control house design.

Volume IX, Substation Structures. Covers the design of bus support structures and connectors.

Volume X, Grounding. Covers the design of the ground grid for safety and proper operation.

Volume XI, Protective Relaying. Covers relay types, schemes, and instrumentation.

Volume XII, Auxiliary Systems. Covers AC & DC systems, automation, and communications.

Volume XIII, Insulated Cable and Raceways. Covers the specifications and application of electrical cable.

Chapter 1
Bare Conductors

This chapter covers bare conductors and includes material types, ampacities, and connectors.

Conductor Materials

Copper and aluminum are the two major conductor materials used for substation buses and equipment connections. Both materials can be fabricated into various types of flexible or rigid conductors. The trend in substation construction is toward use of mostly aluminum conductors. Copper conductors are used principally for expansion of similar systems in existing substations.

The conductivity of aluminum is from 50 to 60 percent that of copper, depending on the aluminum alloy. Consequently, larger aluminum conductors are required to carry the same currents as copper conductors. The larger aluminum conductor diameters result in greater wind and ice loads but tend to minimize corona, which is more of a problem at higher voltages.

For the same ampacity, copper conductors weigh approximately twice as much as aluminum conductors. The higher copper conductor weights can result in more sag as compared with aluminum conductors for equal spans. To reduce the sag, it is usually necessary to increase the number of supports for rigid conductors or, in the case of flexible conductors, increase the tensions.

Rigid Conductors

Rigid electrical conductors are available in a variety of shapes and sizes to suit individual requirements. Some of the more commonly used shapes include flat bars, structural shapes, and tubes. Specific physical and electrical properties and application data can be obtained from the conductor manufacturers.

Flat bars can be utilized for outdoor substation buses and are particularly suitable since they can be easily bent and joined. For high-current applications, a number of flat bars can be grouped together, leaving a small space between the bars to facilitate heat dissipation. The ampacity of a group of flat bars depends on whether the bars are arranged vertically or horizontally. The number of bars that can be grouped together is limited because of skin and proximity effects. Flat bars are usually limited to use at lower voltages because of corona.

Because of their inherent lack of rigidity, supports for flat bar buses are usually closely spaced to minimize the effects of meteorological loads and short-circuit forces.

The *structural shape* conductors that have been used in outdoor substation construction consist primarily of angle and channel types. The flat surfaces permit bolting directly to support insulators and provide convenient connection points. To increase ampacity, two angles or channels can be used. Special fittings are usually required for these configurations. The positioning and grouping of structural shapes have limitations similar to those of flat bars. The rigidity of both angle and channel shapes is somewhat higher than for flat bars of the same ampacity. Consequently, support spacing can usually be increased.

Square and round tubular shapes are considerably more rigid than either flat bars or structural shapes of the same ampacity and permit longer spans. The flat surfaces of square tubes provide convenient connection and support points. To facilitate heat dissipation, ventilation holes are sometimes provided in the square tubes. Round tubular conductors are the most popular shape used in outdoor substation construction. The round shape is very efficient structurally and electrically and minimizes corona at higher voltages. The special fittings required for connecting, terminating, and supporting round tubular conductors are widely available.

Special shapes combining the advantages of several of the standard shapes are also available. Integral web channel buses, uniform thickness angles, and other special configurations can be furnished.

Aluminum conductors are available in a variety of alloys and tempers with different conductor conductivities and strengths. Round tubular conductors are usually specified as either 6061-T6 or 6063-T6 alloy. The 6063-T6 alloy has a conductivity approximately 23 percent higher and a minimum yield strength approximately 29 percent lower than the 6061-T6 alloy. Consequently, the 6063-T6 alloy can carry higher currents but may require shorter support intervals. Both Schedule 40 and 80 pipe are available in either alloy. The Schedule 80 sizes have wall thicknesses approximately 40 percent thicker than the Schedule 40 sizes, resulting in lower deflections for equal span lengths.

Alloy 6106-T61 is frequently utilized for flat bars, structural shapes, and square tubes. Other alloys and tempers are available for special applications.

Flexible Conductors

Flexible electrical conductors can be used as substation buses and equipment taps. The conductors are normally cables fabricated by stranding a number of small conductors into one larger conductor. Stranding provides the required conductor flexibility while maintaining strength. The flexibility can be increased by reducing the diameter and increasing the quantity of individual conductors. Bare electrical cables for substation construction are usually concentric lay stranded with Class A or AA stranding in accordance with ASTM Std. B231.

Most flexible conductors used in substation construction consist of all copper, all aluminum, or aluminum with steel reinforcing (ACSR). The conductor type selected for a particular application is usually based on the span length, tension and tolerable sag, and cost. For long spans, large supporting structures will be required. The size and cost of these structures may depend on the conductor type and should be considered during the selection process.

Flexible conductors are available in many sizes. Size selection is based on ampacity, strength, weight, and diameter. Conductor diameter becomes increasingly important at higher voltages where corona can be a problem. Data concerning the physical and electrical properties of the various wire types can be found in manufacturers' literature.

Conductor Ampacity

The ampacity of bare conductors is based on a number of factors, including the conductor material, proximity of the conductors, climatic conditions, conductor temperature rise, emissivity, and altitude.

Copper conductors can carry about 1.3 or more times as much current as aluminum conductors of the same size. However, based on weight, more than twice as much copper is required for the same ampacity.

The current distribution of closely spaced conductors is affected by their mutual inductance in accordance with the proximity effect. The additional losses attributed to this effect can usually be neglected if conductor spacing is 18 inches or greater.

Climatic conditions have a great effect on conductor ampacity. Ampacities are usually determined based on ambient temperatures of 40C. For prolonged ambient temperatures above this value, ampacities are usually reduced. Wind tends to reduce the temperature of outdoor bare conductors. An assumed steady wind may be reasonable in many areas. The sun's radiation can cause the temperature of bare conductors to increase, which results in lower ampacities and should be considered in predominately sunny locations.

Conductor temperature rise is the temperature increase above ambient at which the conductor is operating. To prevent excessive surface oxidation and possible damage from annealing, the temperature rise is usually limited to 30C for a total maximum conductor temperature of 70C under normal operating conditions. The trend is toward higher operating temperatures. Temperature rises of 50C and higher have been used successfully. However, temperatures that could damage the conductors or connected equipment should be avoided.

The conductor surface emissivity has an effect on conductor ampacity. For aluminum conductors, emissivity is usually taken as 0.5 and for copper conductors 0.8. Both of these values are for heavily weathered conductor surfaces. The ampacity is usually higher for greater emissivity.

Equipment that depends on air for its cooling medium will have a higher temperature rise when operated at higher altitudes than when operating at lower altitudes. For altitudes in excess of 3,300 feet, the correction factors listed in Table 1 should be applied.

