



IEEE Guide for Bus Design in Air Insulated Substations

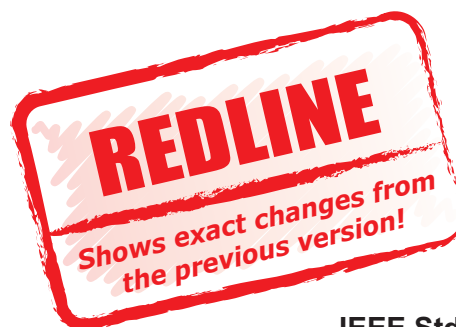
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IEEE Guide for Bus Design in Air Insulated Substations

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Abstract: A proper design of the substation bus ensures a safe and reliable operation of the substation and the power system. Two different types of buses are used in substations, the rigid bus and the strain (cable). This guide provides information on the different bus arrangements used in substations stating the advantages and disadvantages of each. Also it provides information as related to each bus type and construction. Once the bus type is selected, this guide provides the calculation tools for each bus type. Based on these calculations, the engineer can specify the bus size, forces acting on the bus structure, number of mounting structures required, and hardware requirements.

Keywords: ampacity, bus support, corona, electromagnetic, finite-element, forces, ice, mounting structure, rigid bus structures, short circuit, strain-bus structures, substation design, wind

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Introduction

This introduction is not part of IEEE Std 605-2008, IEEE Guide for Bus Design in Air Insulated Substations.

This introduction provides some background on the rationale used to develop this guide. This information is meant to aid in the understanding and usage of this guide.

Buses consisting of conductor structures and the associated hardware comprise a large percentage of the substation equipment investment. The proper design of substation bus structures contributes to the safe and reliable operation of the substation and the power system. Two different types of buses are most commonly used in substations: rigid bus and strain bus (cable). This guide provides information on the different bus arrangements used in substations stating the advantages and disadvantages of each. Also, it provides information on each bus type and construction. Once the bus type is selected, this guide provides the calculation tools for each bus type. Based on these calculations, the engineer can specify the bus size, the forces acting on the bus structure, the number of mounting structures required, and the hardware requirements. However, this guide does not provide any guidance on the seismic design of bus structures, which is given in IEEE Std 693TM-2005^a and IEEE Std 1527TM-2006.

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IEEE Guide for Bus Design in Air Insulated Substations

~~IEEE Guide for Design of Substation Rigid-Bus Structures~~

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1. Overview

1.1 Scope

The information in this design guide is applicable to both rigid bus ~~structures~~ and strain bus designs 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 electromechanical forces ~~due to~~ resulting from gravity, wind, fault current, and thermal expansion are considered. Design criteria for conductor and insulator strength calculations are included.

This guide does not consider the following:

- a) The electrical criteria for the selection of insulators (see IEEE Std 1313.2™-1999 [B22])
- b) The seismic forces to which the substation may be subjected (see IEEE Std 693™-2005 and IEEE Std 1527™-2006)
- c) The design of mounting structures
- d) Design considerations for contaminated environments (see IEEE Std 1313.2-1999 [B22])
- e) Installation methods
- f) Design of direct current buses

1.2 Purpose

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

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

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~~ANSI C29.1-1988 (R1996), American National Standard Test Methods for Electrical Power Insulators~~ [AA-ADM-1, Aluminum Design Manual, 2005.](#)¹

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ANSI C29.9-1983 (~~R1996~~ [Reaff 2002](#)), American National Standard for Wet-Process Porcelain Insulators (Apparatus, Post Type).³

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

ASCE 7-~~95~~ [05](#), Minimum Design Loads for Buildings and Other Structures.⁴

ASTM B188-~~96~~ [02](#), Standard Specification for Seamless Copper Bus Pipe and Tube.⁵

ASTM B241/B241M-~~96~~ [02](#), Standard Specification for Aluminum and Aluminum-Alloy Seamless Pipe and Seamless Extruded Tube.

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

[AWS D1.2-2003, Structural Welding Code—Aluminum.](#)⁶

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

~~IEEE Std 100-1996, IEEE Standard Dictionary of Electrical and Electronics Terms. IEEE Std 693-1997, IEEE Recommended Practice for Seismic Design of Substations. NEMA CC 1-1993, Electric Power Connectors for Substations.~~^{5,7,8}

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3. Definitions

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

[For the purposes of this document, the following terms and definitions apply. The IEEE Standards Dictionary: Glossary of Terms & Definitions should be referenced for terms not defined in this clause.](#)¹¹

aeolian vibration: [The vibration of a structure induced by the flow of air around or through it.](#)

ampacity: [The current-carrying capacity, expressed in amperes, of an electric conductor under stated thermal conditions.](#)

annealing: [The sustained heating of a material, such as metal or glass, at a known high temperature, followed by the gradual cooling of the material; a process that is carried out to reduce hardness or brittleness, to eliminate various stresses and weaknesses, or to produce other qualities.](#)

bus: [A conductor or group of electrical conductors serving as common connections between circuits, generally in the form of insulated cable, rigid rectangular or round bars, or stranded overhead cables held under tension.](#)

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

bus support: An insulating support for a bus.

NOTE—A bus support includes one or more insulator units with fittings for fastening to the mounting structure and for receiving the bus.¹²

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

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

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

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

³ASTM publications are available from the American Society for Testing and Materials, 100 Barr Harbor Drive, West Conshohocken, PA 19428-2959, USA. ⁴IEEE

conduction: [The transfer of heat through a medium while the medium itself experiences no mass movement as a whole. Contrast: convection; radiation.](#)

convection: [The transfer of heat that occurs when a fluid flows over a solid body \(like wind around a conductor\), when the temperature of the fluid and the solid boundary are different. Contrast: conduction; radiation.](#)

corona: [A luminous discharge due to ionization of the air surrounding a conductor, caused by a voltage gradient exceeding a certain critical value.](#)

⁸IEEE publications are available from the Institute of Electrical and Electronics Engineers, 445 Hoes Lane, P.O. Box 1331, Piscataway, NJ 08855-1331, USA-08854, USA (<http://standards.ieee.org>).

⁹NEMA⁹NEMA publications are available from Global Engineering Documents, 15 Inverness Way East, Englewood, CO 80112, USA (<http://global.ihs.com/>).

¹⁰NFPA publications are available from Publication Sales, National Fire Protection Association, 1 Batterymarch Park, P.O. Box 9101, Quincy, MA 02269-9101, USA (<http://nfpa.org/codes/index.html>). the National Electrical Manufacturers Association, 1300 17th St., Ste. 1847, Rosslyn, VA 22209, USA. ⁶NFPA publications are available from Publications

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¹²Notes in text, tables, and figures are given for information only and do not contain requirements needed to implement the standard.

damping: (1) The temporal decay of the amplitude of a free oscillation of a system, associated with energy loss from the system. (2) A dynamic property of a vibrating structure that indicates its ability to dissipate mechanical energy. (3) An energy dissipation mechanism that reduces the response amplification and broadens the vibratory response over frequency in the region of resonance.

drag: The force acting on a body when a fluid flows around it (like wind around a conductor).

drag coefficient: A factor representing the effect of drag on a body.

emissivity: The ratio of power radiated by a material body to the power radiated by a blackbody at the same temperature.

mounting structure: A structure for mounting an insulating support.

natural frequency: A frequency at which a body or system vibrates due to its own physical characteristics (mass and stiffness) when the body or system is distorted and then released.

radiation: (1) The action of emitting radiant energy in the form of waves or particles. (2) The transfer of heat by radiation. *Contrast:* **conduction; convection.**

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

spring constant: A constant representing the equivalent resistance to displacement of a support under a load in a given direction.

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

tensile strength: The maximum tensile stress (stretching) that a material can withstand without failure.

yield strength: The stress level at which a material attains a specified permanent (plastic) deformation, usually 0.2% of the original gauge length, indicative of when a material begins to deform permanently (plastically) under loading.

Young's modulus: A mechanical property of a material representing its resistance to elongation in the elastic range of deformation. Specifically, Young's modulus is the elastic modulus for tension or tensile stress, and it is the force per unit cross section of the material divided by the fractional increase in length resulting from the stretching of a standard rod or wire of the material.

4. Bus arrangements

Several important factors affect the selection of bus arrangements. These factors include but are not limited to cost, safety, reliability, simplicities of relaying, flexibility of operation, ease of maintenance, available ground area, location of connecting lines, provision for expansion, and appearance.

In general, bus arrangements require disconnect switches to be installed on each side of the breaker to provide a visual opening when a breaker is taken out of service during maintenance or repair. For safety and reliability, the electric clearances must meet appropriate codes and recommendations. Insulation coordination studies should be performed to calculate the voltage levels that result from lightning surge, switching surge, or due to temporary fault conditions. To improve reliability, the electric connections should be simple; the more complex the connections, the more chances that a faulty condition will occur.

Buses are typically arranged to allow access to equipment for maintenance or replacement due to failure or upgrades. In addition, bus arrangements should provide for future growth, including consideration of disconnect switches that allow for continuity of service during construction.

This subclause consists of descriptions of substation bus arrangements that are used today.

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4.1 Single bus single breaker arrangement (SBSB)

The single bus single breaker arrangement shown in Figure 1 consists of one main bus that contains positions for several circuits. The circuits are normally connected via circuit breakers but can be connected via circuit switchers, which are motor or manually operated switches. The single bus single breaker arrangement is generally applied in substations from distribution voltage through 121 kV to 161 kV and in locations where system reliability is not critical.

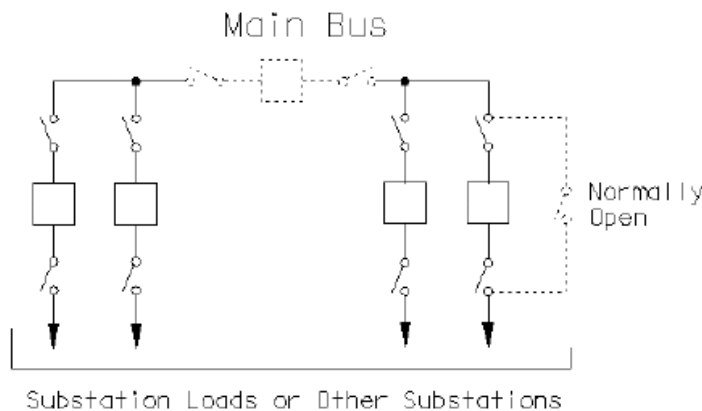


Figure 1—Single bus breaker

The single bus single breaker arrangement is the simplest to operate but offers the least reliability and operational flexibility.

A breaker failure or bus fault condition will require the tripping of all breakers connected to the bus causing power loss to all the circuits connected to that bus.

To increase the reliability of a single bus single breaker arrangement, a bus-sectionalizing breaker can be installed on the bus, as shown in Figure 1 with dashed lines. As a result, a bus fault or breaker failure will lead to the loss of only part of the substation.

