Substation Bus Design: Current Methods Compared with Field Results

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ABSTRACT

Current standards define accepted methods of substation bus design. These standards also require certain strength and deflection criteria. This paper will examine commonly proscribed rigid bus design methodologies and compare them with actual field experience in the design of a 500kV switching station. Special attention will be given to required deflection criteria, methods commonly used to achieve these criteria, and results actually measured in the field.

INTRODUCTION

The bus work in a substation are the structures that carry the electrical current. They are usually made of aluminum pipe or cable and are supported by porcelain or polymer insulators which are in turn supported by steel supports on foundations. Since the buses are typically energized at high voltages they must be separated from each other by distances that increase as the voltages increase. The air between the buses serves as the insulation between the voltages on each bus preventing electrical arcs from developing between the buses which would cause their destruction. This paper will consider the bus types used in this type of typical air-insulated substation using aluminum pipe bus. Gas insulated substations or substations using cable or materials other than aluminum will not be discussed.

Several forces, some electrically produced and some resulting from environmental effects, must be resisted by the bus design. Short circuits occurring either near or remote from the substation cause high current flows for short periods of time in the buses. These high currents cause high magnetic fields between the buses which produce large forces that must be considered in design. Buses must also be designed for gravity forces, including the weight of ice during icing conditions, wind, and seismic forces.

The approach normally taken in design is to choose a minimum bus diameter dependent upon current carrying ability and corona limitations and then determining the maximum span between bus supports dependent upon both deflection and strength limits of the aluminum pipe used. Bus diameter may need to be adjusted due to required span lengths between bus supports. After an adequate span and bus diameter are chosen, the necessary cantilever strength of support insulators is calculated and insulator types are chosen. If sufficiently strong insulators are not available, or are determined to be too costly, additional supports may be added to reduce maximum bus spans.

BUS SIZE DUE TO AMPACITY REQUIREMENTS

Bus ampacity (the amount of current a bus can safely carry) sets the lower limit for bus size. Every substation must carry a certain maximum amount of current and the bus work must be large enough to carry this current. As the amount of current a conductor carries increases, the temperature of that conductor will increase. Aluminum may be safely operated continuously at a temperature of 90°C; however, to prevent excessive oxidation this is usually limited to 70°C. There are two aluminum alloys available for pipe bus, 6061-T6 (with a conductivity of 40%) and 6063-T6 (with a conductivity of 53%). If the bus work needs to be designed for maximum ampacity, then 6063-T6 should be the choice. 6063-T6 allowable stress is somewhat less than 6061-T6, so the higher conductivity is counterbalanced by the need to provide more frequent supports. If minimizing the number of bus support points is the most important criteria, then 6061-T6 should be chosen. The current carrying capacity of the aluminum is also affected by the emissivity of the material. For both alloys the emissivity may be taken as 0.5.

Certain ambient conditions must be assumed. Conservatively, full sun and no wind (or very small wind) may be used. IEEE Std. 605 contains equations which may be used to determine bus ampacity under nearly any condition, but using the above assumptions (full sun, emissivity = 0.5, no wind, maximum temperature rise of 30°C at 40°C ambient resulting in a maximum temperature of 70°C) Table 1 may be used to choose the minimum bus size required based on ampacity.

Table 1: Pipe bus Ampacity 30° rise over 40° ambient.

	6063-T6		6061-T6	
Nominal Bus Size (in)	Schedule 40 Ampacity (Amps)	Schedule 80 Ampacity (Amps)	Schedule 40 Ampacity (Amps)	Schedule 80 Ampacity (Amps)
1.0	572	650	510	580
1.5	805	930	718	830
2.0	991	1161	884	1037
2.5	1314	1507	1173	1345
3.0	1582	1833	1412	1637
3.5	1796	2092	1603	1868
4.0	2015	2358	1800	2105
5.0	2474	2912	2009	2532
6.0	2943	3547	2628	3167
8.0	3830	4556	3420	4068

CORONA EFFECTS ON REQUIRED BUS SIZE

Corona is a physical condition caused by the ionization of air near an energized conductor. It results in energy loss, noise, and light emissions. Its major effect is radio interference. Corona must be minimized to prevent excessive electromagnetic interference (EMI). Corona discharges increase as the voltage on a bus increases or its diameter decreases. Corona will also increase on sharp edges or at corners. Bus size must be chosen to keep corona below allowable levels. Typically, corona only becomes a concern when station voltages equal or exceed 230kV line-to-line. IEEE Std. 605 contains methods to determine the minimum bus size necessary to prevent excessive corona. Assuming typical bus configurations, spacing, and heights given in IEEE Std. 1427, Table 2 gives the minimum bus diameters which may be used at various altitudes.