Table 1
Altitude Correction Factors Current

Altitude (Feet)	Current Rating	Ambient Temperatures
3,300	1.00	1.00
4,000	0.995	0.992
5,000	0.99	0.980
6,000	0.985	0.968
7,000	0.98	0.956
8,000	0.97	0.944
9,000	0.965	0.932
10,000	0.96	0.920
12,000	0.95	0.896
14,000	0.935	0.872

Consider a conductor with an ampacity of 1,000 amperes in a 40C ambient temperature with a 30C temperature rise at an altitude of 3,300 feet. If this conductor is to be used at a higher altitude, the ampacity has to be corrected. At 18,000 feet, this conductor will have an ampacity of 1000 x 0.910 = 910 amperes in an ambient temperature of 40C with a 30C temperature rise. The conductor may be operated at 1000 amperes at 18,000 feet, provided the ambient temperature does not exceed 40C x 0.824 = 33C and the temperature rise does not exceed 30C.

Bus Connections

It is customary to purchase rigid bus conductors in lengths ranging from 10 feet to 40 feet. Sections need to be joined together for longer lengths. Taps are required from buses to electrical equipment. Bus conductors need to be attached to support insulators. For greatest reliability and lowest cost, fewer connections are best.

The various substation bus connections can be made by using any of four main methods—bolting, clamping, compressing, and welding—depending on the conductor type and material. Bolted connections are utilized in connecting two or more flat surfaces together. Clamp-type connections generally involve the use of special fittings fabricated to permit conductors to be joined together or connected to other equipment. Compression connections are principally used for splicing or terminating flexible conductors. Welded connections are used primarily with rigid aluminum conductors. Weldment fittings are available that eliminate extensive conductor cutting and shaping prior to welding. Compression fittings are now available for rigid tubular bus.

Whenever connectors are utilized for making electrical connections, they should be equivalent electrically and mechanically to the conductors themselves. Bolted connections are the primary means of making connections to equipment terminals. Bolted joints permit the disconnection of equipment for maintenance or replacement. The most common bolted connection involves joining a conductor to an equipment terminal. A terminal lug is attached to the conductor by clamping, compressing, or welding, and the lug is bolted to the equipment terminal.

When a copper conductor is connected to a flat copper or electrical bronze equipment terminal, a copper or electrical bronze terminal lug is utilized. The lug is usually bolted to the equipment terminal with a minimum of two ½-inch, 13 threads per inch, high-strength silicon bronze bolts normally torqued to 40 pound-feet. Silicon bronze flat washers are normally used under both the bolt heads and the nuts.

When an aluminum conductor is connected to a flat copper or electrical bronze equipment terminal, an aluminum terminal lug is utilized. The lug is usually bolted to the equipment terminal with a minimum of two ½-inch, 13 threads per inch, anodized aluminum bolts normally torqued to 25 pound-feet. The bolts are usually aluminum alloy 2024-T4 and the nuts alloy 6061-T6. Flat washers of aluminum alloy 2024-T4 are normally used under both the bolt heads and the nuts. An anti-oxidation compound should also be considered for aluminum connections.

When a copper conductor is connected to a flat aluminum equipment terminal, a copper or electrical bronze terminal lug is utilized. The lug is usually bolted to the equipment terminal with a minimum of two ½-inch, 13 threads per inch bolts, normally of stainless steel or tin-plated high-strength silicon bronze. Flat washers of the same material as the other hardware are used under both the bolt heads and the nuts. Stainless steel spring washers are used between the flat washers and the nuts. Bolts are torqued to the spring washer manufacturer's recommendations.

When an aluminum conductor is connected to a flat copper or electrical bronze equipment terminal, an aluminum terminal lug is utilized. The lug is usually bolted to the equipment terminal with a minimum of two ½-inch, 13 threads per inch bolts, normally of stainless steel or tin-plated high-strength silicon bronze. Flat washers of the same material as the other hardware are used under both the bolt heads and nuts. Stainless steel spring washers are used between the flat washers and the nuts. Bolts are torqued to the spring washer manufacturer's recommendations.

For aluminum–copper connections, the copper component should be installed <u>below</u> the aluminum component to prevent the copper salts from washing onto the aluminum. Additionally, the aluminum component should be massive, compared with the copper component. It is recommended the copper connector be tinned when connecting to aluminum connectors.

A large variety of clamp-type electrical connectors are available for both flexible and rigid conductors of copper and aluminum. Most clamp-type connectors achieve their holding ability as a result of tightening a number of bolts. The quantities and sizes of bolts used should be as listed in NEMA Std. CC1. Copper or electrical bronze connectors should be utilized with copper conductors. All-aluminum connectors should be used with aluminum conductors.

Compression connections are used in splicing or installing terminal lugs on flexible conductors and for round tubular aluminum conductors. All-aluminum compression connectors should be used for aluminum conductors. Copper compression connectors should be used for copper conductors.

For connection on flexible conductors, installation of compression connectors in a vertical position with the lug down should be avoided to prevent the entrance of moisture and possible damage from freezing. Compression connection on rigid or flexible conductors can be made under any weather condition. The fitting is compressed using a portable hydraulic pump. It compresses the fitting radially 360 degrees. An inspection gauge is then used to verify that the connection is acceptable.

Compression connectors should always be installed in strict accordance with the manufacturer's instructions concerning the quantity and location of compressions. Connectors designed for a minimum of two circumferential compressions are recommended.

Welded connections are used primarily with round tubular aluminum conductors. Use of the special fittings available simplifies the procedures to permit faster installation. Properly made welded connections have resistances that are not appreciably higher than the conductors themselves to eliminate conductor hot spots. Welded aluminum connections are extensively used in the construction of large substations. Construction costs are usually slightly less with welded than clamp-type connections. In smaller installations with fewer connections, it may not be economically feasible to weld connections.

Chapter 2
Rigid Bus Design

The design of a rigid bus system involves many factors. There must be ample clearance to permit equipment maintenance and removal. The bus must allow entrance of construction and maintenance equipment into the substation and it is important to plan for future expansion by sizing and positioning buses to facilitate modifications.

The bus conductors are selected based on ampacity, physical properties, and cost. Conductors should be selected that they have sufficient size and capacity to withstand system faults and over-currents without damage from overheating.

During short circuits, large forces can be developed in the bus system. The rigid bus design includes consideration of these forces to prevent damage during short-circuit conditions. The bus centerline-to-centerline spacing and the short circuit current both have effects on these forces.

If not properly considered, wind and ice loads can cause extensive damage to bus conductors and insulators. The usual practice is to consider National Electrical Safety Code loadings as a minimum. Also consider local conditions since they may necessitate the use of more severe loading criteria.

Since the number of different insulator ratings is limited, exercise care in the bus layout so that a practical system is achieved. The strength of the insulators required is based on the total bus loading and particularly the short-circuit forces.

The sag of the bus conductors must be limited in the design. A flat horizontal system looks much neater than one with excessive sag. The conductor sag is influenced by the conductor weight and section modulus, the span length, and the vertical loading.