To improve operating flexibility, a normally open bypass circuit may be installed in parallel with the breaker (see Figure 1). The bypass may be a switch or fuse, depending on voltage and current levels. When the bypass is closed, the breaker may be taken out of service for maintenance or replacement without disrupting the circuit. While the breaker is bypassed, the associated protective relays will be disabled, and a fault on the circuit may result in the loss of the entire bus. See Table 1 for the advantages and disadvantages of a single bus single breaker arrangement.

4.2 Main and transfer bus arrangement (MTB)

The main and transfer bus arrangement is a modification to the single bus arrangement as shown in Figure 2. This arrangement consists of two buses, a main and a transfer. Each circuit bay consists of one breaker and three switches, except the transfer breaker bay, which requires only two switches. The main bus is normally energized, and all circuits are serviced from the main bus as shown in Figure 2(a).

The addition of the transfer bus and transfer breaker allows taking any breaker out of service while the associated circuit remains in service. When a breaker is taken out of service, the transfer breaker and its normally open switches are closed, the circuit breaker and its switches are opened. Figure 2(b) shows circuit #1 breaker out of service and circuit #1 serviced by the transfer breaker.

The use of a transfer breaker for more than one circuit requires a selector switch to select the appropriate protective and control scheme. The selector switch arrangement complicates the protective and control schemes, which result in additional work during the initial construction period and operation.

The main and transfer bus arrangement shown in Figure 2(a) requires a considerable amount more of bus conductor, insulators, and material for bus and switch mounting structures as compared with the single breaker arrangement (Figure 1). This increases the foundation requirements and therefore drives the cost high. See Table 1 for the advantages and disadvantages of a main and transfer bus arrangement.

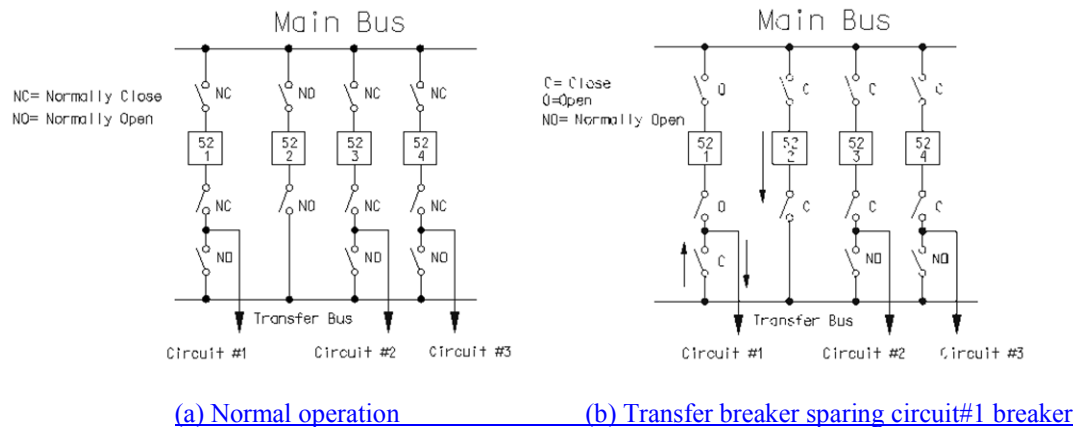


Figure 2—Main and transfer bus arrangement

4.3 Double bus single breaker arrangement (DBSB)

The double bus single breaker arrangement shown in Figure 3 is a modification of the sectionalized radial single bus. This arrangement consists of two main buses connected together through a circuit breaker. Each circuit uses a circuit breaker and three disconnect switches and can be connected to either bus through disconnect switches. This arrangement allows all circuits to be connected to one bus in case of an outage on the other bus.

This arrangement is used in areas where high contamination is expected. Buses are taken out of service to clean the insulators. It also allows split bus operation if system conditions require it. A bus tie breaker may be added to increase the system flexibility by allowing split bus operation. A transfer breaker may be added, as shown in Figure 3(b), to allow bypassing a circuit breaker. Additional disconnect allows for connecting circuits #1 or #2 directly to the main bus #1, if a corresponding circuit breaker should be taken out of service. For example, to spare circuit #1 breaker, we should open all three disconnects adjacent to the breaker and close a normally open disconnect between circuit #1 and the main bus #1. After this is done, circuit #1 may stay in service; it will be switched by a breaker installed between main buses #1 and #2. During this period of time, circuit #2 should be fed from main bus #2; see Table 1 for the advantages and disadvantages of a double bus single breaker arrangement.

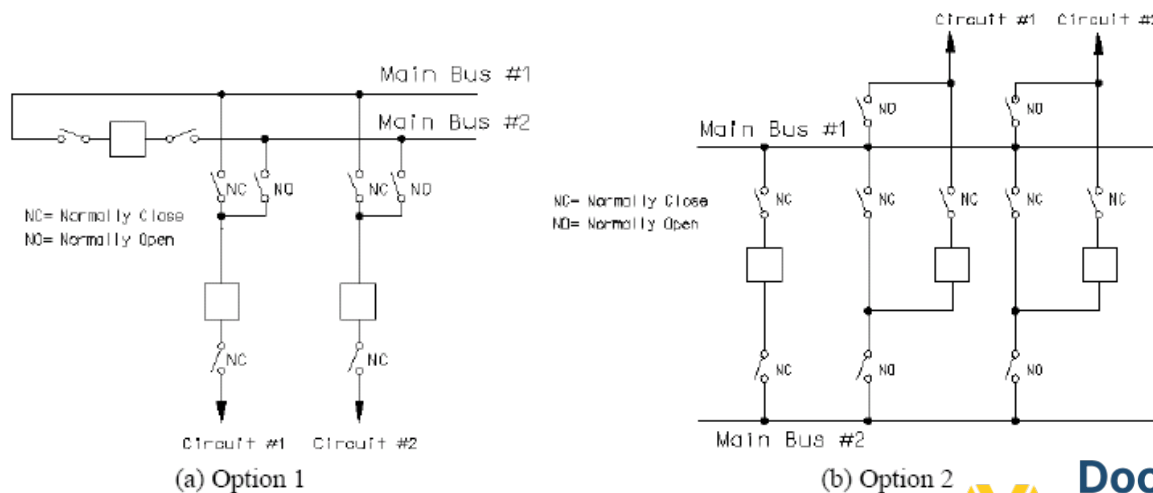


Figure 3—Double bus single breaker arrangement

4.4 Ring bus arrangements (RB)

In the ring bus arrangement, each circuit is connected between two breakers. The breakers are arranged in a series connection to form the “ring.” In the ring bus arrangement, one breaker per circuit is possible as shown in Figure 4. The switchyard is normally operated with all breakers in the closed position. Power flow is evenly distributed because the ring bus operates as a single node.

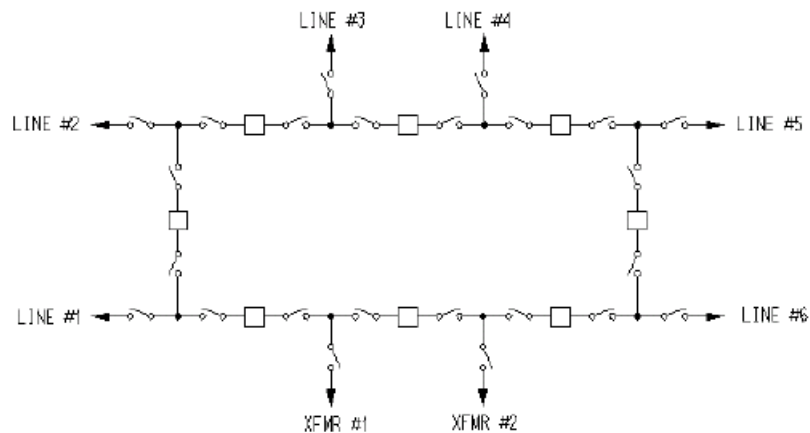


Figure 4—Ring bus arrangement (eight breakers—eight circuits¹³)

By opening selected breakers, any circuit can be removed from service without affecting service to the other lines. Line disconnect switches are often applied to allow a circuit to be removed from service and to allow the remaining elements to remain in service with the ring partially open. Sources of generation or redundant circuits should not be terminated on adjacent positions of the ring bus; this strategy will prevent a failed circuit breaker from removing two sources of generation or two feeds to the same load from service.

The bus is reduced to connections between equipment; therefore, typically it requires much less bus, insulators, and mounting structures than the other arrangements discussed previously except the single bus single breaker arrangement. The protective and operating schemes are simple compared with the main transfer bus arrangement.

Breaker maintenance is easily accomplished without taking a line out of service by opening that breaker and associated disconnect switches. Portions of the bus can be de-energized, but a circuit would also have to be taken out of service at the same time. Power flow may be restricted during maintenance and emergency operations.

The ring bus arrangement is very reliable when all breakers are closed and the ring is intact. Typically, the breakers on either side of a circuit are opened when the circuit is taken out of service, opening the ring. Under this scenario, a fault on a second circuit may split the remaining circuits into two isolated operating systems. A similar situation may occur if a single breaker is taken out of service for maintenance. However, with breakers becoming more maintenance free, the ring bus arrangement is becoming more popular. See Table 1 for the advantages and disadvantages of a ring bus arrangement.

4.5 Breaker and half bus arrangement (B-1/2)

The breaker and half bus arrangement shown in Figure 5 consists of two main buses that are normally energized. Three breakers are required to serve two circuits. The middle breaker is common between two circuits and, hence, the name breaker and half bus arrangement. Any breaker or bus can be taken out of service without interruption of service. Faults on one circuit do not affect the other circuit unless the associated breaker fails to trip.

¹³Usually a ring bus is limited to eight breakers in a ring, but there may be more than eight breakers depending on particular conditions, which include loading of the circuits, reliability constraints, and so on.

However, it uses approximately 25% less equipment than the double bus double breaker arrangement for each circuit.

This arrangement is used for substations where reliability and service continuity is important. This arrangement is used extensively for voltage levels above 345 kV and some 230 kV substations due to the importance of these substations. Line switches can be added if required.

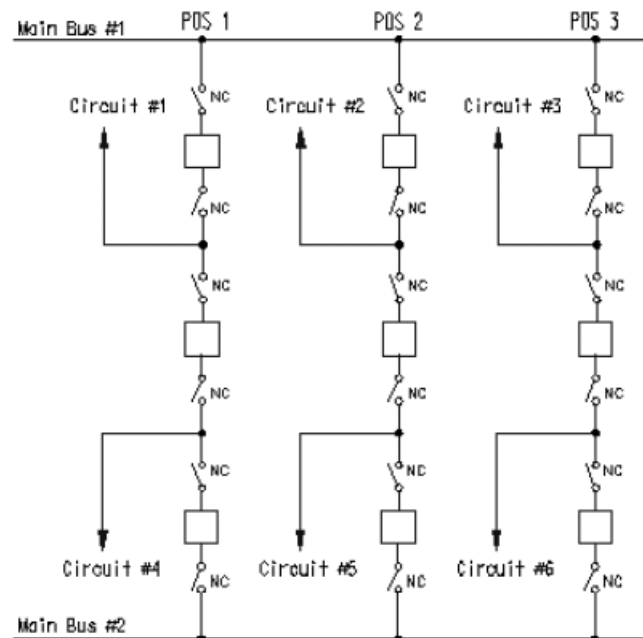


Figure 5—Breaker and half bus arrangement

4.6 Double bus double breaker arrangement (DBDB)

This bus arrangement, shown in Figure 6, consists of two main buses with two breakers and four switches per circuit. Any breaker or bus can be taken out of service for maintenance without an interruption to service. Split bus operation is possible. This bus arrangement is considered to be the most reliable.

