

IEEE Guide for Bus Design in Air Insulated Substations

IEEE Power and Energy Society

Developed by the
Substations Committee

IEEE Std 605™-2023
(Revision of IEEE Std 605-2008)



STANDARDS

IEEE Guide for Bus Design in Air Insulated Substations

Developed by the

Substations Committee
of the
IEEE Power and Energy Society

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IEEE SA Standards Board

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Abstract: A proper design of the substation bus is aimed towards 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). Information is provided by this guide on the different bus arrangements used in substations stating the advantages and disadvantages of each. Information as related to each bus type and construction is also provided. Once the bus type is selected, the calculation tools for each bus type are provided by this guide. Based on these calculations, the bus size, forces acting on the bus structure, the number of mounting structures required, and hardware requirements can be specified by the engineer.

Keywords: ampacity, bus support, corona, electromagnetic, finite-element, forces, ice, IEEE 605™, 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 605-2023, 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 693™ and IEEE Std 1527™.

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1. Overview

1.1 Scope

~~The information in~~ This design guide provides direction for the substation engineer in the design of air insulated substations. This guide provides users with information on typical bus arrangements, including various criteria necessary to develop bus arrangement decisions. The guide is applicable to both rigid bus and strain bus designs for outdoor and indoor, air insulated, ac alternating current substations. This guide includes a method to calculate ampacity for electrical bus ~~, radio influence, vibration,~~ and ampacity tables for typical bus types and sizes. This guide also provides design criteria and a method to calculate electromechanical forces on insulators and bus resulting from gravity, wind, ice, short-circuit forces ~~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. 2TM [B41]⁶ ~~-1999 [B22]~~)
- b) The seismic forces to which the substation may be subjected (see IEEE Std 693TM ~~-2005~~ and IEEE Std 1527TM [7] ~~-2006~~)

⁶ The numbers in brackets correspond to those of the bibliography in Annex A.

⁷ Information on references can be found in Clause 2.

- c) The design of mounting structures [\(see ASCE 113 \[B8\]\)](#)
- d) Design considerations for contaminated environments (see IEEE Std 1313.2 [\[B41\]](#) ~~-1999 [B22]~~)
- e) Installation methods
- f) Design of direct current [bus](#) ~~buses~~
- g) [Fault loads other than between conductors such as in the presence of other magnetic fields \(e.g., air core reactors\)](#)

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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⁸ [The use of the word *must* is deprecated and cannot be used when stating mandatory requirements; *must* is used only to describe unavoidable situations.](#)

⁹ [The use of *will* is deprecated and cannot be used when stating mandatory requirements; *will* is only used in statements of fact.](#)

2. Normative references

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AA-~~ADM-1~~, Aluminum Design Manual, ~~2005~~. ¹⁰ ⁺

Accredited Standards Committee C2, National Electrical Safety Code[®] (NESC[®]).¹¹ ²

ANSI/~~NEMA~~ C29.9-~~1983 (Reaff 2002)~~, American National Standard for Wet-Process Porcelain Insulators ~~— (Apparatus, Post Type)~~.¹² ³

[ANSI/NEMA CC 1, Electric Power Connection for Substations.](#)¹³

~~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-~~05~~, Minimum Design Loads for Buildings and Other Structures. ¹⁴ ⁴

ASTM B188-~~02~~, Standard Specification for Seamless Copper Bus Pipe and Tube. ¹⁵ ⁵

¹⁰ ⁺Aluminum Association publications are available from The Aluminum Association, 1525 Wilson Boulevard, Suite 600, Arlington, VA 22209 (www.aluminum.org).

¹¹ ²The NESC is available from the Institute of Electrical and Electronics Engineers (<https://standards.ieee.org/>). ~~445 Hoes Lane, Piscataway, NJ 08854, USA (<http://standards.ieee.org>).~~

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¹⁴ ⁴ASCE publications are available from the American Society of Civil Engineers, 1801 Alexander Bell Drive, Reston, VA 20191-4400, USA (www.asce.org).

¹⁵ ⁵ASTM publications are available from the American Society for Testing and Materials (<https://www.astm.org/>). ~~100 Barr Harbor Drive, West Conshohocken, PA 19428-2959, USA (<http://www.astm.org/>).~~

ASTM B241/B241M-02, Standard Specification for Aluminum and Aluminum-Alloy Seamless Pipe and Seamless Extruded Tube.