Table 2: Minimum allowable bus diameter (in.) to minimize corona discharge.

	Altitude above sea level (ft)										
System Voltage (kV)	0	1,000	2,000	3,000	4,000	5,000	6,000	8,000	10,000	15,000	20,000
230	1.5	1.5	1.5	1.5	1.5	1.5	2	2	2	2.5	2.5
345	2	2.5	2.5	3	3.5	3.5	3.5	4	4	5	5
500	3.5	4	5	5	5	6	6	8	8	8	8
765	8	8	8	8	>8	>8	>8	>8	>8	>8	>8

FORCES ON SUBSTATION BUSES

After the preliminary bus size is chosen using ampacity and corona criteria, the forces on the bus can then be calculated with the objective of determining the required spacing between support structures. This distance is typically limited by deflection but may also be limited by strength considerations of the bus type or the supporting insulators.

Three forces must be computed.

1. Gravitational = bus weight+ice load weight+damping conductor weight
2. Short circuit forces
3. Wind forces

Ice loading for any location in the U.S. may be determined from IEEE Std. C2 or ASCE 7-05. Ice weight per foot may then be found using equation 1.

$$W_i = 1.24r(d + r) \qquad [1]$$

Where:
W_i = Ice weight (lb/ft)
r = radial ice thickness (in)
d = bus diameter (in)

Weight of bus of varying diameter may be found in Table 3.

Table 3: Unit weight and section modulus of aluminum bus.

Nominal Bus Size (in)	Schedule 40			Schedule 80		
	Unit Weight (lb/ft)	Section Modulus (in^3)	Moment of Inertia (in^4)	Unit Weight (lb/ft)	Section Modulus (in^3)	Moment of Inertia (in^4)
1.0	0.581	0.1328	0.0873	0.751	0.1606	0.1056
1.5	0.94	0.3262	0.3099	1.256	0.4118	0.3912
2.0	1.264	0.5606	0.6657	1.737	0.7309	0.8679
2.5	2.004	1.064	1.530	2.65	1.339	1.924
3.0	2.621	1.724	3.017	3.547	2.225	3.894
3.5	3.151	2.394	4.788	4.326	3.140	6.281
4.0	3.733	3.214	7.232	5.183	4.272	9.611
5.0	5.057	5.451	15.16	7.188	7.432	20.67
6.0	6.564	8.498	28.15	9.884	12.227	40.501
8.0	9.878	16.813	72.51	15.008	24.520	105.743

Bare aluminum conductors may be installed inside tubular bus to attenuate wind induced vibrations. Typically these conductors are chosen to have a unit weight equal 10%-30% of the bus unit weight. Vibration damping conductors should be installed if maximum span lengths exceed those shown in Table 4.

Table 4: Maximum span length allowed without vibration damping conductors.

Nominal Bus Size (in)	Maximum Span Length Without Vibration Damping
1.0	5’
1.5	7’
2.0	9’
2.5	10’-9”
3.0	13’-3”
3.5	15’-3”
4.0	17’
5.0	21’-3”
6.0	25’-3”
8.0	28’

When a short circuit occurs inside or outside the substation currents will flow through the buses which may be orders of magnitude higher than normal current. These high currents produce magnetic fields surrounding the buses which will try to either force the buses toward or away from each other depending upon the direction of current flow. These forces must be computed and resisted by the buses and their supports. The Design Guide for Rural Substations (RUS 2001) gives Equation 2 for calculating the maximum short circuit forces which will occur on evenly spaced buses.

$$F_{sc} = \left(37.4\times10^{-7}\right)0.67\frac{i^2}{D} \qquad [2]$$

Where:
F_{sc} = Short Circuit Forces (lb/ft)
i = Short Circuit Current (Amps rms)
D = Centerline-Centerline spacing of buses (in.)

Wind loading may be calculated using pressures derived from ASCE 7-05 or from IEEE Std. C2. When ASCE 7-05 is used there are three loading cases that must be considered and two wind values are needed. The three loading cases are:

1. Extreme wind on bus without ice.
2. Coincident wind on bus including ice.
3. Extreme ice no wind.

The first load case requires determining the fastest possible wind for the location in question. The second load case requires the value of wind shown coincidental with the worst icing conditions. The wind force is then calculated using the first value on a bus diameter without ice and the second value on a bus diameter including ice. The third case is a vertical load only. The largest resultant force is then used in the design. If IEEE Std. C2 is used, only one calculation is needed (unless the bus is over 60 feet above ground level) based upon the value for wind pressure given for the loading district (light, meduim or heavy) at the location. In either case Equation 3 is then used to calculate the force per unit length on the bus.

$$F_w = 0.083P_W d \qquad [3]$$

Where:
F_W = Wind loading (lb/ft)
P_W = Wind pressure (lb/ft^2) from ASCE 07 or IEEE Std. C2
d = Outside diameter of the conductor including ice if needed (in.)