This arrangement requires a large ground area. It is the most expensive one because it requires the most equipment per circuit. This bus arrangement requires a considerable amount of material for mounting structures.

This bus arrangement is rarely used at this time due to its cost and the space required.

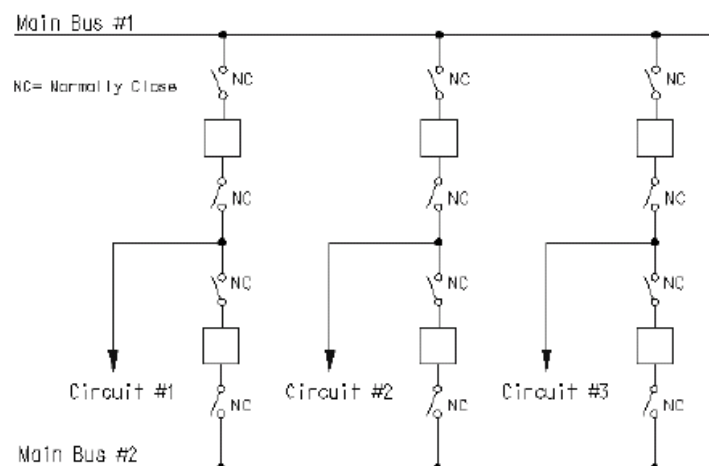


Figure 6—Double bus double breaker arrangement

4.7 Bus arrangements comparison

The advantages and disadvantages of each of the arrangements are listed in Table 1.

Table 1—Bus arrangements comparison

<u>Bus arrangements</u>	<u>Advantages</u>	<u>Disadvantages</u>	<u>Cost (NOTE 1)</u>	<u>Land (m²) (NOTE 2)</u>
<u>SBSB</u>	<u>Lowest cost</u> <u>Small land area</u> <u>Easy to expand</u> <u>Simple to operate</u> <u>Simple protective schemes</u>	<u>Low reliability</u> <u>Bus or breaker fault causes loss of entire station</u> <u>Breaker maintenance requires the associated circuit outage</u>	<u>100%</u> <u>120% (with sect. breaker)</u>	<u>3160</u> <u>3810 (with sect. breaker)</u>
<u>MTB</u>	<u>Easy to expand</u> <u>Allows for breaker maintenance</u> <u>Increased flexibility over single bus</u>	<u>Low reliability</u> <u>Bus or breaker fault causes loss of entire station</u> <u>Increased complexity over single bus</u> <u>Complex protective scheme</u> <u>Large land area required</u>	<u>140%</u>	<u>5960</u>
<u>DBSB</u>	<u>Allows for outage on any one of the buses</u> <u>Increased flexibility over single bus</u> <u>May allow for breaker maintenance</u>	<u>Low reliability</u> <u>Bus or breaker fault causes loss of entire station</u> <u>Increased complexity over single bus</u> <u>High cost</u> <u>Very large land area required</u>	<u>175% (Opt.1)</u> <u>190% (Opt.2)</u>	<u>9290 (Opt.1)</u> <u>11 520 (Opt.2)</u>
<u>RB</u>	<u>High reliability</u> <u>Flexible operation</u> <u>Allows for breaker maintenance</u> <u>Bus fault does not affect continuity of operation</u>	<u>Extensive relaying and control schemes</u> <u>Breaker failure results in loss of two circuits</u> <u>Large land area required</u> <u>May split into two operating systems</u>	<u>125%</u>	<u>5720</u>
<u>B-1/2</u>	<u>Easy to expand</u> <u>High reliability</u> <u>Flexible operation</u> <u>Allows for breaker maintenance</u> <u>Bus fault does not affect continuity of operation</u>	<u>High cost</u> <u>Extensive relaying and control schemes</u> <u>Large land area required</u>	<u>145%</u>	<u>4600</u>
<u>DBDB</u>	<u>Easy to expand</u> <u>Very high reliability</u> <u>Very flexible operation</u> <u>Allows for breaker maintenance</u> <u>Bus fault does not affect continuity of operation</u> <u>Breaker failure results in loss of only one circuit</u>	<u>High cost</u> <u>Large land area required</u> <u>Extensive relaying and control schemes</u>	<u>190%</u>	<u>5810</u>

NOTE 1—Cost in percent is given to illustrate the cost relationship among the different bus arrangements with the SBSB design as the base.

NOTE 2—Metric values have been rounded to the nearest square meter.

NOTE 3—System voltage is 230 kV.

NOTE 4—Number of circuits in all bus arrangements is 4.

NOTE 5—Similar protective schemes have been used for each bus and line as required.

NOTE 6—Cost of land or control house is not included in the estimate.

NOTE 7—Unit costs used in this table to obtain estimates for each arrangements are installed costs, including cost of equipment, foundation, steel design, engineering, construction supervision, control circuits and so on.

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4. The design problem

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

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

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

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

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

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

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

5. Bus design considerations

Substation bus systems provide the following functions:

- a) The means to allow more than one electric circuit to connect to the substation
- b) The means for incoming and outgoing circuit termination
- c) The means for electrically interconnecting switching and other equipment such as transformers, capacitor banks, reactors, and so on

Today, several types of bus systems are used in substations: rigid bus, strain (flexible) bus, and gas-insulated bus. The rigid bus is a common type of bus system in use in North America. The strain conductor bus is often used in high- and extra-high-voltage substations (230 kV and higher) where either high-capacity or increased seismic withstand capability is required, and the area is available. The gas-insulated bus is suitable for unique environmental or space-constrained applications. The gas bus may be suitable when available ground area in a substation is very small, requiring only 10% of the area of air-insulated substations. Also, it is used in urban and industrial locations subject to space constraints and pollution, mountainous areas (extra site preparation, altitude, snow, and ice concerns), coastal areas (salt associated problems), underground substations, and areas where aesthetics are major concerns.

5.1 Preliminary bus design considerations

Prior to the start of a bus design, several design conditions need consideration. These design conditions shall establish the minimum electrical and structural requirements for the type of bus being considered. Preliminary design considerations are as follows:

- a) Number and type of circuits served by the bus, and the reliability desired or required for these circuits
- a) Site location and size
- b) Seismic activity
- c) Conductor ampacity
- d) Maximum anticipated fault current
- e) Maximum operating voltage
- f) Fault clearing time
- g) Electrical and safe working clearances
- h) Phase spacing
- i) Bus conductor temperature
- j) Maximum and minimum ambient temperature
- k) Maximum anticipated wind speed
- l) Maximum anticipated icing conditions combined with wind
- m) Altitude and latitude of the substation
- n) Basic substation layout
- o) Standard design practices
- p) Hardware and equipment availability

In addition to these preliminary design considerations, the local public may have input concerning the noise and aesthetics of the substation and surrounding area.

The bus design can begin after all of the design conditions are firmly established and the bus arrangement has been determined. Several factors must be considered to determine the appropriate bus arrangement for a substation. These factors may include the following:

- Construction type
- Material type
- Type of disconnect switches

The following subclauses discuss the above factors.

5.2 Construction type

5.2.1 Box structure

The box structure is generally applied at 138 kV and below. It requires the least amount of land area and uses layers of bus, disconnect switches, and related equipment, one above the other, connected with vertical bus runs and supported on a common structure. Rigid or strain bus can be used. The bus configurations most easily applied to a box structure are single bus, split single bus, main and transfer, and single breaker double bus. This construction is generally considered the least attractive and is predominantly installed in rural or industrial locations.

5.2.2 Low-profile rigid bus

Low-profile rigid bus construction can be used for all voltage levels. The main and cross buses run horizontally on two relatively low levels supported by insulators on mounting structures. Other substation equipment, such as switches and fuses, are supported on individual structures.

The advantages and disadvantages of this type of bus construction are as follows:

Advantages

- a) Use low-level mounting structures. This will result in a low profile bus, which is important in populated areas.
- b) The conductors are not under strain, which improves the reliability by reducing the probability of breakage.
- c) The station post insulators are more accessible for cleaning in an area of high contamination.
- d) A rigid bus requires less area because the phase-to-phase clearance is less for the rigid bus than for the strain bus.

Disadvantages

- e) Due to the span length limitation, the rigid bus requires more mounting structures than the strain bus. As a result, more foundations and grounding will be required.
- f) Additional design features may be needed to allow access to equipment for maintenance.
- g) Experience shows that in seismic areas, the rigid bus is less reliable than the strain bus and may break during earthquakes. Expansion fittings may create impact loads during an earthquake, because the thermal expansion fitting gap is too small to allow for relative displacements at the top of insulators. Conductors may also pull out of the expansion fittings during an earthquake. Cast bus fittings may be brittle and lack sufficient strength to resist earthquake loads; forged fittings should then be considered. Other aspects may also influence the seismic behavior of rigid bus assemblies. Therefore, careful considerations should be given to the behavior of rigid bus assemblies on insulators in areas subjected to earthquakes.

5.2.3 Strain bus

Strain bus construction uses one or more flexible conductors attached to supporting structures via insulator and hardware assemblies. The main bus conductors are normally under medium-to-high tension. Bus taps and equipment jumpers are under low tension. Strain bus may be used at any voltage level, but it has typically been used at extra-high-voltage (EHV) and ultra-high-voltage (UHV) levels due to the very large phase-phase and phase-to-ground clearances required.

The advantages and disadvantages of the strain bus construction are as follows:

Advantages

- a) Less mounting structures are used, and therefore, the substation area is open and clear to allow access to equipment for maintenance.
- b) Strain bus may be more effective to earthquake loads.
- c) Fewer insulators and less hardware are used in the strain bus.
- d) Strain bus requires fewer man-hours to construct than the rigid bus.

Disadvantages

- e) Strain bus requires larger phase-to-phase clearance to allow for conductor swing due to wind and short circuit forces. This will result in a larger substation area.

- f) Strain bus requires a higher structure to allow for phase-to-ground clearance due to conductor sag.
- g) The strain bus uses a larger structure than rigid bus.
- h) Careful consideration should be given to strain bus between interconnected equipment subjected to earthquakes, to allow enough slack to permit differential displacement (see IEEE Std 1527-2006).