AWS D1.2/D1.2M -2003, Structural Welding Code–Aluminum. ^{16 6}

[IEEE Std 693TM, IEEE Recommended Practice for Seismic Design of Substations.](#)^{17,18}

[IEEE Std 1527TM, IEEE Recommended Practice for the Design of Buswork Located in Seismically Active Areas.](#) IEEE Std C37. [30.1TM](#), ~~30TM-1997~~, IEEE Standard Requirements for [AC](#) High-Voltage [Air Switches Rated Above 1000 V](#). ^{7,8}

~~IEEE Std 693TM-2005, IEEE Recommended Practice for Seismic Design of Substations.~~

~~IEEE Std 1527TM-2006, IEEE Recommended Practice for the Design of Flexible Buswork Located in Seismically Active Areas.~~

~~NEMA CC 1-2005, Electric Power Connectors for Substations.~~⁹

~~NFPA 70, 2007 Edition, National Electrical Code® (NEC®).~~¹⁰

3. Definitions

For the purposes of this document, the following terms and definitions apply. The *IEEE Standards Dictionary Online* ~~:Glossary of Terms & Definitions~~ should be [consulted](#) ~~referenced~~ for terms not defined in this clause. ^{19 11}

^{16 6}AWS publications are available from the American Welding Society, 2671 W. 81st Street, Hialeah, FL 33016 (www.awspubs.com).

¹⁷ IEEE publications are available from The Institute of Electrical and Electronics Engineers, Inc. (<https://standards.ieee.org/>).

^{18 7} The IEEE standards or products referred to in this clause are trademarks of The Institute of Electrical and Electronics Engineers, Inc.

¹⁹IEEE Standards Dictionary Online is available at: <http://dictionary.ieee.org>. An IEEE account is required for access to the dictionary, and one can be created at no charge on the dictionary sign-in page.

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

~~⁹NEMA 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>).~~

~~¹¹The IEEE Standards Dictionary: Glossary of Terms & Definitions is available at <http://shop.ieee.org/>.~~

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 [conductors](#) ~~cables~~ held under tension.

bus structure: An assembly of bus conductors, with associated connection joints, ~~and~~ insulating supports, [and mounting structure](#).

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. [20](#) ~~42~~

[characteristic length:](#) [a specified conductor dimension that scales with size, depends on conductor shape, and that is used to calculate the convective heat transfer coefficient.](#)

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 ([such as](#) ~~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.

[20](#) ~~42~~ Notes in text, tables, and figures are given for information only and do not contain requirements needed to implement the standard.

damping: (A 1) The temporal decay of the amplitude of a free oscillation of a system, associated with energy loss from the system. (B 2) A dynamic property of a vibrating structure that indicates its ability to dissipate mechanical energy. (C 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 (such as ~~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: (A 1) The action of emitting radiant energy in the form of waves or particles. (B 2) The transfer of heat by radiation. *Contrast:* **conduction; convection.**

rigid-bus structure: A bus structure composed of rigid conductors, ~~supported by~~ rigid insulators, and a mounting structure.

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, and a mounting structure.

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

4.1 General

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.