Long conductor spans can be damaged by vibrations caused by winds. Excessive conductor sag can add to this problem. Span lengths whose natural frequency is near that set up by a wind that has a high recurrence should be avoided. Dampering conductors or other devices can be used in the bus to minimize vibration.

As the temperature of the conductors increases, longitudinal expansion occurs. If the bus system is not provided with means to absorb this expansion, insulators or other connected equipment can be damaged. A wide temperature range is required to accommodate the bus length when de-energized at the lowest design temperature up to the maximum bus operating temperature.

Long buses usually require the use of more than one section of conductor. Consequently, couplers have to be utilized to join the sections together. These couplers have to be properly located to prevent damage from bus loading and short-circuit forces. Plan the bus system carefully by considering these aspects and other factors as they may develop.

Procedure for Rigid Bus Design

The following procedure can be used in designing a rigid bus system. Select the material and size of the bus conductors based on continuous current requirements. In higher voltage systems with longer bus spans, the structural capabilities of the conductors may be the factor that determines the conductor material and size. However, the conductors selected have to be capable of carrying the required continuous current in any case.

Using Tables 2 and 3, determine the bus conductor centerline-to-centerline spacing.

Table 2
Substation Clearances

Nominal Voltage (Phase-to-Phase)	Max Voltage P-P (kV)	BIL (kV)	Rigid Conductors (in)	Phase Spacing Rigid Bus P-P (in)	Rigid Conductors to Ground (in)	Overhead conductors to Ground (personnel safety) (feet)	Overhead Conductors to Roadway inside fence (feet)
7.5	8.3	95	7	18	6	8	20
14.4	15.5	110	15	24	7	9	21
23	25.8	150	15	30	10	10	22
34.5	38	200	18	36	13	10	22
46	48.3	250	21	48	17	10	22
69	72.5	350	31	60	25	11	23
115	121	550	53	84	42	12	25
230	242	1050	89	132	71	15	27

Table 3 lists the phase spacing of various types of outdoor air switches. The minimum metal-to-metal clearances should be maintained at all times with the switches in the open position, closed position, or anywhere between the open and closed positions.

Table 3
Outdoor Air Switch Phase Spacing

Nominal Voltage (Phase-to-Phase)	Max Voltage P-P (kV)	BIL (kV)	Metal-to-Metal Minimum Separation (inches)	Centerline-to-Centerline Phase Spacing		
				Vertical Break	Side Break	All Horn Gap
7.5	8.3	95	7	18	30	36
14.4	15.5	110	12	24	30	36
23	25.8	150	15	30	36	48
34.5	38	200	18	36	48	60
46	48.3	250	21	48	60	72
69	72.5	350	31	60	72	84
115	121	550	53	84	108	120
138	145	650	63	96	132	144
161	169	750	72	108	156	168
230	242	900	89	132	192	192
230	242	1050	105	156	216	216
345	362	1050	105	156	216	216
345	362	1300	119	174	-	-

Calculate the maximum short circuit forces the bus has to withstand. These forces can be determined using the following equation,

$$\mathbf{F_{SC} = 37.4 * 10^{-7} * K_{SC} * \frac{i^2}{D}}$$

Where:
F_{SC} = Maximum short-circuit force on center conductor for a three-phase flat bus configuration of round or square tubular conductors with the conductors equally spaced, in pounds per foot

K_{SC} = Short-circuit force reduction factor (0.5 to 1.0; 0.67 recommended)
i = RMS value of three-phase symmetrical short-circuit current, in amperes
D = Centerline-to-centerline spacing of bus conductors in inches

Determine the total bus conductor loading. Table 4 lists values for wind and ice loading for the various loading districts defined in the National Electrical Safety Code. Consider these values as minimum. Also consider extreme wind.

Table 4
NESC Conductor Wind & Ice Loads

Load	Loading District		
	Heavy	Medium	Light
Radial Thickness of Ice	0.50	0.25	0
Horizontal Wind Pressure (PSF)	4.0	4.0	9.0

Conductor loading is usually based on these criteria. However, in locations where more severe conditions are frequent, the conductor loading should be based on actual local conditions.
The ice loading can be determined using,

$$\mathbf{W_I = 0.311 * \left(d_1^2 - d_2^2\right)}$$

Where:
W_I = Ice loading, in pounds per foot
d_1 = Outside diameter of conductor with ice, in inches (determine ice thickness from Table 4)
d_2 = Outside diameter of conductor without ice, in inches

The wind loading can be determined using,

$$\mathbf{F_W = 0.083 * C_D * P_W * d_1}$$

Where:
F_W = Wind loading, in pounds per foot
C_D = Drag coefficient (See Figure 1)
P_W = Wind pressure, in pounds per foot^2 (from Table 4)
d_1 = Outside diameter of conductor with ice, in inches

The total bus conductor loading can be determined using,

$$\mathbf{F_T} = \sqrt{[(\mathbf{F_{SC}} + \mathbf{F_W})^2 + (\mathbf{W_C} + \mathbf{W_i})^2]}$$

Where:
F_T = Total bus conductor loading, in pounds per foot
F_{SC} = Maximum short-circuit force, in pounds per foot
F_W = Wind loading, in pounds per foot
W_C = Conductor weight, in pounds per foot (if damping cables are used to control conductor vibration, add the cable weight to the conductor weight)
W_I = Ice loading, in pounds per foot

Figure 1 shows the drag coefficients for various structural shapes.

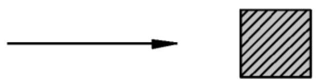
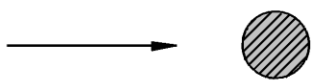
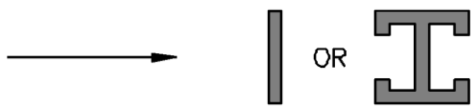
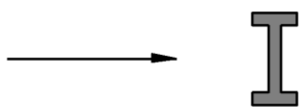
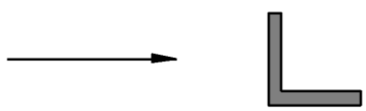
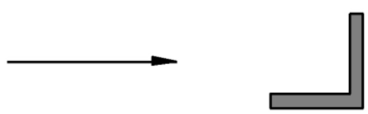
$\lambda \rightarrow \infty$ λ = The Ratio of Span Length to Vertical Dimension of Bus Conductor.	
Profile & Wind Direction	**C_D**
	**2.03**
	**1.00**
	**2.00**
	**2.04**
	**2.00**
	**1.83**
	**1.99**

Figure 1

The preceding equation applies maximum wind and maximum ice at the same time. NESC and ANSI/IEEE Std. 605 apply these forces individually, which reduces F_T. Engineering judgment based on site conditions and design loads should determine the maximum loading conditions of the bus.