5.2.4 Gas insulated bus

This type of bus construction consists of completely enclosed rigid bus conductors and equipment insulated with pressurized SF₆ gas. Because of the excellent insulating properties of this gas phase, spacing can be very compact to allow construction in a much smaller physical space than an open-air insulated bus. SF₆ gas bus construction is typically used at EHV and UHV levels where land costs or environmental hazards offset the much higher SF₆ equipment costs.

Advantages

- a) Require minimum land area
- b) Enclosed live parts not exposed to the environment
- c) Modularized designs minimize construction man-hours

Disadvantages

- d) Requires very expensive specialized equipment
- e) Pressurized bus may create potential safety issues

5.3 Disconnect switches

The clearance requirements for each switch must be determined. For example, if the available phase-to-phase clearance is 3 m, a switch that requires 4.5 m clearances cannot be used. The installation, operation, and adjustment of a switch must be evaluated.

Considerations must be given to switch maintenance requirements and to the availability of spare parts.

The mechanical loads that can be applied to a switch must be considered and evaluated. Similarly the effect on the switch of thermal expansion and contraction of the rigid bus must be considered.

6. Conductors

6.1 General

Conductors are available in a wide variety of materials, alloys, and types of construction. The intent of this subclause is to describe the more common types of conductors that are installed in outdoor, air-insulated substations.

6.2 Materials

6.2.1 General

Overhead conductors used for transmitting electrical power are normally constructed of copper or aluminum materials. If greater strength is required, then alloys or steel reinforcing may be added to the copper or aluminum materials to increase the strength of the overall conductor assembly.

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Alternative metals such as gold, silver, and other materials may be applied for special applications, but these materials are generally not used in the power industry based on economic or physical considerations. In contrast, copper and aluminum metals are readily available and provide a relatively good blend of electrical, mechanical, and economic properties.

6.2.2 Copper

Copper is a highly conductive metal with tensile and ductile strengths that can be altered to achieve the desired properties. There are three basic types of copper conductor: hard-drawn copper, medium-hard-drawn copper, and annealed copper, also known as soft-drawn copper.

Copper rod drawn into wire without heat treatment will provide relatively high-strength wire with low elongation properties. Such wire is known as hard-drawn copper and is suitable for overhead transmission line applications.

Heat treatment of the copper conductor will anneal the material to a more ductile metal that is easier to form and shape. However, the heating process will also lower the tensile strength of the conductor. This type of conductor is known as soft-drawn copper. Typical applications for soft-drawn copper wire include ground wire, insulated conductors, and other locations where it is necessary to bend and shape the conductor.

Medium-hard-drawn copper is annealed copper drawn to a slightly smaller diameter. The characteristics of this conductor tend to approach hard-drawn copper, but a uniform tensile strength is difficult to obtain. As a result, the tensile strength of medium-hard-drawn copper is typically specified in ranges. Typical applications for medium-hard-drawn copper include overhead distribution lines.

The resistivity of copper increases slightly with increasing hardness. Other properties of copper conductors are listed in Table 2.

Table 2—Properties of common bus materials

<u>Metal</u>	<u>Alloy and temper</u>	<u>ASTM reference standard</u>	<u>Minimum tensile strength MPa (ksi)</u>	<u>Minimum yield strength MPa (ksi)</u>	<u>Minimum Conductivity at 20 °C in % of IACS (NOTE 1)</u>	<u>Modulus of elasticity GPa (ksi)</u>
<u>Copper tube</u>	<u>H80 Hard (<4" OD)</u>	<u>B-188</u>	<u>275 (40.0)</u>	<u>172 (25.0) (NOTE 6)</u>	<u>96.6 (NOTE 2)</u>	<u>110 (16 000)</u>
	<u>H80 Hard (>4" OD)</u>	<u>B-188</u>	<u>260 (38.0)</u>	<u>163 (23.8) (NOTE 6)</u>	<u>97.4 (NOTE 2)</u>	<u>110 (16 000)</u>
	<u>O60 Soft</u>	<u>B-188</u>	<u>—</u>	<u>—</u>	<u>100 (NOTE 2)</u>	<u>110 (16 000)</u>
<u>Copper wire</u>	<u>Hard</u>	<u>B-1</u>	<u>430 (62.1) (NOTE 3)</u>	<u>—</u>	<u>96.16</u>	<u>110 (16 000)</u>
	<u>Medium-hard</u>	<u>B-2</u>	<u>340 (49.0) (NOTE 3)</u>	<u>—</u>	<u>96.66</u>	<u>110 (16 000)</u>
	<u>Soft</u>	<u>B-3</u>	<u>—</u>	<u>—</u>	<u>100</u>	<u>110 (16 000)</u>
<u>Aluminum tubes and shapes</u>	<u>6061-T6</u>	<u>B-241</u>	<u>260 (38.0)</u>	<u>240 (35.0)</u>	<u>40 (typical)</u>	<u>69 (10 000)</u>
	<u>6063-T6</u>	<u>B-241</u>	<u>205 (30.0)</u>	<u>170 (25.0)</u>	<u>53 (typical)</u>	<u>69 (10 000)</u>
	<u>6101-T6</u>	<u>B-317</u>	<u>200 (29.0)</u>	<u>172 (25.0)</u>	<u>55.00</u>	<u>69 (10 000)</u>
	<u>6101-T61</u>	<u>B-317</u>	<u>138 (20.0)</u>	<u>103 (15.0)</u>	<u>57.00</u>	<u>69 (10 000)</u>
	<u>6101-T63</u>	<u>B-317</u>	<u>186 (27.0)</u>	<u>152 (22.0)</u>	<u>56.00</u>	<u>69 (10 000)</u>
	<u>6101-T64</u>	<u>B-317</u>	<u>103 (15.0)</u>	<u>55 (8.0)</u>	<u>59.50</u>	<u>69 (10 000)</u>
<u>Aluminum wire</u>	<u>1350-H19 (NOTE 5)</u>	<u>B-230</u>	<u>180 (26) (NOTE 4)</u>	<u>—</u>	<u>61.00</u>	<u>69 (10 000)</u>
	<u>6201-T81</u>	<u>B-398</u>	<u>315 (46) (NOTE 4)</u>	<u>—</u>	<u>52.50</u>	<u>69 (10 000)</u>

NOTE 1—The international standard for the resistivity of annealed copper is 0.15328 $\Omega\text{-g/m}^2$ at 68 °F (20 °C). This value represents 100% of the International Annealed Copper Standard (IACS).

NOTE 2—Applicable to copper UNS nos. C10200, C10400, C10500, C10700, C11000, C11300, C11400, and C11600.

NOTE 3—Nominal value, see ASTM B-1, B-2, or B-3 as applicable.

NOTE 4—Nominal value, see ASTM B-230 or B-398 as applicable.

NOTE 5—Prior to 1975, aluminum alloy 1350 was identified as EC aluminum.

NOTE 6—The *Chase Electrical Handbook* [B11] states on page 47 that, “Copper has no true elastic limit, its stress-strain diagram having no section which is a perfectly straight line. For a practical engineering figure it is common practice to use as the yield strength of copper the stress which will produce an elongation under load of $\frac{1}{2}$ of one percent.” The yield strength values listed in the Table 1 are based on 62.5% of the ASTM minimum tensile strength as indicated in Tables 8 and 9 of the *Chase Electrical Handbook*.

6.2.3 Aluminum

Aluminum is generally considered to be more cost effective than copper and has become the standard of most utilities for overhead transmission lines and substation bus applications. Copper and copper-based materials are still in use but are primarily associated with high-current and grounding applications, short equipment jumpers or spans, and substation expansion projects to match the existing conductor.

The tensile strength and conductivity of aluminum is less than hard-drawn copper. However, if the cross-sectional area of aluminum is increased to match the electrical conductivity of a copper conductor, the resulting breaking strength of equivalent conductors will be about the same, except the aluminum conductor will weigh only about 55% of its copper counterpart. This fact gives aluminum conductors a definite advantage over equivalent copper conductors to reduce loadings on substation structures or to increase span lengths on transmission lines.

Pure aluminum has a conductivity of about 65% of IACS. Alloying the material or adding other elements to the metal typically reduces the conductivity.

Aluminum is available in a wide variety of alloys and tempers. Electrical-grade (Type EC) conductors are defined as aluminum materials that exhibit a minimum conductivity of 61% of IACS. Various tempers of EC conductors are available. EC-H12 and EC-H112 have greater conductivity but lower strength and tend to be applied in low-voltage, high-current applications. Tempers EC-H13 and EC-H17 provide slightly lower conductivity but have greater strength.

In recent years, a second grade of aluminum was developed for the electrical industry and was designated as No. 2 EC. No. 2 EC is an aluminum-magnesium-silicone alloy with minimum conductivity ranging from 55% to 57% of IACS, depending on the applied tempering.

The selection of an outdoor, high-voltage substation tubular bus is typically governed by mechanical strength considerations rather than by electrical characteristics. As a result, structural aluminum alloys have been commonly applied for substation bus applications. Aluminum alloys 6061, 6063, and 6101 are the most common alloys used for tubular bus applications.

Aluminum alloys can also be hardened by tempering the metal, with the most common temper classifications being T6, T61, and T63. The characteristics of various aluminum alloys and tempers is shown in Table 2.

Aluminum alloys 6063-T6 and 6101-T6 have a typical conductivity of 53% to 55% of IACS and provide an excellent blend of mechanical, electrical, and economic properties. If greater strength is required, 6061-T6 is also a common substation bus with a typical conductivity of 40% of IACS, but it is stiffer and more difficult to shape in the field.

6.3 Rigid conductors

Rigid conductors may take several forms but are generally flat rectangular bars, angles, tubes, or another structural shape. Flat bars can be bent easily and joined together but tend to lack the mechanical strength necessary for long spans. Stiffer cross sections such as angles increase the structural strength of the conductor and may be installed in distribution substations, but the application may be limited to lower voltages under certain conditions due to corona and radio noise considerations. A structural shape such as an integral web bus might be used for high-current applications or to gain added mechanical strength for long spans in EHV substations. The load capability of substation equipment may not be adequately addressed by connection with rigid buses, which can transmit loads directly to them; flexible conductors are more appropriate because they generally provide more flexibility and thus diminish the loads transmitted.

Tubular buses have gained wide acceptance in the utility industry because they possess good conductive, mechanical, and corona characteristics. A tubular bus may be either square or round, but a round tubular bus is much more common because cylindrical shapes have the following characteristics:

- a) Maintain equal rigidity in all directions, which is an inherent advantage for withstanding wind, short circuit, and ice loading conditions
- b) Bend easier than other shapes when forming bends or offsets
- c) Minimize corona, audible noise, and radio noise
- d) Avoid large sags to provide a more pleasing appearance

The mechanical strength and stiffness of the rigid bus also allows the conductor spacing and height to be decreased when compared with flexible conductor alternatives. This can be an important factor if there are height restrictions or if a low-profile or very low-profile substation is desired for aesthetic considerations.