The total bus loading F_T, in lb/ft may then be determined using Equation 4 where W_C is the sum of the bus and the dampening conductor weight in lb/ft.

$$F_T = \sqrt{\left(F_{SC} + F_W\right)^2 + \left(W_C + W_i\right)^2} \qquad [4]$$

If wind loads were computed using ASCE 7, then Equation 4 must be solved three times. The first case will include wind without ice in which case W_i is not included. The second case will be coincident wind with ice. The third case is ice only and F_w is not included. In all cases short circuit forces F_{sc} should be included. The worst total F_T will then be used to determine the maximum bus support spacing. If wind loads are computed using IEEE Std. C2, then Equation 4 applies both wind and ice loads simultaneously for the approriate loading district. However, IEEE Std. 605 suggests applying laterial and gravity loads individually and calculating F_T first with only maximum wind and then with only maximum ice and then using the largest value of F_T. If the bus height were to exceed 60 ft. then IEEE Std. C2 would also require an additional computation for the extreme wind condition in which case Equation 4 must be solved again using the extreme wind pressure but no ice load. RUS 1724E-300 takes a more conservative approach and suggests extreme wind be considered for all bus designs no matter their height. So, while the design standards are not completely consistent, it would seem prudent to consider the following load cases for F_w and W_i when solving Equation 4.

1. Simultaneous NESC wind and ice for district loading.
2. Extreme wind (taken from ASCE 7 or IEEE Std. C2) and no ice.
3. Coincident wind and ice (taken from ASCE 7 or IEEE Std. C2).
4. Extreme ice (taken from ASCE 7 or IEEE Std. C2) and no wind.

CALCULATING MAXIMUM DISTANCE BETWEEN BUS SUPPORTS

After all forces are determined, the maximum allowable distance between bus supports may be calculated. Strength criteria and then deflection criteria will be used to determine a maximum possible bus length between supports for each case. Then the shorter of the two distances will be used. The RUS suggests Equation 5 to determine the maximum allowable bus span considering strength criteria only.

$$L_M = \sqrt{K_{SE}\left(\frac{F_B S}{F_T}\right)} \qquad [5]$$

Where:

L_M = Maximum bus support spacing (ft)
K_{SE} = Multiplying factor from Table 5
F_B = Maximum allowable fiber stress (lb/in^2)
28,000 lb/in^2 for 6061-T6
20,000 lb/in^2 for 6063-T6
S = Section modulus of the bus (in^3) from Table 3.
F_T = Total conductor loading (lb/ft)

Table 5: Values of K_{SE} and K_{DE} to be used in Equations 5, 6, 7 and 8.

Bus System	K_{SE}	K_{DE}
Fixed Both Ends	1.0	4.5
Fixed-Simply Supported	0.82	9.34
Simply Supported Both Ends (single span)	0.82	22.5
Simply Support (two equal spans)	0.82	9.34
Simply Supported (three or more equal spans)	0.88	11.9

The RUS gives Equation 6 for calculating vertical bus deflection and recommends limiting deflection to L/200 including the effects of ice. IEEE Std. 605 however, suggests limiting deflection to a maximum of L/150 while not including ice in the calculation.

$$y = K_{DE} \frac{(W_C + W_i) L_D^4}{EI} \qquad [6]$$

Where:
y = Maximum bus deflection (in)
K_{DE} = Multiplying factor from Table 5
E = Modulus of elasticity = $10 \text{ X } 10^6$ lb/in^2
I = Moment of inertia (in^4) from Table 3
L_D = Bus Support spacing (ft)

The maximum allowable length (ft) between supports using IEEE Std. 605 deflection limits would then be calculated from Equation 7.

$$L_D = 92.8 \sqrt[3]{\frac{I}{K_{DE} W_C}} \qquad [7]$$

The maximum allowable length (ft) between supports using RUS deflection limits would be calculated using Equation 8.

$$L_D = 84.3 \sqrt[3]{\frac{I}{K_{DE}(W_C + W_i)}} \qquad [8]$$

The calculation of deflection requires that the fixity of both ends of the span in question be determined. No end conditions will produce either completely fixed or simply supported, and the condition becomes more difficult to determine when some bus work is welded at the supports and some is not. One common condition is that a bus span is continuous on one side and supported by several supports over a long length, and simply supported on the other side. IEEE Std. 605 suggests a bus span of this type should be considered fixed on the continuous end and pinned on the other end. The RUS suggests, as may be seen in constant K_{DE} from Table 5, that the continuous end should not be considered entirely fixed.