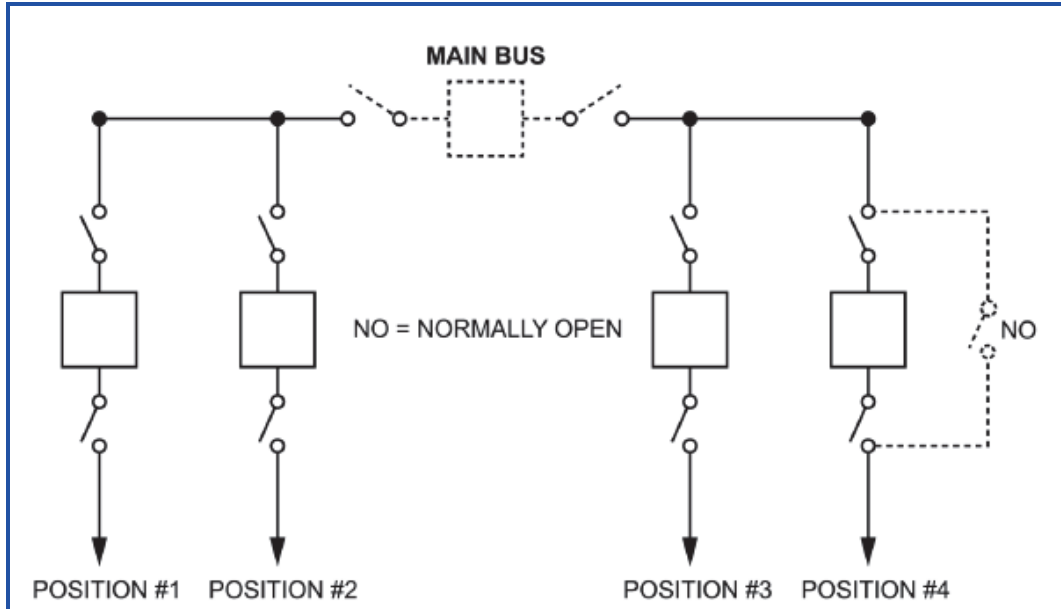
In general, bus arrangements require disconnect switches to be installed on each side of the breaker to provide a visual opening when a breaker is taken out of service during maintenance or repair. For safety and reliability, the electric clearances must meet appropriate codes and recommendations. Insulation 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.

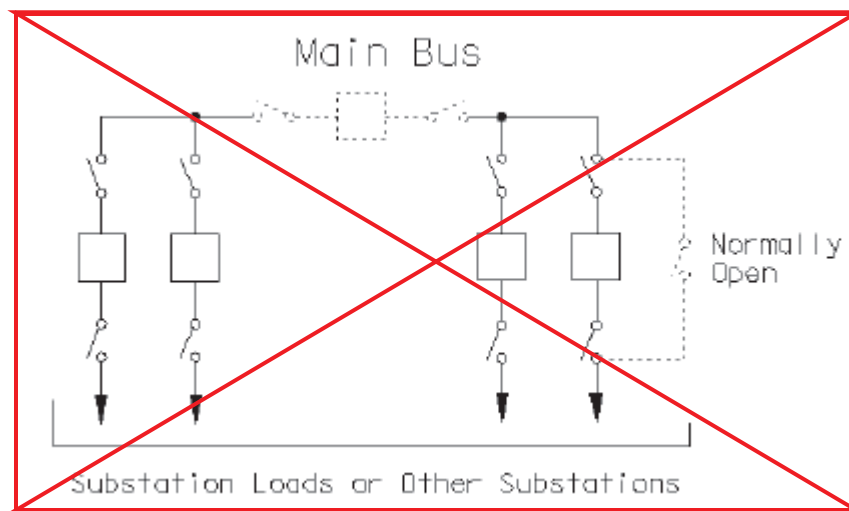
Clause 4 ~~This subclause~~ consists of descriptions of substation bus arrangements that are used today.

4.2 Single bus single breaker (SBSB) arrangement ~~(SBSB)~~

The single bus single breaker (SBSB) arrangement shown in Figure 1 consists of one main bus that contains positions for several circuits. The SBSB ~~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.



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Figure 1—Single bus breaker

The ~~SBSB 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 [SBSB](#) ~~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 [SBSB](#) ~~single bus single breaker~~ arrangement.