An aluminum bus may be purchased as a structural pipe or seamless pipe. A structural pipe is intended only for structural applications and is not suitable for situations where the pipe is repeatedly flexed. The reason is that the structural pipe is manufactured with a continuous die-welded seam located along the length of the pipe that tends to split during vibration. In the case of a substation bus, aeolian vibration is common, which means that structural pipes are not recommended for substation applications. Splitting of a structural pipe can also be a problem during field bending operations.

An aluminum bus installed in substations is normally designated as extruded, seamless round pipes or tubes fabricated from the hollow ingot process in conformance with ASTM B-241 or ASTM B-317. Extruded seamless round tubes are defined as an extruded hollow product having a round cross section and a uniform wall thickness.

Pipes and tubes are similar, but a subtle difference does exist between the two. Pipes are manufactured to nominal diameters with wall thicknesses defined by a schedule. In contrast, tubes are defined or described by a specific outside diameter and by a specific wall thickness.

6.4 Flexible conductors

6.4.1 Stranding

Conductors are generally categorized as being either solid or stranded. A solid conductor is a conductor with a solid, circular, cross section. As the size of the conductor increases, solid conductors become stiff and difficult to handle and can be damaged more easily during installation. As a result, larger conductor sizes tend to be stranded.

ASTM stranding classifications for power cable applications are generally indicated with an AA, A, or B designation. Bare outdoor cables used for overhead transmission line applications are typically Class AA. Class A cables are generally covered with weather-resistant materials and are sometimes specified for bare conductors where greater flexibility is needed. Class B stranded conductors are typically applied in insulated power cables where additional flexibility is required.

6.4.2 Types of flexible conductors

Although copper is a very good conductor material, economics have tended to favor aluminum. As a result, most utilities install aluminum bus in outdoor substation locations.

An all-aluminum conductor (AAC) is manufactured with 1350-H19 grade aluminum. An AAC is a relatively low-cost conductor that has good conductivity and moderate strength characteristics. Substation buses and transmission lines with relatively short spans are ideal applications for an AAC.

Aluminum conductor, steel-reinforced (ACSR) cables consist of a solid or stranded galvanized steel core surrounded by one or more layers of 1350-H19 aluminum wires. The size of an ACSR cable is determined by the cross-sectional area of the aluminum contained in the ACSR cable. Stranding for ACSR cables is indicated by the number of aluminum wires followed by the number of galvanized steel wires. For example, a 795 kcmil 26/7 ACSR cable has 26 aluminum wires totaling 795 kcmil of aluminum cross-sectional area placed over a steel core composed of seven galvanized steel wires. The presence of a steel core in ACSR conductors provides a high mechanical-strength-to-weight ratio that makes it well suited for long-span applications.

An all-aluminum alloy conductor (AAAC) was developed as a replacement for 6/1 and 26/7 ACSR conductors. The AAAC is constructed from 6201-T81 aluminum alloy, giving it characteristics similar to ACSR but with improved corrosion characteristics. As a result, an AAAC can be a good choice for coastal locations or other corrosive environments.

An aluminum conductor, aluminum-alloy reinforced conductor (ACAR) mixes 6201-T81 and 1350-H19 aluminum strands of the same diameter. The strands of the conductor are therefore interchangeable to allow the conductor assembly to be designed to optimize the mechanical and electrical properties of the aluminum and aluminum alloy.

An aluminum conductor, steel-supported conductor (ACSS) is similar to standard ACSR cables except the aluminum is fully annealed. Because the aluminum is already annealed, the conductor can be operated at temperatures in excess of 200 °C. However, care should be taken when applying ACSS inside a substation to be sure the conductor does not exceed the temperature rating of equipment that may be connected to the conductor.

Other types of construction such as trapezoidal-shaped wire (TW), vibration-resistant wire (VR), self-damping conductor (SD), and many more variations are possible but are seldom found in substations.

6.5 Field bending of rigid conductors

Rigid conductors are normally routed in relatively straight lines, but occasional turns and offsets are required. Bus fittings can be used to accomplish the turns or offsets, but rigid conductors can also be bent. The following factors must be considered when bus conductors are bent:

- a) Ductile properties of the metal
- b) Size and shape of the conductor
- c) Bending method
- d) Bending equipment to be used

The metal must be ductile, which means that the metal must be soft enough to allow sufficient stretching or compressing without fracturing as the conductor is bent. Ideally, the conductor should have a high elongation value and a low ratio of yield strength to tensile strength.

The size and shape of the conductor should also be considered. For example, rectangular bars can be bent flatwise to form a 90° elbow without cracking, but the minimum bending radius is dependent on the ductility of the bar and the ratio of bar width to bar thickness. The minimum flatwise bending radius of aluminum rectangular bus bars required to avoid visible cracks or ruptures is indicated in Table 3.

Aluminum bus bars can also be bent edgewise. Typically, the minimum edgewise bending radius of the rectangular bar is equal to the width of the bar. An edgewise bend is considered successful if no cracks or ruptures are visible and the bar at the outer radius is not thinned to less than 90% of bar thickness.

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Table 3—Minimum flatwise bending radius of rectangular aluminum bus

<u>Alloy and temper</u>	<u>Maximum bar width mm (in)</u>	<u>Bar thickness mm (in)</u>	<u>Minimum bending radius</u>
6101-T6	150 (6)	3–9 (0.125–0.375)	2.0 × thickness
		10–13 (0.376–0.500)	2.5 × thickness
6101-T61	150 (6)	3–13 (0.125–0.500)	1.0 × thickness
		14–19 (0.501–0.749)	2.0 × thickness
		20–25 (0.750–1.000)	3.0 × thickness
		26–41 (1.001–1.625)	4.0 × thickness
6101-T63	150 (6)	3–9 (0.125–0.375)	1.0 × thickness
		10–13 (0.376–0.500)	1.5 × thickness
6101-T64	300 (12)	3–19 (0.125–0.750)	1.0 × thickness
		19–25 (0.751–1.000)	2.0 × thickness
6101-T65	150 (6)	3–13 (0.125–0.500)	1.0 × thickness
		13–19 (0.501–0.749)	2.0 × thickness

6.6 Connections

6.6.1 General

An electrical connector is any device that joins two or more conductors for the purpose of providing a continuous electrical path. Connectors may be the bolted, compression, swaged, welded, or brazed type and should conform to NEMA CC 1-2005. Care is required when specifying connectors to be sure the maximum rated operating temperature of the connector is not exceeded, corona and audible noise requirements are within acceptable limits, mechanical strength is sufficient, dissimilar metals are properly interfaced; and so on.

6.6.1.1 Bolted

Bolted connections normally require no special tools and are easier to install with an unskilled workforce than other connectors. The common types of bolting hardware for joining various bus materials are indicated in Table 4.

Table 4—Common bolting hardware

<u>Bus bar materials to be joined</u>	<u>Bolting hardware</u>
Copper to copper	1. Silicon bronze 2. Stainless steel 3. Galvanized steel
Aluminum to copper	Stainless steel or galvanized steel. Usually, either a bimetallic transition plate is inserted between the two flat-to-flat pads of the dissimilar metals or tinned connectors are used for the transition.
Aluminum to aluminum	1. Aluminum 2. Stainless steel
Galvanized steel to copper	1. Silicon bronze 2. Stainless steel or galvanized steel
Galvanized steel to aluminum	1. Aluminum 2. Stainless steel or galvanized steel

A good mechanical connection between two conductors is often assumed to be a good electrical connection. However, this may not be a good assumption because the electrical characteristics of the connection will largely be determined by the condition of the contact surfaces. Metallic surfaces, if exposed to air and not properly cleaned, may contain surface oxides that are semiconductive, resulting in a relatively high contact resistance. In addition, contact surfaces may appear to be smooth, but microscopic hills and valleys are present that will reduce the actual contact area to a small percentage of the total mating surface area. By applying pressure, the initial contact points will be deformed to gain additional contact area, but even under maximum pressure, the actual contact area will be only a fraction of the total mating surface area.

Bolt hole sizes are oversized, and the bearing area of a hex-head bolt or nut is very small. As a result, the bolt head or nut may slowly embed itself into the conductor under normal bolting pressures. This is typically avoided by placing two large flat washers, one on each outer side of the joint, to distribute pressure uniformly as the bolt is tightened. Table 5 provides typical torque values for bolted power connections installed without spring washers.

Table 5—Typical torque values for bolted connectors

<u>Diameter of bolt mm (in)</u>	<u>Silicon bronze N-m (ft-lbs)</u>	<u>Stainless and galvanized steel N-m (ft-lbs)</u>	<u>Aluminum N-m (ft-lbs)</u>
8 (5/16)	20 (15)	20 (15)	—
10 (3/8)	27 (20)	27 (20)	19 (14)
13 (1/2)	54 (40)	54 (40)	34 (25)
16 (5/8)	75 (55)	75 (55)	54 (40)
19 (3/4)	95 (70)	95 (70)	—

It is important for bus bolting hardware to apply a relatively constant pressure as the joint heats and cools. If the bolting hardware and bus bars being connected contain dissimilar metals, then it is important to accommodate the differential expansion and contraction of the dissimilar metals as the connector cycles through cold and hot temperatures. In such applications, a spring washer, such as a Belleville washer, is typically installed to accommodate the expansion and contraction. Belleville washers are a specialized type of spring washer that are round but slightly conical in shape unless flattened under pressure. In practice, the bolt assembly is tightened until the Belleville washer is flattened and then the nut is backed off slightly, not to exceed a quarter turn. This practice ensures the best possible result because the washer is firmly seated on the bus, and the washer exerts a force that is very close to its maximum capacity.

6.6.1.2 Compression

Compression fittings are intended to be installed on stranded conductors. The fitting typically consists of a hollow sleeve into which a bare conductor is inserted. A hand, pneumatic, or hydraulic press will then crimp the sleeve onto the conductor one or more times as recommended by the manufacturer. A properly crimped compression fitting will deform the conductor strands slightly to provide good electrical continuity and mechanical strength. Close attention to coordinating compression dies with compression fittings and conductors is required to assure the crimp is installed properly. In some instances, it may be desirable to perform a sample compression and then to cut through the compression to confirm the compression die is truly coordinated with the compression fitting.

In most cases, compression accessories are filled with a specified amount of compound prior to installing the conductor. The compound is intended to seal the accessory from water that may otherwise corrode or possibly damage the accessory over time. Whenever possible, the compressed area of the accessory should be oriented down to prevent the entrance of moisture into the barrel of the connector. If the compressed area of the accessory is oriented up, then the manufacturer of the accessory should be contacted to determine whether a special fitting is recommended to allow periodic filling of the connector barrel.

Compression joints require special tools to crimp or indent the connector. However, the material cost of the connector is lower than bolted connectors so that a properly equipped and skilled workforce can make the selection of compression joints economical.

6.6.1.3 Swage

Swage fittings are similar to traditional compression fittings but can be applied to tubular bus or stranded conductors. The compression technique produces a 360° radial swage on the connector with dies that are slotted to collapse on each other to maintain equal pressure on all sides. Swage fittings approach the characteristics of welded fittings but do not require the degree of skill required for welded fittings. As a result, swage fittings can be an economical alternative to welded fittings.