Calculate the maximum bus span or support spacing. Maximum bus support spacing can be determined using,

$$\mathbf{L_M = K_{SE} * \sqrt{\left(\frac{F_B * S}{F_T}\right)}}$$

Where:
L_M = Maximum bus support spacing, in feet
K_{SE} = Multiplying factor from Table 5
F_B = Maximum desirable fiber stress of conductor, in pounds per inch^2

For round tubular conductors of:

Copper, F_B = 20,000 lb/in^2*
6061-T6 aluminum alloy, F_B = 28,000 lb/in^2*
6063-T6 aluminum alloy, F_B = 20,000 lb/in^2*

**Includes a safe*ty factor of 1.25.

S = Section modulus of conductor, in inches^3
F_T = Total bus conductor loading, in pounds per foot

Table 5 **Conductor Maximum Span & Deflection Mulitipliers**		
Bus System	K_{SE}	K_{DE}
Conductor Fixed Both Ends (Single span)	1.0	4.50
Conductor Fixed One End Simply Supported on other end (Single Span)	0.82	9.34
Conductor Simply Supported (Single span)	0.82	22.5
Conductor Simply Supported (Two equal spans)	0.82	9.34
Conductor Simply Supported (Three or more equal spans)	0.88	11.9

Calculate the maximum vertical conductor deflection using,

$$\mathbf{y = K_{DE} * \frac{(W_C + W_I) * L^4}{E * I}}$$

Where:
y = Maximum vertical conductor deflection, in inches.*
K_{DE} = Multiplying factor from Table 5
W_C = Conductor weight, in pounds per foot (if damping cables are used to control conductor vibration, add the cable weight to the conductor weight)
W_I = Ice loading, in pounds per foot
L = Bus support spacing, in feet
E = Modulus of elasticity, in pounds per inch^2
I = Moment of inertia, in (inches^4)

*Note. Limit the *Maximum vertical conductor deflection* value to 1/200 of the span length. If the value calculated is greater than 1/200 of the span length, select a conductor with a larger diameter or reduce the span length. Recalculate as required.

Determine the minimum required support insulator cantilever strength using,

$$\mathbf{W_S = 2.5 * (F_{SC} + F_W) * L_S}$$

Where:
W_S = Minimum insulator cantilever strength, in pounds
F_{SC} = Maximum short-circuit force, in pounds per foot
F_W = Wind loading, in pounds per foot
L_S = One half of the sum of the lengths of the two adjacent conductor spans, in feet

Note: This equation includes an insulator safety factor of 2.5. This results in the insulator's working load being equal to 40 percent of the insulator's rated cantilever strength.

Select support insulators from manufacturers' data with cantilever strength ratings equal to or greater than W_S. If sufficiently high ratings are not available, it will be necessary to modify the bus design. This can be done by increasing the centerline-to-centerline conductor spacing to reduce the short-circuit forces or by decreasing the bus span lengths.

Provide for thermal expansion of conductors. The amount of conductor thermal expansion can be calculated using,

$$\boldsymbol{\Delta \ell = \alpha * \ell * \Delta T}$$

Where:
$\Delta\ell$ = Conductor expansion, in inches (final length minus initial length)
α = Coefficient of linear thermal expansion:
For aluminum, $\alpha = 2.3 \times 10^{-5}$ per degree Celsius
For copper, $\alpha = 1.7 \times 10^{-5}$ per degree Celsius
ℓ = Initial conductor length, in inches (at initial temperature)
ΔT = Temperature variation, in degrees Celsius (final temperature minus initial temperature)

Bus sections with both ends fixed without provision for conductor expansion should be avoided. Make connections to power circuit breakers, power transformers, voltage transformers, and other device bushings or terminals that could be damaged by conductor movement either with flexible conductors or expansion-type connectors.

Connections to switches utilizing apparatus insulators may require the use of expansion-type terminal connectors to prevent damage from excessive conductor expansion. Use of expansion-type terminals in this situation depends on the bus configuration and location of other expansion points. It is recommended that expansion fittings used on long horizontal buses be limited to those permitting longitudinal expansion only.

It is usually desirable to limit the length of sections of continuous buses to 100 feet or less to limit the amount of conductor expansion in each section. This can be done by fixing certain points in the bus and permitting other points to move freely. An example of a typical bus system is diagrammed in Figure 2.

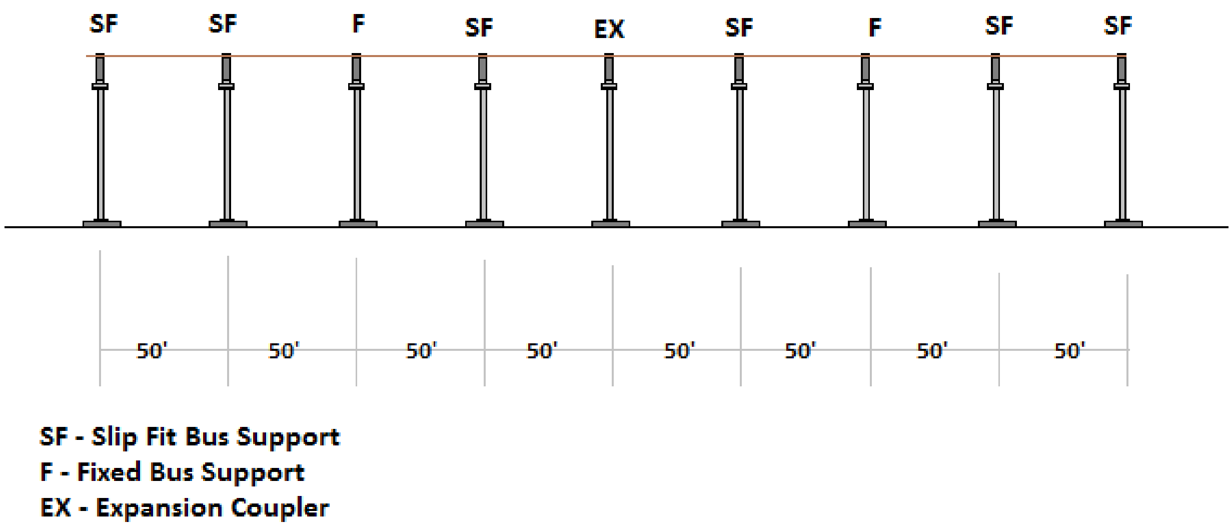


Figure 1

The system illustrated in Figure 2 can freely expand as necessary and is free of “captured spans” that permit no expansion. The locations of slip-fit and fixed bus supports and expansion-type couplers or bus supports divide the bus into four sections, each of which will expand approximately the same total amount. If it is desirable to connect the end sections of the bus to other equipment, provide flexible conductors or expansion-type connectors.