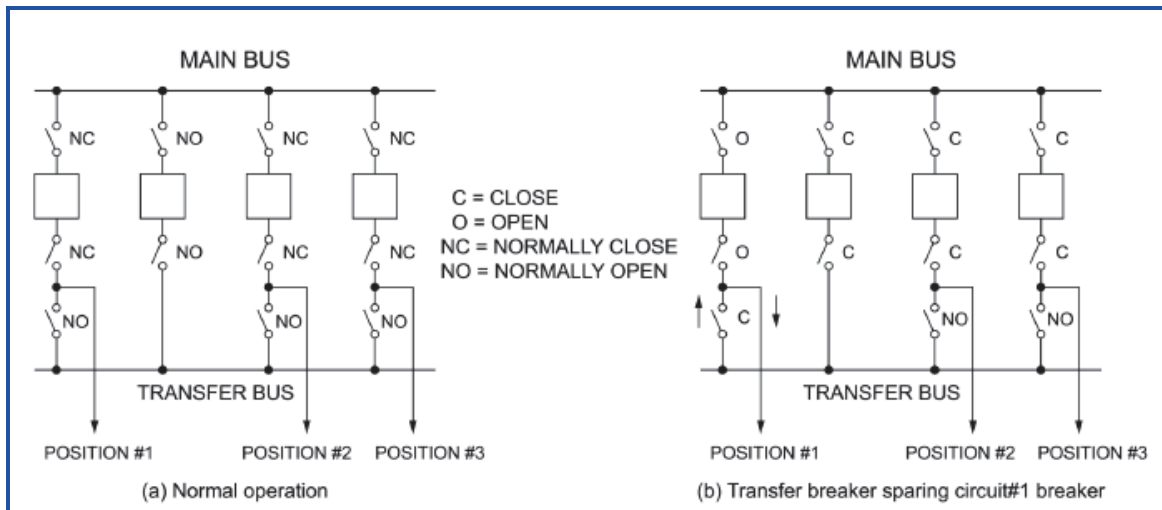
4.3 Main and transfer bus ([MTB](#)) arrangement ~~(MTB)~~

The main and transfer bus ([MTB](#)) arrangement, [as shown in Figure 2](#), is a modification ~~of~~ ~~to~~ the single bus [breaker](#) arrangement ~~as shown in (Figure 1) 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).

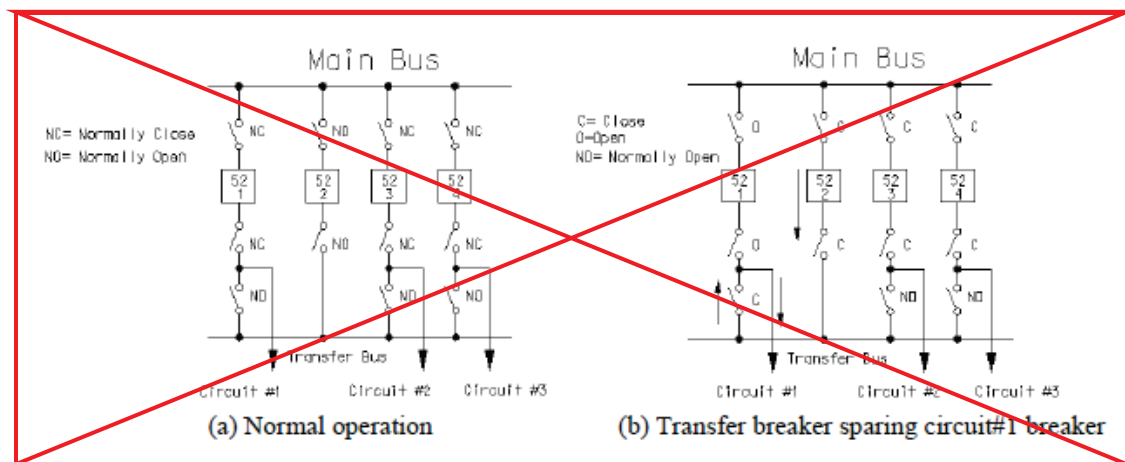
The addition of the transfer bus and transfer breaker allows taking any breaker out of service while the associated circuit remains in service. When a breaker is taken out of service, the transfer breaker and its normally open switches are closed, the circuit breaker and its switches are opened. Figure 2(b) shows [position circuit](#) #1 breaker out of service and [position 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 ~~MTB 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 ~~increases~~ ~~drives~~ the cost ~~high~~. See Table 1 for the advantages and disadvantages of a ~~MTB main and transfer bus~~ arrangement.