6.6.1.4 Welded

Welded joints melt the conductors to form a solid, homogeneous union. Welded joints that are properly installed are generally considered to be the most reliable type of connector from an electrical viewpoint because there is no contact resistance to generate heat when high currents are present.

Workmanship is a key element to attain a properly installed welded connection. Welders should be qualified in accordance with AWS D1.2-2003. To ensure good weld penetration, all welds on the aluminum bus should be made with the gas metal-arc (MIG) welding process. The shielding gas should be welding grade argon, helium, or a mixture of the two. Filler alloy 4043 should be used for 6061-T6 base metal.

The heat applied during welding will anneal the base metal and weaken the conductor. The Aluminum Electrical Conductor Handbook [B1] recommends an allowable yield stress of 50% of the yield stress for welded conductors. This accounts for not only the annealing but also for possible weld defects. Couplers typically use internal sleeves to overcome the annealing problem.

Welded joints may be relatively expensive in situations where there are few joints to be installed, and access to equipment and qualified welders is limited. However, welded joints can be economical if there are a large number of joints to be installed, and a qualified workforce is available.

6.6.1.5 Brazed

Brazed joints are similar to welded joints except the brazing does not require melting of the metals being joined. Brazing does require a uniform heating of the joint to the temperature that will allow all of the brazing filler material to flow into the joint. Although brazing can be successfully applied to smaller tubes and shapes, it is generally not applied in outdoor substations.

6.6.2 Aluminum-to-copper connections

Aluminum-to-copper connections require care because of the corrosion that can occur between dissimilar metals. Over time, corrosion will cause increased joint resistance, which will result in heating during periods of high current and will ultimately lead to failure of the joint. In certain clean applications, it is possible to connect copper to aluminum directly with a suitable joint compound, but this practice is generally not recommended. Typically, one of the following methods is recommended for connecting aluminum to copper:

- a) Tin-plate or copper-line the aluminum contact surface
- b) Tin-plate the copper contact surface
- c) Install a bimetallic transition plate between the contact surfaces
- d) Silver-plate the copper contact surface

Whenever possible, copper should not be placed above aluminum. Rain will wash copper salts down onto the aluminum metal and cause discoloration.

6.6.3 Joint compounds

Joint compound or sealants are generally not applied to bolted copper connections unless the connector is placed in a highly corrosive environment. However, it is prudent to install a sealant inside the barrel of a copper or bronze compression connector to seal out moisture that may otherwise infiltrate the connection.

Aluminum-to-aluminum and aluminum-to-copper joints should be coated with a suitable joint compound. In fact, the primary cause of aluminum conductor accessory failures in high-voltage transmission line applications involves inadequate or improper application of joint compounds.

Joint compounds are installed to do the following:

- a) Protect the compressed steel barrels or sleeves of conductor accessories from corrosion. During compression, galvanizing is removed from the accessory and the filler compound acts as a barrier to corrosion.
- b) Clean conductor strands during compression. Filler compounds applied to aluminum conductors often contain aluminum particles that abrade the conductors during the compression.
- c) Fill the conductor strands to block moisture infiltration into the conductor.
- d) Enhance the ultimate holding strength of the conductor accessory.

Particular care is required with aluminum because nonconducting surface oxides develop very quickly when the metal is exposed to air. In most instances, the manufacturer of the joint compound will recommend that the metal be cleaned, coated with a joint compound, and wire brushed through the compound, with the compound remaining in place while the connector is installed. The wire brushing abrades the oxide layers, and the compound forms a barrier to minimize the creation of new surface oxides that can lead to a high resistive joint.

If solid-dielectric cable insulation such as PVC, polyethylene, or rubber is present, the joint compound should be a nonpetroleum base to avoid adverse chemical reactions.

Joint compounds used to connect flat surfaces do not require grit in the compound. Gritted joint compounds should be applied only in compressive joints that will be placed under tension. Grit normally refers to hard metallic particles mixed into the compound that are intended to increase the holding strength of the joint when tension is applied.

6.6.4 Maintenance

Periodic inspection of substation conductors is generally recommended to assess the condition of the conductors and the associated electrical connections. Normally, maintenance activities will consist of an infrared scan of the substation to identify locations where the operating temperature is higher than adjacent areas. Areas of high temperature should be investigated to verify that the conductors are properly sized and that the electrical connectors are properly installed.

7. Design procedure

The recommended design procedure in this guide is summarized in Figure 7, and its main steps are described in 7.1 through 7.7.

7.1 Design specification

The specification for a station required to design bus includes a one-line diagram as well as station capacity (MVA), fault level (kA), and continuous and emergency bus ratings (A). The one-line diagram should indicate the required station equipment and connections for both the initial and the future stages of development.

7.2 Select bus arrangement

Clause 4 covers various bus arrangements that may be considered. Bus layouts should be prepared for the various stages of the station development. This is to ensure that there is minimal disruption to the station operation when going from one stage to another.

7.3 Design considerations

Additional considerations must be made to finalize the design. These include the following items:

- a) Clearances (12.8).
- b) Transitions between different bus type and/or heights.
- c) Bus to equipment connections.
- d) Grade changes. A large station may have a grade change. To minimize bus bends, the footing height may be varied to maintain a constant bus elevation. Footing elevation changes can compensate for a certain amount of elevation change, and beyond this, bus transitions will be required.
- e) Access to the equipment and bus during construction and maintenance.

7.4 Select conductor type

There are many types of conductors that may be used, and they are detailed in Clause 6. Factors considered include the following:

- a) Ampacity (Clause 8)
- b) Corona (Clause 9)
- c) Mechanical strength and deflection (Clause 12)
- d) Seismic withstand
- e) Cost

Multiple conductor types may be required to accommodate the design. For example, rigid and flexible conductors may both be used in a design.

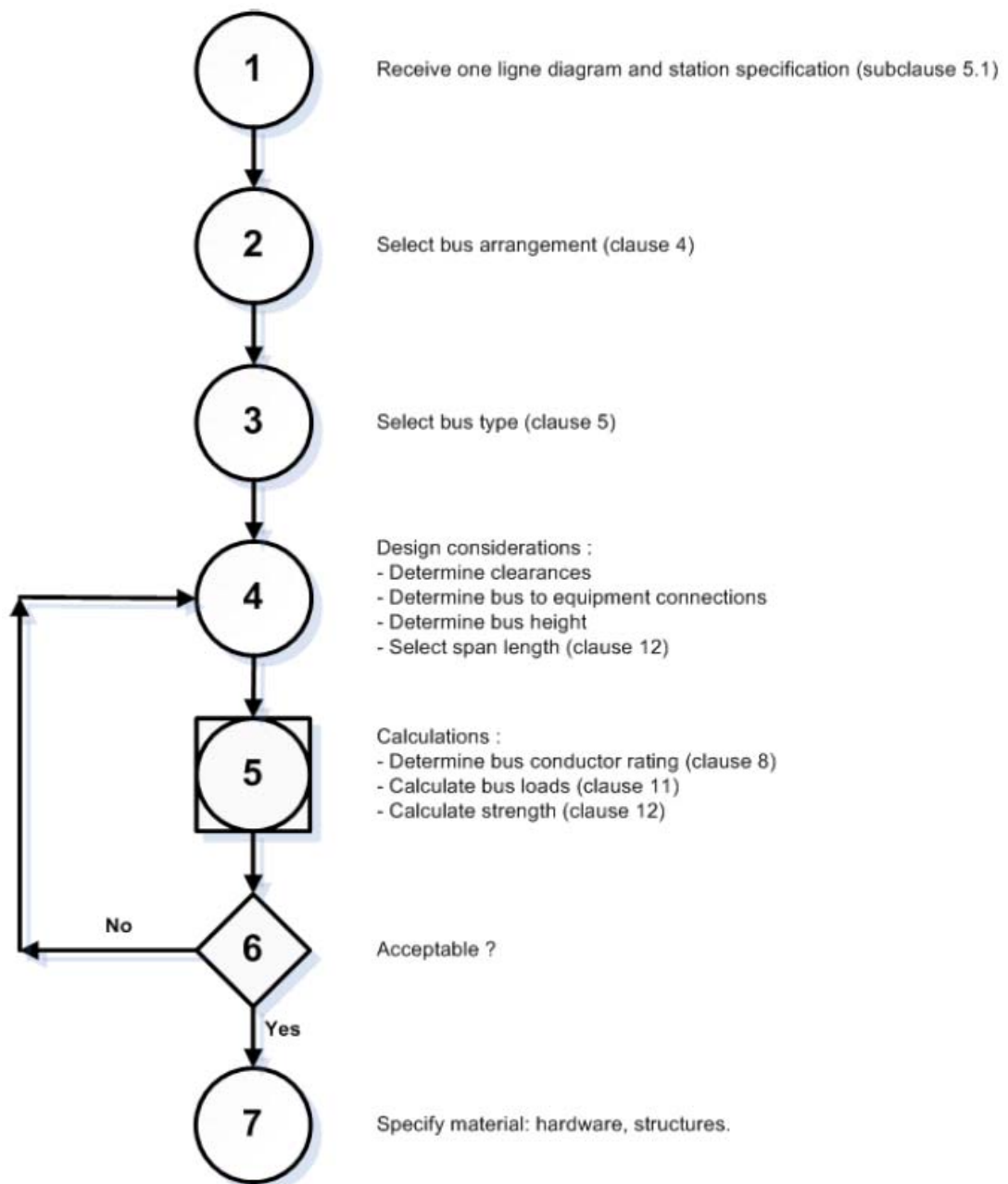


Figure 7—Bus design procedure flow chart

7.5 Structure design

Design the support structures to withstand permanent and exceptional loads on them. The calculation methods are presented in Clause 10, the loads to consider in Clause 11, and the strength and other considerations in Clause 12.

7.6 Review calculations

Verify that the structures are able to withstand the design loads in an acceptable manner. If the structures are found to be unacceptable, then they must be redesigned.

7.7 Select materials

Based on the calculations performed, materials such as insulators, bus conductors, fittings and other components will be selected. The information from the design would then be provided to the civil engineer to design support structures and foundations for the bus design.

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8. Ampacity

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

8.1 Heat balance

The temperature of a conductor depends on the balance of heat input and output. For balance, the heat input due to [ohmic losses](#) (I^2R) and solar radiation equals the heat output due to convection, radiation, and conduction. The heat balance may be expressed as follows:

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

where

I	is the current through the bus conductor, A
R	is the direct-current resistance at the operating temperature, Ω/m [Ω/ft]
F	is the skin-effect coefficient
q_s	is the solar heat gain, W/m [W/ft^2]
q_c	is the convective heat loss, W/m [W/ft^2]
q_r	is the radiation heat loss, W/m [W/ft^2]
q_{cond}	is the conductive heat loss, W/m [W/ft^2]

Solving the current for a given conductor temperature rise is as follows:

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

where

I	= current for the allowable temperature rise, A
R	= direct-current resistance at the operating temperature, Ω/m [Ω/ft]
F	= skin-effect coefficient
q_s	= solar heat gain, W/m [W/ft^2]
q_c	= convective heat loss, W/m [W/ft^2]
q_r	= radiation heat loss, W/m [W/ft^2]
q_{cond}	= conductive heat loss, W/m [W/ft^2]

NOTE—Values for convective or conductive heat [gains transfer into the conductor element](#) on the right side of Equation (2) are entered as negative numbers. [Heat transfer out of the conductor element are entered as positive numbers.](#)

8.1.1.1 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.