The couplers used on rigid buses should be as long as possible to provide maximum joint rigidity and strength. Clamp-type bolted couplers should have the quantity and size of clamping bolts listed in NEMA Std. CC1. Welded couplers for aluminum conductors should be of the internal type. Compression connectors should be appropriately sized and located. To prevent conductor damage from bending caused by its own weight and external loads, carefully position couplers. Welding and bolting can cause appreciable loss of conductor strength in the immediate coupler locations. Consequently, position couplers where the least amount of bending will occur. The ideal locations are points of zero bending moment along the conductor. Table 6 lists the ideal locations for conductor couplers for continuous conductors.

Table 6 **Ideal Locations for Couplers in Continuous Uniformly Loaded Rigid Conductors**	
Conductor Spans (No.)	**Location (measured right from left-most support L=distance between bus supports)**
1	Couplers not recommended
2	0.750L, 1.250L
3	0.800L, 1.276L, 1.724L, 2.200L
4	0.786L, 1.266L, 1.806L, 2.194L 2.734L, 3.214L,
5	0.789L, 1.268L, 1.783L, 2.196L, 2.804L, 3.217L, 3.732L, 4.211L
6	0.788L, 1.268L, 1.790L, 2.196L, 2.785L, 3.215L, 3.804L, 4.210L, 4.732L, 5.212L

If couplers have to be positioned in other than the ideal locations listed in Table 6, reduce the maximum allowable fiber stress by as much as 50 percent, depending on the degree of variation from the ideal location, and recalculate the maximum span length used. If the span length being considered exceeds this maximum, reduce it as necessary. Conductor couplers can now be positioned wherever convenient.

Aeolian conductor vibration is primarily the result of steady low-velocity transverse winds striking the conductor and causing it to vibrate. When the frequency of the driving force (wind) is approximately equal to the natural frequency of the bus span, resonance occurs. The resulting vibrations can cause insulator damage.

Vibrations will occur in almost all bus spans independently of the conductor material, diameter, or length. In short spans, the vibrations are usually of small enough magnitude to be neglected. However, in spans longer than about 20 feet, methods for vibration damping should be considered.

Two primary methods have been used to dampen aeolian vibrations. The first and most widely used method consists of installing scrap cables in the horizontal buses. When this method is used, it is necessary that the cables be loose in the bus tubing to permit vertical movement. If new cables are used, they should be straightened prior to installation to prevent the cables from jamming against the tubing sides. Additionally, end caps, preferably of the driven type, should be installed on the ends of the buses containing the damping cables to prevent horizontal cable movement out of the tubing. To be effective, damping cables should be installed for the entire bus length for buses where excessive vibration is suspected.

The second method used to dampen aeolian vibrations consists of installing internal or external prefabricated bus dampers on the bus conductors. Usually, one damper is installed in each bus span to control the vibrations. Location and installation should be in accordance with the manufacturer's instructions.

Bus Design Example

Design a three-phase rigid bus with the following characteristics:

- Total bus length: 150 feet, assuming four equal spans of 37.5 ft
- Voltage: 161 kV
- BIL: 750 kV
- Insulator type: post
- Continuous current rating: 1800 amperes
- Short-circuit current: 24,000 RMS symmetrical amperes
- Altitude: 1,000 ft
- NESC loading: heavy
- Disconnect switch connected to one end of bus
- External prefabricated dampers to control conductor vibration

Step1. Select the material and size of the bus conductors.

Based on the continuous current requirements, 3 in. IPS, schedule 40 6063-T6 aluminum alloy (1,890 amperes) is selected with the following properties:

W_C (weight) = 2.62 lb/ft*; see Table 7

d_2 (outside diameter) = 3.50 inches; see Table 7
I (moment of inertia) = 3.017 in^4; see Table 7
E (modulus of elasticity) = 10 x 10^6 lb/in^2)
S (section modulus) = 1.72 in^3 see Table 7
F_B (maximum allowable fiber stress) = 20,000 lb/in^2

* If damping cables are to be used to control conductor vibration, the cable weight has to be added to the conductor weight. In this example, external prefabricated dampers will be used for vibration control.

Table 7
ASA Schedule 40 Aluminum Pipe Conductor Physical Properties

Nominal Pipe Size (in)	Diameter		Wall Thickness (in)	Area (in2)	Weight per foot (lb)	Moment of Inertia (in4)	Section Modulus (in3)	Radius of Gyration (in)
	Outside (in)	Inside (in)						
½	0.840	0.622	0.109	0.250	0.294	0.017	0.041	0.261
¾	1.050	0.824	0.113	0.333	0.391	0.037	0.071	0.334
1	1.315	1.049	0.133	0.494	0.581	0.087	0.133	0.421
1 ¼	1.660	1.380	1.140	0.669	0.786	0.195	0.235	0.540
1 ½	1.900	1.610	1.145	0.800	0.940	0.310	0.326	0.623
2	2.375	2.067	0.154	1.075	1.264	0.666	0.561	0.787
2 ½	2.875	2.469	0.203	1.704	2.004	1.530	1.064	0.947
3	3.500	3.068	0.216	2.229	2.621	3.017	1.724	1.164
3 ½	4.000	3.548	0.226	2.680	3.151	4.788	2.394	1.337
4	4.500	4.026	0.237	3.174	3.733	7.232	3.214	1.510
5	5.563	5.047	0.258	4.300	5.057	15.160	5.451	1.878
6	6.625	6.065	0.280	5.581	6.564	28.150	8.498	2.245

Step 2. Spacing

Determine the bus conductor centerline-to-centerline spacing from Table 2.

D (bus centerline-to-centerline spacing) = 108 in.

Step 3. Short Circuit Forces

Short Circuit Forces:

$$F_{SC} = 37.4 * 10^{-7} * K_{SC} * \frac{i^2}{D}$$

$$F_{SC} = 37.4 * 10^{-7} * (0.67) * \frac{24{,}000^2}{108}$$

F_{SC} = 13.4 lb/ft^2

Step 4. Loading: Determine the total bus conductor loading

From Table 4, Radial thickness of ice: 0.50 in. Horizontal wind pressure: 4.0 lb/ft^2.

$$W_I = 0.311 * (d_1^2 - d_2^2)$$

$$W_I = 0.311 * (4.5^2 - 3.5^2)$$

W_I = 2.49 lb/ft

$$F_W = 0.083 * C_D * P_W * d_1$$

$$F_W = 0.083 * 1.0 * 4.0 * 4.5$$

Fw = 1.49 lb/ft

$$F_T = \sqrt{[(F_{SC} + F_W)^2 + (W_C + W_i)^2]}$$

$$F_T = \sqrt{[(13.3 + 1.49)^2 + (2.62 + 2.49)^2]}$$

F_T = 15.6 lb/ft

Step 5. Calculate the maximum bus support spacing

$$L_M = K_{SE} * \sqrt{\left(\frac{F_B * S}{F_T}\right)}$$

Four equal spans of 37.5 feet were assumed. From Table 5, K_{SE} = 0.88 for three or more equal spans.

$$L_M = 0.88 * \sqrt{\left(\frac{20{,}000 * 1.72}{15.6}\right)}$$

L_M = 41.3 ft.