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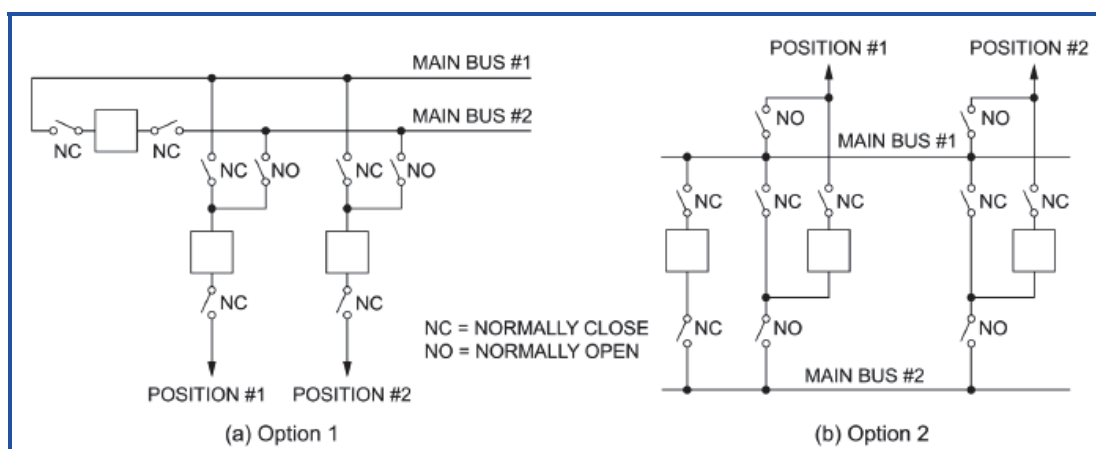
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Figure 2—Main and transfer bus arrangement

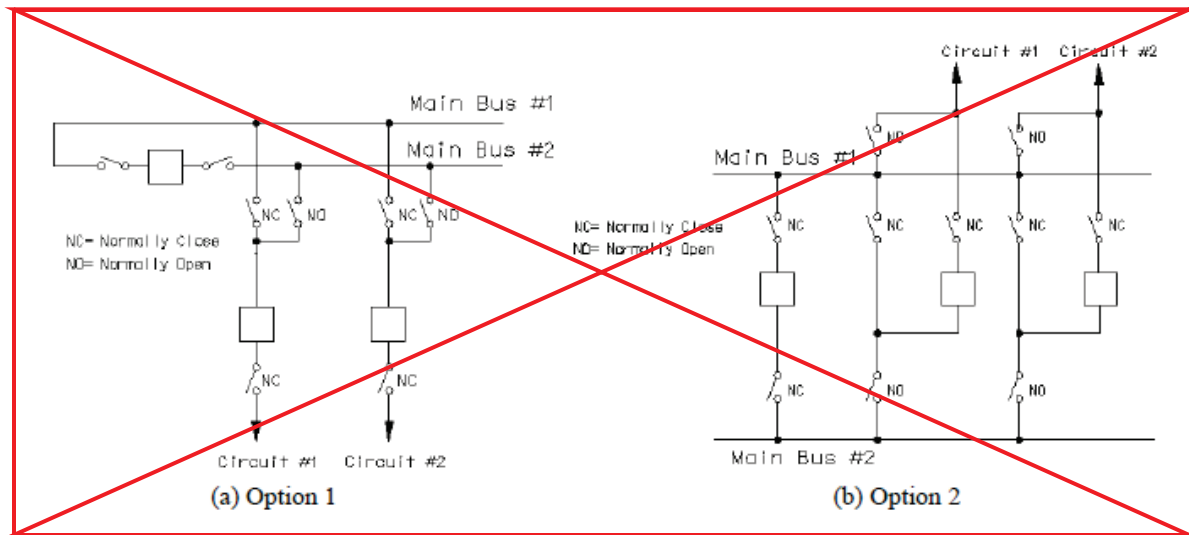
4.4 Double bus single breaker (DBSB) arrangement ~~(DBSB)~~

The double bus single breaker (DBSB) 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 positions ~~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 position ~~circuit~~ #1 breaker, we should open all three disconnects adjacent to the breaker and close a normally open disconnect between position ~~circuit~~ #1 and the main bus #1. After this is done, position ~~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, position ~~circuit~~ #2 should be fed from main bus #2. See Table 1 for the advantages and disadvantages of a DBSB ~~double bus single breaker~~ arrangement.