8.1.2 Solar heat gain, q_s

The amount of solar heat gained is a function of the following:

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

8.1.3 Convective heat loss, q_c

A bus conductor loses heat through natural or forced convection.

8.1.3.1 Natural convective heat loss

Natural convective heat loss is a function of the following:

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

8.1.3.2 Forced convective heat loss

Forced convective heat loss is a function of the following:

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

8.1.4 Radiation heat loss, q_r

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

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

8.1.5 Conductive heat loss, q_{cond}

Conduction is a minor method of heat transfer because 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.

8.2 Conductor temperature limits

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

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

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

A conductor's temperature will rise rapidly under fault conditions. This is due to the inability of the conductor to dissipate the heat as rapidly as it is generated. Annealing of conductor alloys may occur rapidly at these elevated temperatures. The maximum fault current that can be allowed for copper and aluminum alloy conductors may be calculated using Equation (3) and Equation (4). [Refer to 11.3.1 of IEEE Std 80™-2000 \[B19\] for other materials.](#) In general, the final temperature of the conductor is limited to the maximum temperature considered for thermal expansion ~~(see Clause 13).~~

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

$$I = C \times 10^6 A_c \sqrt{\frac{1}{t} \log_{10} \left(\frac{T_f - 20^\circ\text{C} + (15\,150/G)}{T_i - 20^\circ\text{C} + (15\,150/G)} \right)} \quad (3)$$

where

C is $2.232 \times 10^{-4} \text{ A s}^{0.5}/\text{mm}^2$ for A_c in mm^2 ($0.144 \text{ A s}^{0.5}/\text{in}^2$ for A_c in in^2)
 I is the maximum allowable root-mean-square (RMS) value of fault current, A
 A_c is the conductor cross-sectional area, mm^2 (in^2)
 G is the conductivity in percent International Annealed Copper Standard (IACS)
 t is the duration of fault, s
 T_f is the allowable final conductor temperature, $^\circ\text{C}$
 T_i is the conductor temperature at fault initiation, $^\circ\text{C}$

[And for copper conductors \(95% to 100% IACS conductivity\):](#)

$$I = C \times 10^6 A_c \sqrt{\frac{1}{t} \log_{10} \left(\frac{T_f - 20^\circ\text{C} + (25\,400/G)}{T_i - 20^\circ\text{C} + (25\,400/G)} \right)} \quad (4)$$

where

C is $3.410 \times 10^{-4} \text{ A s}^{0.5}/\text{mm}^2$ for A_c in mm^2 ($0.220 \text{ A s}^{0.5}/\text{in}^2$ for A_c in in^2)

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

I = maximum allowable root-mean-square (rms) value of fault current, A
 A_c = conductor cross-sectional area, mm^2 [in^2]

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

t = duration of fault, s

T_f = allowable final conductor temperature, $^\circ\text{C}$

T_i = conductor temperature at fault initiation, $^\circ\text{C}$

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

~~$C = 142$ for Metric units [0.22 for English units] All other variables have been defined previously.~~

8.2.3 Attached equipment

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

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8.3 Ampacity tables

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

9. Corona and radio interference

~~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. Corona discharges occur on air insulated conductors when the electric field intensity at the conductor surface causes ionization in air. The field intensity at the initiation of the discharges is known as “corona onset gradient.” Electromagnetic interference (EMI) is caused by the corona.~~

However, the rigid-bus designer should be aware that ~~radio influence~~ EMI can be produced at any voltage by arcing due to poor bonding between bus conductors and associated hardware.

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

Substation bus corona will probably occur. There is no physical law that supports any specific onset voltage. The probability that corona will occur depends on many factors (e.g., bus contamination, weather, surface nicks, and field voltage gradient).

The designer's problem is to select a bus conductor and to specify bus hardware that will have acceptable corona performance ~~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~~The numbers in brackets preceded by the letter B correspond to those of the bibliography in Clause 14.~~

9.1 Determination of corona performance ~~-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 .~~

The onset of corona can only be treated statistically. The corona and EMI performance of a substation bus design could be evaluated to determine the “excedence level” (the probability that EMI will exceed a reference level) and the EMI magnitude and frequency spectrum.

There is a tradition of treating the corona as a deterministic value. Peek's equation, published in 1929, has been used in corona onset voltage, and more information about Peek's equation is given in Annex D.

However, Peek's equation has no mechanism to calculate the probability of corona below the calculated voltage. Also, Peek's equation has no mechanism to calculate the magnitude and frequency spectrum of radiated EMI due to the design of the substation bus.

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

- Conductor diameter or shape
- Distance from ground
- Phase spacing
- Applied voltage

Although electric field intensity is an important variable, the corona onset gradient is affected by many other variables. The relationship between the onset of corona and these other variables is difficult to determine, and the occurrence of these variables is difficult to predict. In Juette [B27], test data show a 16-to-1 variation in EMI from “very clean conductors” to “very polluted conductors,” as well as a 16-to-1 variation from dry weather to heavy rain EMI. Research has shown that corona and EMI will occur at voltage gradients from 10 kV/cm to more than 30 kV/cm.

9.2 EMI tolerance of substation equipment

The principal concern for EMI in substations is interference with station relaying, control, and communications equipment. Protection equipment is a particular concern. Five IEEE standards do include some treatment of radiated EMI and conducted signal interference. However, CISPR 24 [B12] is the only standard that provides broadband radiated and conductor EMI tolerance limits for equipment that bears some resemblance to the type of equipment that is used in substations.

9.3 Reducing EMI

There is some probability that corona generated interference will occur. Following good practices in design and specification of substation bus hardware assemblies, and proper installation of the hardware, will reduce the probability.

9.3.1 Conductor selection

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

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

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

9.3.2 Hardware specification

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

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

9.3.2.1 Hardware testing methods

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

6.2.1.1 Visual corona

The visual corona extinction voltage should be tested according to NEMA CC 1-2005.

6.2.1.2 Radio-influence voltage (RIV) level

[IEC 61284 \[B17\]](#) provides guidance for testing of some fittings that may be used in substation bus design.

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

9.3.2.2 Hardware test acceptance criteria

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

6.2.2.1 Visual corona

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

6.2.2.2 Radio-influence voltage (RIV)

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

- a) For fittings and connectors, see NEMA CC 1-2005.
- b) For insulators and hardware assemblies, see ANSI C29.9-1983.

9.4 Reducing corona generated radiated and conductor signal interference

[Enclose switchyard and control house protection control and communications equipment in grounded metal enclosures to reduce the corona radiated EMI exposure of the equipment.](#)

[Proven methods to reduce conducted corona generated signal interference are given in the recommendations given in IEEE Std 525™-2007 \[B20\].](#)

10. Overview of mechanical design of bus structures

10.1 Introduction

[Bus structures should be designed to withstand the permanent and exceptional loads that act on them during their operational lives. They should also be designed so that their operational behavior is acceptable and in accordance with expectations, such as to have deflections and sags within a permissible range, to have an acceptable strength and level of vibrations, and so on.](#)

[The purpose of this clause is to introduce the loads applied to bus structures to consider in design, as well as the available calculation methods to evaluate their effects on structure. Clause 11 describes the loads in detail, and Clause 12 describes the required design considerations such as insulator strength, deflection criteria, induced vibrations, and clearances.](#)

10.2 General mechanical design procedure

[To design a bus structure:](#)

- a) Assume preliminary design data: choice of dimensions (span lengths), material, and section properties.
- b) Evaluate the loads applied on the bus structure.
- c) Combine these loads in a statistically coherent manner since they cannot generally all happen at the same time. The load combination may be determined by utility design standards or published guidelines applicable to substation bus structures
- d) Calculate the structure's response to the load combination established in item c).
- e) Verify that the structure can withstand the load combination and has an acceptable operational behavior.

Note that at item e), one can also decide to redesign the structure (or parts of it) in order to optimize it and save on construction costs.

Both the load-resistant factor design (LRFD) methodology (also called the ultimate strength design (USD) methodology) and the allowable stress design (ASD) methodology are design approaches acceptable as per this guide. The LRFD methodology is the current predominate method used in the design of steel structures in the United States and Canada.

10.2.1 Loads to consider in design

The loads to consider are the permanent loads and the exceptional loads. Note that the loads as well as their intensity vary generally according to substation location and according to design and application requirements. The loads described herein are preceded by the abbreviation under which they will be referred to in the next subclauses.

The permanent loads are as follows:

- a) D : dead load: weight of the structure, of components and of rigid/strain buses
- b) T_c : tension loads from strained conductors
- c) T : thermal loads from thermal expansion of the material

The exceptional loads are as follows:

- a) W : wind loads
- b) W_i : wind load including effects of augmented section by ice (wind-on-ice)
- c) I_w : ice weight load
- d) SC : electromagnetic loads (short circuits)
- e) E : earthquakes
- f) WS : wet snow loads

NOTE 1—Earthquake loads are not defined in this guide. See IEEE Std 693-2005 and IEEE Std 1527-2006 for the evaluation of seismic loads acting on rigid and flexible bus, as well as their seismic design requirements.

NOTE 2—The wind speed for load W_i is not the same as for W . W_i acts on an augmented section due to the ice thickness. For the United States, W_i can be obtained from Figure 8 to Figure 13, whereas W is obtained from Figure 14 to Figure 18.

NOTE 3—The tension load from strain conductors T_c will be increased under low-temperature and/or transverse wind.

NOTE 4—Wet snow or rain-on-snow loads may be significant in regions such as Colorado, Northern California, and some areas in Canada (and possibly elsewhere). This load is not described in this guide but will be considered in the next revision. See ASCE 7-05 for details.

10.2.2 Nominal strength

The nominal strength for the conductors and structural members should be defined according to the design methodology retained (LRFD or ASD) based on the yield and ultimate strength of the material used.

Typical values of strengths used in bus design are presented in Table 6 for informative purposes, in addition to the values for aluminum and copper already presented in Table 2. Precise values based on the alloy use or rated strength of porcelain shall be used in design.

Table 6—Typical material properties for support and insulators

Material	Young's modulus E	Yield strength (F_y)	Ultimate tensile strength (F_u)
Steel (note that there are large variations according to alloy type—values here are for structural steel)	200 GPa (2.9×10^4 ksi)	250 MPa (36 ksi)	395 MPa (58 ksi)
Porcelain	70–100 GPa (10×10^6 psi to 15×10^6 psi)	30–100 MPa (4 ksi to 15 ksi) or per manufacturer's recommendation.	Porcelain is brittle: Ultimate strength is the same as yield strength.