The assumed spacing of 37.5 ft is structurally permissible for the conductors.

<u>Step 6. Calculate the maximum vertical conductor deflection</u>

$$y = K_{DE} * \frac{(W_C + W_I) * L^4}{E * I}$$

Four equal spans of 37.5 feet were assumed. From Table 5, K_{DE} = 11.9 for three or more equal spans.

$$y = 11.9 * \frac{(2.62 + 2.49) * 37.5^4}{10 * 10^6 * 3.017}$$

y = 3.99 in.

Maximum permissible deflection is 1/200 of the span length:

y_{max} = (37.5*12) / 200

y_{max} = 2.25 in.

Since the calculated deflection is greater than the maximum permissible deflection, the design has to be modified. The span length will be reduced to five equal spans of 30 feet each. The maximum vertical deflection is then recalculated:

$$y = 11.9 * \frac{(2.62 + 2.49) * 30.0^4}{10 * 10^6 * 3.017}$$

y = 1.63 in.

Maximum permissible deflection is:

y_{max} = (30*12) / 200

y_{max} = 1.80 in.

Since the calculated value with 30 feet support spacing is less than the maximum permissible deflection, this support spacing is adequate.

Step 7. Determine the minimum required support insulator cantilever strength

$$W_S = 2.5 * (F_{SC} + F_W) * L_S$$

$$W_S = 2.5 * (13.3 + 1.49) * (\frac{30}{2} + \frac{30}{2})$$

$$W_S = 1{,}109 \text{ lbs.}$$

Therefore, we will need to select a post insulator with 1,109 pounds or greater cantilever strength.

Step 8. Provide for conductor expansion

Assuming a total conductor temperature variation of 50C, the total conductor expansion is:

$$\Delta\ell = \alpha * \ell * \Delta T$$

$$\Delta\ell = 2.3*10^{-5} * 150 * 12 * 50$$

$$\Delta\ell = 2.11 \text{ in.}$$

Some means has to be provided to account for this change. Figure 3 illustrates one method that can be used that permits free expansion in all spans.

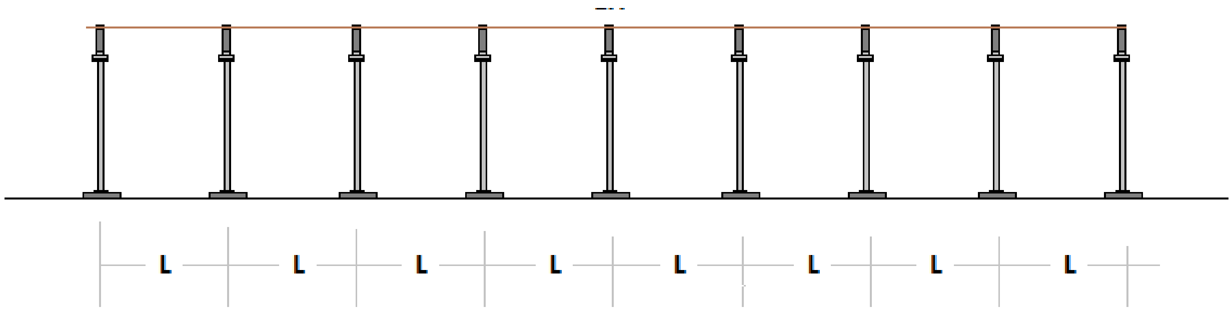


Figure 3

Step 9. Locate conductor couplers

From Table 7, the ideal coupler locations for the five-span bus of 30-foot spans measured to the right from the left-most support are as follows:

1 23.7 ft.
2 38.0 ft.
3 53.5 ft.
4 65.9 ft.
5 84.1 ft.
6 96.5 ft.
7 112.0 ft.
8 126.3 ft.

These locations are illustrated in Figure 4. Assuming that the bus conductor is available in 40-foot lengths, the couplers should be positioned at points 2, 4, 6, and 8. The conductor lengths are cut as required to position the couplers at these approximate locations.

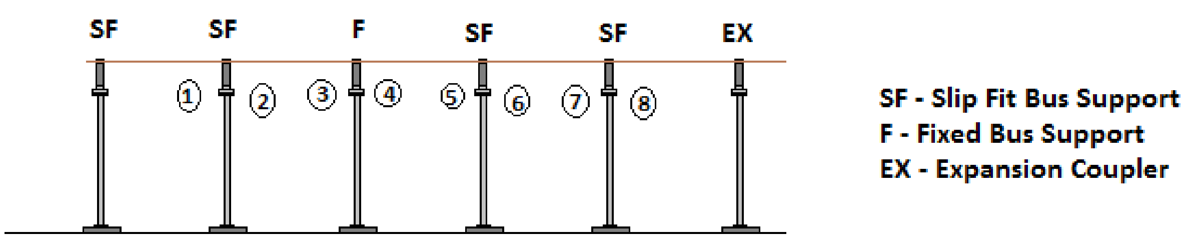


Figure 2

Since the spans are fairly long, damaging vibrations may occur. Consequently, a means for controlling the vibrations should be provided. Prefabricated dampers can be attached to the buses or scrap cables can be installed in the buses. If cables are used, the cable weight has to be added to the conductor weight for the bus calculations.

Chapter 3
Strain Bus Design

Just like a rigid bus, a strain bus design involves many factors. The flexible conductors used for strain bus construction permit significant conductor movement. Consequently, the conductors have to be carefully positioned to prevent contact with other equipment and infringement upon minimum electrical clearances under all loading and climatic conditions. Equipment maintenance and removal should also be considered in locating buses and support structures. The photo below shows a typical strain bus design.

Strain buses usually require large supporting structures. These structures can limit future expansion if not properly positioned. The conductor is selected based on ampacity, physical properties, and cost. Conductors have to be selected so that they have sufficient size and capacity to withstand system faults and overcurrents without damage from overheating.

Wind and ice can increase conductor sags and tensions appreciably. The usual practice is to consider National Electrical Safety Code loadings as a minimum. Local conditions should be considered since they may necessitate the use of more severe loading criteria.

The suspension insulators are selected based on the anticipated maximum loading conditions. The maximum loading for porcelain insulators should not exceed 40 percent of the mechanical–electrical strength ratings. The maximum loading for fiberglass insulators may not exceed 40 percent of the manufacturer's strength ratings.

The span length influences the conductor sag. As the span length increases, the sag increases if the same tension is maintained. To limit the sag, the tensions can be increased. Springs can also be used to limit the tension and sag.

Strain buses are usually positioned above other substation equipment. Conductor breakage could result in equipment damage or outage. To prevent breakage and to minimize support structure size, the conductors are usually installed at tensions of approximately 3,000 pounds or less. Sag may increase because of the deflection of support structures.

Temperature variations cause changes in conductor lengths. As conductor temperature increases, the sag increases and the tension decreases. Taps from the conductors to other buses or equipment should be limited in tension to prevent damage to equipment. The taps are usually installed as slack connections.