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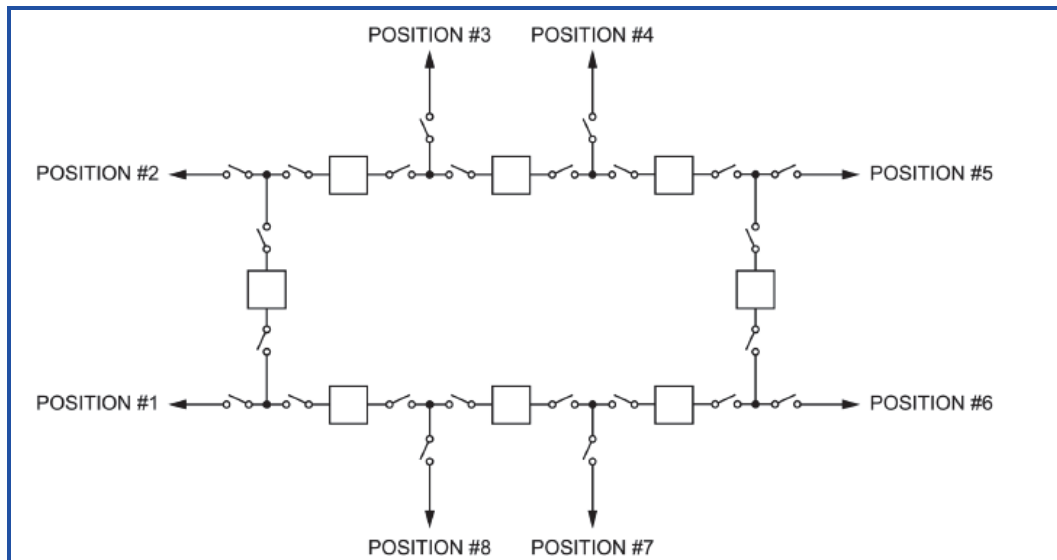


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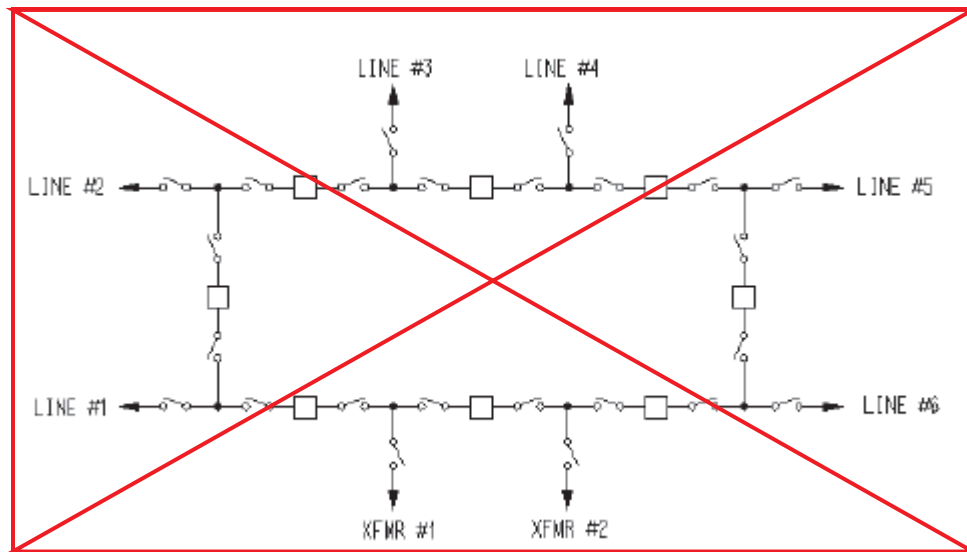
Figure 3—Double bus single breaker arrangement

4.5 Ring bus (RB) arrangements~~(RB)~~

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



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Figure 4_—Ring bus arrangement (eight breakers—eight positions)²¹
circuits⁴³)

^{21 43} Usually, 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 positions circuits, reliability constraints, and so on.

By opening selected breakers, any [position 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, [or reclosed to increase reliability](#). Sources of generation or redundant circuits should not be terminated on adjacent positions of the [RB 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 [significantly fewer much-less](#) bus, insulators, and mounting structures than the other arrangements discussed previously except the [SBSB 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 [position circuit](#) would also have to be taken out of service at the same time. Power flow may be restricted during maintenance and emergency operations [when RB operates in open configuration mode](#).