NOTE 1—Usually, porcelain strength is defined not as stress but as cantilever rating, which is defined as the maximum horizontal load that can be applied at the top of insulator with its base fixed.

NOTE 2—Porcelain strength may vary greatly depending on the composition and manufacturing. The exact properties from the supplier shall be used in the design.

10.3 Calculation methods

10.3.1 Introduction

Today, different calculation methods are available to calculate both the loads and the corresponding response of the structure. These range from simplified calculations to the use of finite-element software. This guide will describe both the use of simplified calculations and finite-element calculations, whenever they apply.

In general, simplified calculations are conservative and are limited to specific design cases such as simple beam assemblage with given boundary conditions. Finite-element calculations permit generally a more detailed and precise analysis of a structure, especially under three-dimensional (3D) dynamic loading such as short circuits, and are more suitable to design optimization. However, either methods (or a combination of them) should lead to a proper design if used in accordance with the recommendation of this guide.

10.3.2 Calculation steps

To evaluate a structure's response to the applied loads (and/or different combinations of them), the following calculation steps are necessary, either by hand and/or numerically:

- Evaluate the loads and their combinations
- Calculate the resulting internal forces and displacements in the members to the external applied loads
- Analyze the members' strength from the results of item b) and compare with corresponding nominal strength according to the design methodology used (LRFD or ASD)

10.3.3 Simplified calculations

Simplified calculations consist of calculating manually the response of a structure to the applied loads. For an isostatic structure, this requires the use of static analysis principles and basic notions of strength of material as described in many textbooks on the subject. A civil, structural, or mechanical engineer is required for such calculations for rigid and strain bus structures.

10.3.4 Finite-element calculations

Finite-element calculations require describing the geometry in the program by specifying end points for each structural member such as supports, conductors, and insulators. Then, one creates lines between these points and assigns to them the corresponding structural and material properties of the existing members. One divides such lines into a finite number of elements as to discretize the structure; this step is called meshing, and the mesh should be reasonably fine so as to represent correctly the structural behavior.

Different types of elements are generally available in a program such as beams, plates, solids, and so on. In the case of rigid and strain bus structures, the use of beam elements was found to be representative and of sufficient precision. One may use more refined elements such as plates and solids in order to refine the stress analysis in a specific area.

Once the structure has been described in the program, that is, in technical terms, the structure has been “meshed,” and it is ready for analysis. One then specifies the loads acting on the structure in the program, either implicitly for the dead weight using the density specified in the description of the material properties of a given member plus the specification of gravitational acceleration in the vertical direction or manually, to specify for example the pressure on a given section and direction corresponding to the wind speed considered.

The calculation of the structural response to the loads is the final step in the program. Depending on the type of loads as well as on the structure flexibility, static or dynamic analysis is required, either through linear or nonlinear analysis as described in the following clauses. It is recommended that a structural, mechanical or substation engineer who understands the principle of finite-element methodology shall be the key user to run the program for such analysis.

Usually, linear static analysis is adequate to calculate the response to dead (weight and tension loads), climatic loading (wind and ice), and thermal loads. Linear dynamic analysis is adequate to calculate the dynamic response to short circuit and earthquakes for rigid buses. Nonlinear dynamic analysis is mandatory to calculate the response to short circuit for strain buses.

11. Loads on bus structure

Unless otherwise noted, the loads defined in this clause apply to both rigid and strain buses. Also note that gravitational loads, which include ice and wind loads, apply to the insulators and bus supporting structure.

11.1 Gravitational loads

Gravitational loads consist of the weight of the conductor, insulators, supporting structure, ice, damping material, and concentrated loads (equipment attachments, tap conductors, etc.).

11.1.1 Weight of the conductor

The unit weight of circular rigid bus conductors, which includes pipes and tubes, is given as follows:

$$F_c = \frac{\pi w_c}{4} (D_o^2 - D_i^2) = \pi w_c t_c (D_o - t_c)$$

where

E_c is the conductor unit weight (N/m) [lbf/in]
 w_c is the specific conductor weight (N/m³) [lbf/in³], (for aluminum $w_c = 26\,500$ N/m³ [0.0977 lbf/in³])
 D_o is the conductor outside diameter (m) [in]
 D_i is the conductor inside diameter (m) [in]
 t_c is the conductor wall thickness (m) [in]

The weight of other conductor types should be obtained from manufacturer's specifications.

NOTE—Multiply the result in lbf/in by 12 to get results in lbf/ft.

11.1.2 Weight of the damping material, concentrated masses, and mounting structure

The weight of the material used to damp vibration of the conductor should be included in the computation of the gravitational forces. If a cable or chain is used inside the bus conductor, then the weight of the vibration damping material should be given as a continuous unit weight.

The gravitational forces due to concentrated masses (commercial vibration dampers, equipment attachments, and tap conductors) should be included in the summation of gravitational forces.

The weight of supporting structure should be evaluated using the section properties of the structure.

11.1.3 Ice load

For engineering design purposes, it is assumed that the conductors, insulators, and supporting structure are covered with a uniform ice thickness. The ice weight on a circular conductor is given as follows:

$$E_I = \pi w_I r_I (D_o + r_I) \quad (6)$$

where

E_I is the ice unit weight (N/m) [lbf/in]
 w_I is the ice weight (8820 N/m³) [0.0330 lbf/in³]
 r_I is the equivalent uniform radial thicknesses of ice due to freezing rain (m) [in]
 D_o is the conductor outside diameter (m) [in]

NOTE—Multiply the result in lbf/in by 12 to get results in lbf/ft.

For sections other than circular, the ice weight is given as follows:

$$E_I = w_I A_I \quad (7)$$

where

A_I is the area covered by ice on the section considered (m²) [in²]

The ice thickness used by the utility for transmission line design should be considered as the criteria for the loading on rigid or strain bus conductors. The thickness of ice will depend on the user's standard; it could be 6.4 mm (1/4 in) to 12.7 mm (1/2 in) or higher depending on the winter conditions or the location of the installation, for it cannot always be assumed that ice will not accumulate even with a conductor temperature above 0 °C. The only exceptions to this general rule of thumb are regions where the ambient temperature does not fall below 0 °C and regions that are too dry to prevent ice from forming.

Alternatively, the minimum ice thickness for the United States can be determined according to the 50 YR mean recurrence interval uniform ice thickness due to freezing rain with concurrent 3 s gust wind speeds used in ASCE 7-05. These are shown in Figure 8 through Figure 13 for the contiguous United States. Thicknesses for Hawaii, and for ice accretions due to other sources in all regions, shall be obtained from local meteorological studies. Note that in those figures, the ice thickness is given in inches and must be converted to the proper units used in calculations. For other countries, refer to national codes and related maps.

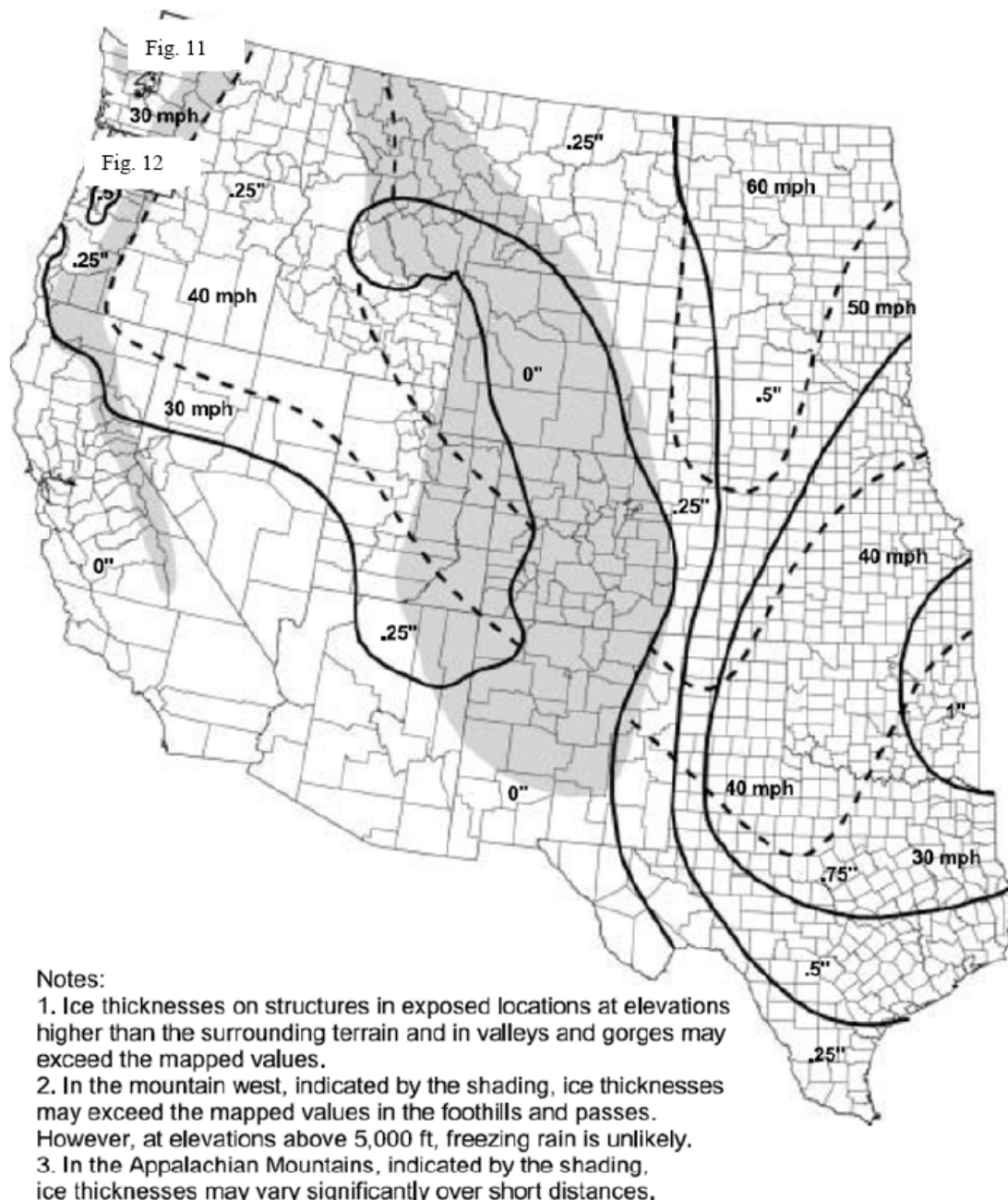


Figure 8—Extreme radial glaze ice thickness (in) Western United States (except the Pacific Northwest), 50-year return period with concurrent 3 s wind speeds¹⁴

¹⁴This figure is reproduced from ASCE 7-05 Figure 10.2a with permission.