Procedure for Strain Bus Design

The following procedure can be used to design a strain bus system:

Select the material and size of the bus conductors, based on continuous current requirements.

Using Tables 2 and 3 determine the bus conductor centerline-to-centerline spacing. The minimum metal-to-metal, bus centerline-to-centerline, and minimum ground clearances listed in Table 2 should be increased at least 50 percent for non-rigid conductors.

Select the quantity of suspension insulators from Table 8.

Table 8
Minimum Quantity of Suspension Insulators

NominalVoltage (Phase-to-Phase)	BIL (kV)	Qty
7.5	95	1
14.4	110	2
23	150	2
34.5	200	3
46	250	4
69	350	5
115	550	8
161	750	10

230	1050	12

Determine the total bus conductor loading. Table 9 lists values for wind and ice loading for the various loading districts defined in the National Electrical Safety Code. These values should be considered as minimum.

Table 9
NESC Conductor Loading Criteria

Load	Loading District		
	Heavy	Medium	Light
Radial Thickness of Ice	0.50	0.25	0
Horizontal Wind Pressure (PSF)	4.0	4.0	9.0
Temperature (C)	-20C	-10C	-1C
Constant (k) added to resultant	4.4	2.5	0.73

Conductor loading is usually based on these criteria. However, in locations where more severe conditions frequently occur, the conductor loading should be based on actual local conditions. The ice loading can be determined from,

$$\mathbf{W_I = 0.311 * \left(d_1^2 - d_2^2\right)}$$

Where:
W_I = Ice loading, in pounds per foot
d_1 = Outside diameter of conductor with ice, in inches (determine ice thickness from Table 9)
d_2 = Outside diameter of conductor without ice, in inches

The wind loading can be determined using,

$$\mathbf{F_W = 0.083 * P_W * d_1}$$

Where:
F_W = Wind loading, in pounds per foot
P_W = Wind pressure, in pounds per foot^2 (from Table 9)
d_1 = Outside diameter of conductor with ice, in inches (determine ice thickness from Table 9)

Note: the coefficient of drag, C_d, is omitted since it is 1.0 for round conductors.

The total bus conductor loading can be determined using,

$$\mathbf{F_T = \sqrt{\left[F_W^2 + (W_C + W_1)^2\right]} + k}$$

Where:
F_T = Total bus conductor loading, in pounds per foot
F_W = Wind loading, in pounds per foot
W_C = Conductor weight, in pounds per foot
W_I = Ice loading, in pounds per foot
k= NESC constant (from Table 9)

Calculate or obtain the maximum conductor sag. Methods for this calculation can be found in conductor manufacturers' literature. In some cases the maximum sag may occur during the most severe loading condition. For substation strain buses, the design tension is usually limited to 3,000 pounds per conductor under the most severe loading to minimize the size of support structures. These conductor tensions have to be coordinated with the support structure designs to ensure compatibility under all loading conditions. The tensions that will occur under unloaded conditions will be considerably less than the maximum. For light loading conditions where ice loads are not considered, the maximum conductor sag may occur at the highest conductor temperature when the conductor length is at a maximum. For other loading conditions, sags should be determined for both high conductor temperatures and maximum loading so that adequate clearance from other equipment can be provided.

Calculate the suspension insulator effect on conductor sag.

For short dead-ended spans, such as substation strain buses, the suspension insulators can have an appreciable effect on span sags. The following procedure can be used to calculate the insulator effect, which is added to the conductor sag for the total bus sag. See Figure 5.

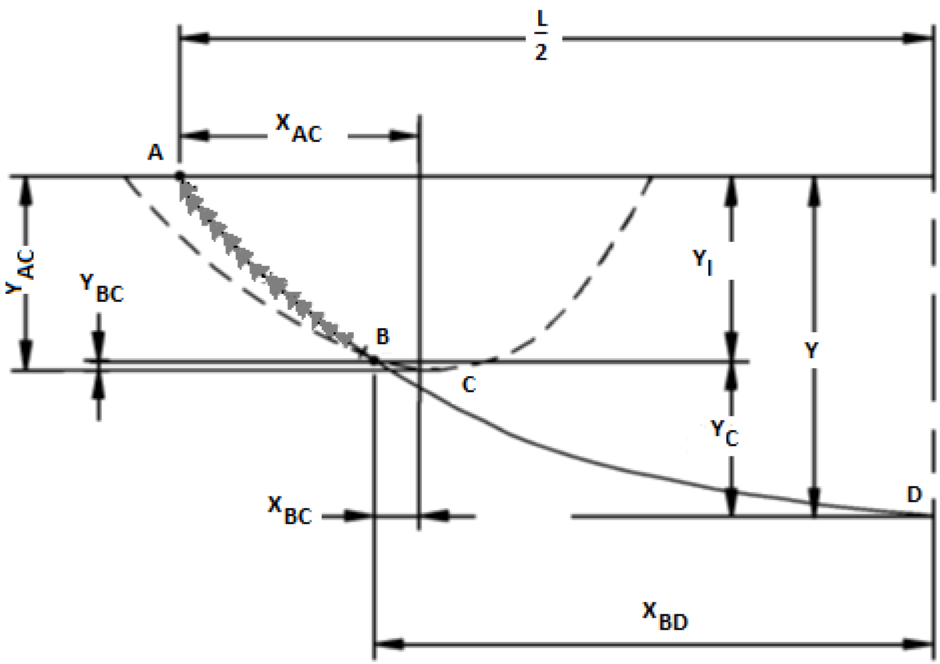


Figure 3

$$\mathbf{C_1} = \frac{\mathbf{T_C}}{\mathbf{W_{IN}}}$$

$$\mathbf{C_c} = \frac{\mathbf{T_C}}{\mathbf{W_C}}$$

$$\mathbf{X_{BC}} = \frac{\mathbf{C_1}}{\mathbf{C_C}} * \boldsymbol{X_{BD}}$$

$$\mathrm{X_{BD}} = \frac{\mathbf{L}}{\mathbf{2}} - \boldsymbol{\ell}_{\mathbf{AB}}$$

$$\mathbf{Y_{BC}} = \mathbf{C_1} * \left[\left(\mathbf{cosh}\,\frac{\mathbf{X_{BC}}}{\mathbf{C_1}}\right) - \mathbf{1}\right]$$

$$\boldsymbol{\ell}_{\mathbf{AC}} = \boldsymbol{\ell}_{\mathbf{AB}} + \mathbf{C_1}\,\mathbf{sinh}\left(\frac{\mathbf{X_{BC}}}{\mathbf{C_1}}\right)$$