The final factor limiting the allowable distance between bus supports is the strength of the insulators supporting the bus. The RUS recommends Equation 9 for determining the maximum allowable bus support spacing governed by the support insulator cantilever strength. This equation includes a suggested safety factor of 2.5 so the insulators working load will be approximately 40% of the rated cantilever strength.

$$L_S = \frac{W_S}{2.5\left(F_{SC} + F_W\right)} \qquad [9]$$

Where:

L_S = The average of the two adjacent span lengths, or the span length if equal spans (ft)

W_S = Rated insulator cantilever strength (lbs)

The maximum bus span length can now be determined by finding the smaller of L_S, L_D, and L_M.

DESIGN EXAMPLE

In a recent switchyard design a critical long span (60 ft) was included which was needed to cross a service road. This span was critical because it was highly visible and for aesthetic reasons the owner wanted a strict L/150 limitation on the bus deflection. The span in question was supported as shown in Figure 1. It was continuous on one side and supported by more than three supports to which the bus was welded, and simply supported on the other side where it made a connection to an expansion fitting and a switch. Six-inch schedule 80 bus was used. A problem was encountered when the calculated deflection was compared to the actual results after construction was completed.

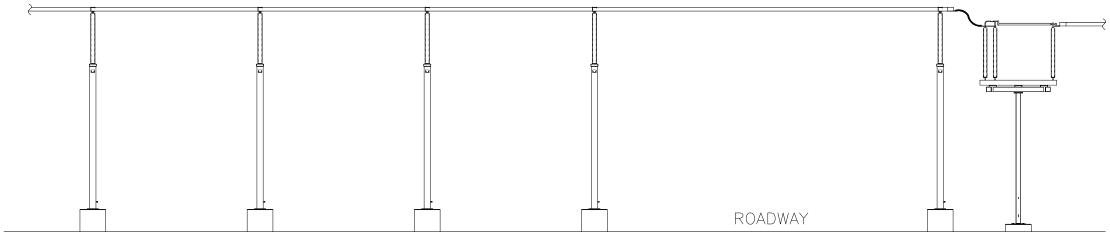

Figure 1: Bus system with supports.

The suggestions given in IEEE Std. 605 for fixity, deflection limits, and ice loading were used in the deflection calculations resulting in assuming a fixed-pinned condition without ice load. Using Equation 6 (and adding 30% to the bus weight due to the addition of the installed damping conductor) the maximum deflection should have been 3.94 inches which is well within the L/150 deflection limit (4.8-inches). A photograph of the bus in question is shown in Figure 2. After construction was complete the deflection was field measured and determined to be approximately 4.7 inches, which is much greater than expected and just barely within the 4.8 inches required. After creep the deflection would likely exceed the deflection criteria. The discrepancy between calculated and measured results is due to the inexactness of the fixity assumption. The continuous end of the span does not perform as perfectly fixed.

Figure 2: Deflection in 60 ft. bus span.

Assuming the span was a simply supported single span Equation 6 predicts a deflection of 9.51 inches which is far too large. Using the more exact assumption of three or more spans simply supported the calculated deflection becomes 5.03 inches which is slightly too large but close to the measured result. It is clear that none of the fixity assumptions contained in the RUS or IEEE Std. 605 design guidelines produces exact results for this condition and using the fixity suggestion contained in IEEE Std. 605 results in calculating a deflection that is much less than the installed condition. A far more exact and conservative result is produced by assuming all the spans are simply supported and using the value of K_{DE} from Table 5 for multiple simply-supported spans even though in the case considered the spans were not of equal length.

CONCLUSION

Methods have been described which are commonly used to design bus systems. Only tubular aluminum materials were considered and no point loads were included in the methods described. In some spans point loads will exist, such as when high-bus is supported by a span of low-bus. These point loads must also be considered for the critical spans in question. The introduction of expansion joints is another condition to be considered for critical spans.

It may be seen that the methodology and assumptions included in RUS sources and IEEE sources may not always completely agree, and the engineer must choose which assumptions best fit their design. Special consideration should be given to deflection calculations. Deflection in a substation bus design is typically not critical from a performance or structural standpoint but may become important for aesthetic considerations. However, when deflection does become critical, the fixity assumptions suggested in some standards were found to be somewhat in error and in the case of those in IEEE Std. 605 were non-conservative. In the case considered here, with a continuous bus on one side of the span and a pinned support on the other side of the span, the results using the assumptions for multiple simply-supported spans given in the RUS documents produced the most accurate results when compared with actual measured deflections, and the suggestions contained in IEEE Std. 605 resulted in considerable error when compared to field measured results.

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