$$\mathbf{X_{AC} = C_1 * sinh^{-1}\left(\frac{\ell_{AC}}{C_1}\right)}$$

$$\mathbf{Y_{AC} = C_1 * \left[\left(cosh\frac{X_{AC}}{C_1}\right) - 1\right]}$$

$$\mathbf{Y_1 = Y_{AC} - Y_{BC}}$$

$$\mathbf{Y = Y_1 + Y_C}$$

Where:
C_I = Insulator catenary constant, feet
C_C = Conductor catenary constant, feet
X_{AC} = Horizontal distance from insulator support point to center of insulator catenary, in feet
X_{BC} = Horizontal distance from connection point of insulator string and conductor to center of insulator catenary, in feet
X_{BD} = Horizontal distance from connection point of insulator string and conductor to center of conductor catenary, in feet
ℓ_{AB} = Length of insulator string, in feet
ℓ_{AC} = Arc length from insulator support point to center of insulator catenary, in feet
Y = Total bus sag
Y_{AC} = Sag from insulator support point to center of insulator catenary, in feet
Y_{BC} = Sag from connection point of insulator string and conductor to center of insulator catenary, in feet
Y_I = Insulator sag, in feet
Y_C = Conductor sag, in feet
y = Total bus sag, including insulators and conductor, in feet
T_C = Horizontal conductor tension, in pounds
W_{IN} = Insulator string weight, in pounds per foot
W_C = Conductor weight, in pounds per foot
L = Span length, in feet

Calculate and chart stringing tensions and corresponding sags for a range of conductor temperatures expected during installation. Base the calculations on the assumed maximum tension that occurs under the most severe conductor loading. Include in the chart and list on the installation drawings span length, tension, and total bus sag for various conductor temperatures. Methods to determine the sags and tensions can be found in conductor manufacturers' literature.

After the conductor sags are calculated, add the suspension insulator sag to the conductor sags to determine the total bus sags as previously described.

Sample Calculation of Bus Conductor Loading

Calculate the total bus conductor loading for the following strain bus:

- Span length: 200 feet
- Voltage: 161 kV
- BIL: 750 kV
- Conductor size: 795 kcmil 26/7 ACSR
- Conductor diameter: 1.108 in.
- Conductor weight: 1.094 lb/ft
- NESC loading: heavy

Ice loading: Select ice thickness from Table 9:

$$W_I = 0.311 * (d_1^2 - d_2^2)$$

$$W_I = 0.311 * (2.108_1^2 - 1.108_2^2)$$

$$W_I = 1.0 \text{ lbs/ft}$$

Wind Loading: Select wind pressure from Table 7

$$F_W = 0.083 * P_W * d_1$$

$$F_W = 0.083 * 4 * 2.108$$

$$F_W = 0.70 \text{ lbs/ft}$$

Total bus conductor loading:

$$F_T = \sqrt{[F_W^2 + (W_C + W_1)^2]} + k$$

$$F_T = \sqrt{[0.70^2 + (1.094 + 1.0)^2]} + 0.30$$

$$F_T = 2.51 \text{ lbs/ft}$$

Sample Calculation of Suspension Insulator Effect on Bus Sag

Calculate the suspension insulator effect on bus sag for the following strain bus:

- Span length: 200 feet
- Voltage: 161 kV
- BIL: 750 kV
- Conductor size: 795 kcmil 26/7 ACSR
- Conductor diameter: 1.108 in.
- Conductor weight: 1.094 lb/ft
- Conductor tension: 2,000 lb
- Number of suspension insulators (from Table 8): 10
- Length of each insulator: 5.75 in.
- Weight of each insulator: 11.0 lb

$C_{I,}$ Insulator catenary constant

$$C_1 = \frac{T_C}{W_{IN}}$$

T_C = 2,000 lbs

$$W_{IN} = \frac{10*11}{10*5.75*\frac{1}{12}} = 22.96$$

$$C_1 = \frac{2000}{22.96}$$

C_1 = 87.1 ft.

C_C, Conductor catenary constant

$$C_c = \frac{T_C}{W_C}$$

$$C_c = \frac{2000}{1.094}$$

C_c = 1,828 ft.

X_{BC}, Horizontal distance from connection point of insulator string and conductor to center of insulator catenary

$$\mathrm{X_{BC}} = \frac{\mathrm{C_1}}{\mathrm{C_C}} * X_{BD}$$

$$\mathrm{X_{BC}} = \frac{87.1}{1{,}828} * \left(\frac{200}{2} - \frac{10*5.75}{12}\right)$$

$\mathrm{X_{BC}} = 4.54$ ft.

$\mathrm{Y_{BC}}$, Sag from connection point of insulator string and conductor to center of insulator catenary

$$\mathrm{Y_{BC}} = \mathrm{C_1} * \left[\left(\cosh\frac{\mathrm{X_{BC}}}{\mathrm{C_1}}\right) - 1\right]$$

$$\mathrm{Y_{BC}} = 87.1 * \left[\left(\cosh\frac{4.54}{87.1}\right) - 1\right]$$

$\mathrm{Y_{BC}} = 0.118$ ft.

ℓ_{AC}, Arc length from insulator support point to center of insulator catenary

$$\ell_{\mathrm{AC}} = \ell_{\mathrm{AB}} + \mathrm{C_1}\sinh\left(\frac{\mathrm{X_{BC}}}{\mathrm{C_1}}\right)$$

$$\ell_{\mathrm{AC}} = 10 * \left(\frac{5.75}{12}\right) + 87.1 * \sinh\left(\frac{4.54}{87.1}\right)$$

$\ell_{\mathrm{AC}} = 9.33$ ft.

$\mathrm{X_{AC}}$, Horizontal distance from insulator support point to center of insulator catenary

$$\mathrm{X_{AC}} = \mathrm{C_1} * \sinh^{-1}\left(\frac{\ell_{\mathrm{AC}}}{\mathrm{C_1}}\right)$$

$$\mathrm{X_{AC}} = 87.1 * \sinh^{-1}\left(\frac{9.33}{87.1}\right)$$

$\mathrm{X_{AC}} = 9.31$ ft.

$\mathrm{Y_{AC}}$, Sag from insulator support point to center of insulator catenary

$$Y_{AC} = C_1 * \left[\left(\cosh\frac{X_{AC}}{C_1}\right) - 1\right]$$

$$y_{AC} = 87.1 * \cosh\left(\frac{9.31}{87.1}\right) - 1$$

$y_{AC} = 0.498$ ft.

Y_I, Insulator sag

$Y_1 = Y_{AC} - Y_{BC}$

$Y_1 = 0.498 - 0.118$

$Y_1 = 0.38$ ft.

The value calculated for Y_I is then added to the conductor sag to determine the total bus sag. Use $2 * X_{BD}$ as the span length to calculate the conductor sag.

Summary

This volume of the substation design series has focused on conductors and bus design. Conductors include both rigid and flexible materials and the ampacity and methods of making connections was covered. In addition the design factors for both rigid and strain bus systems were reviewed with design examples for each type of bus.

The next course in this series covers the application of power transformers in substations.

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