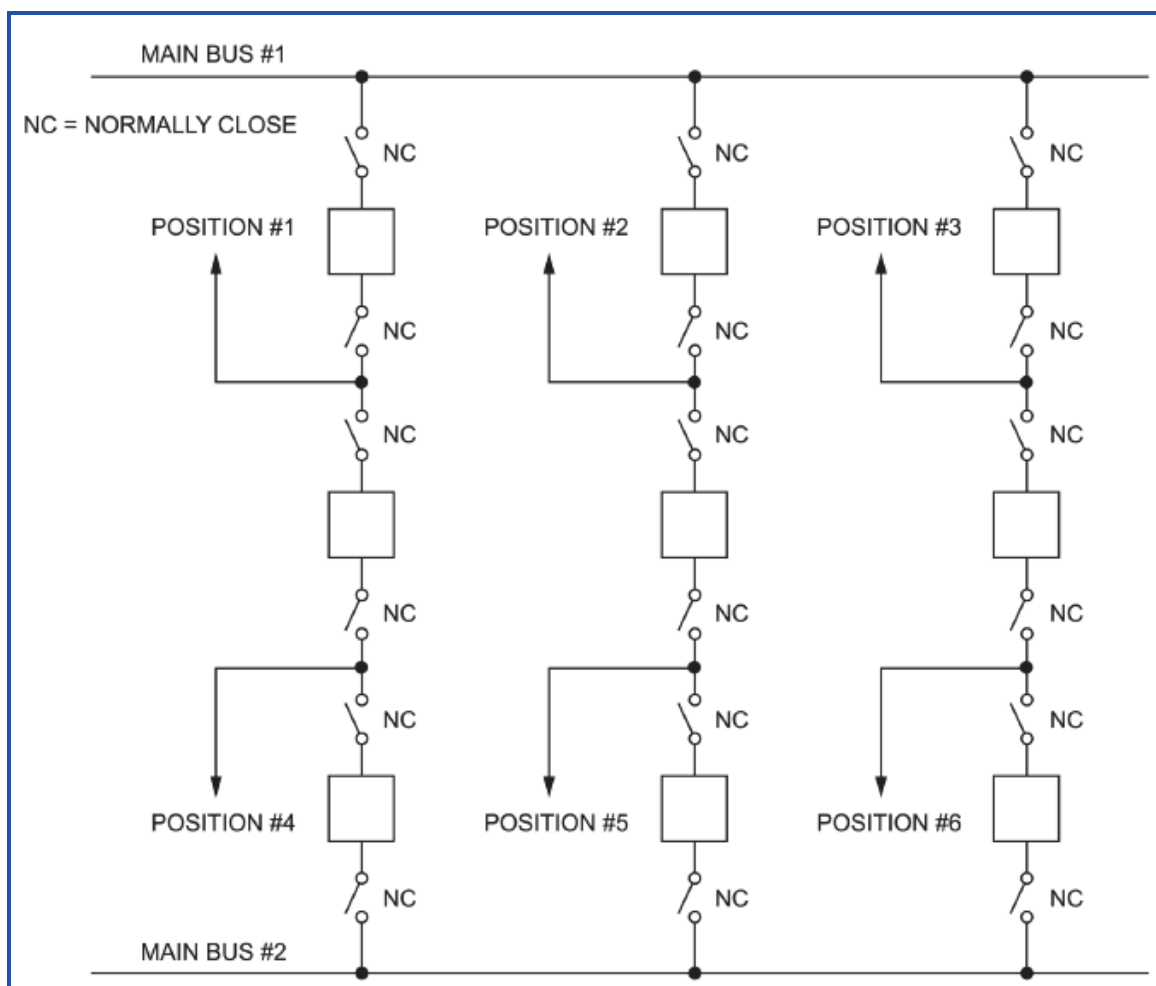
The [RB ring-bus](#) arrangement is very reliable when all breakers are closed and the ring is intact. Typically, the breakers on either side of a [position circuit](#) are opened when the [position circuit](#) is taken out of service, opening the ring. Under this scenario, a fault on a second [position circuit](#) may split the remaining [positions 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 [RB ring-bus](#) arrangement is becoming more popular. See Table 1 for the advantages and disadvantages of a [RB ring-bus](#) arrangement.

4.6 Breaker and half bus ([BAH](#)) arrangement ~~(B-1/2)~~

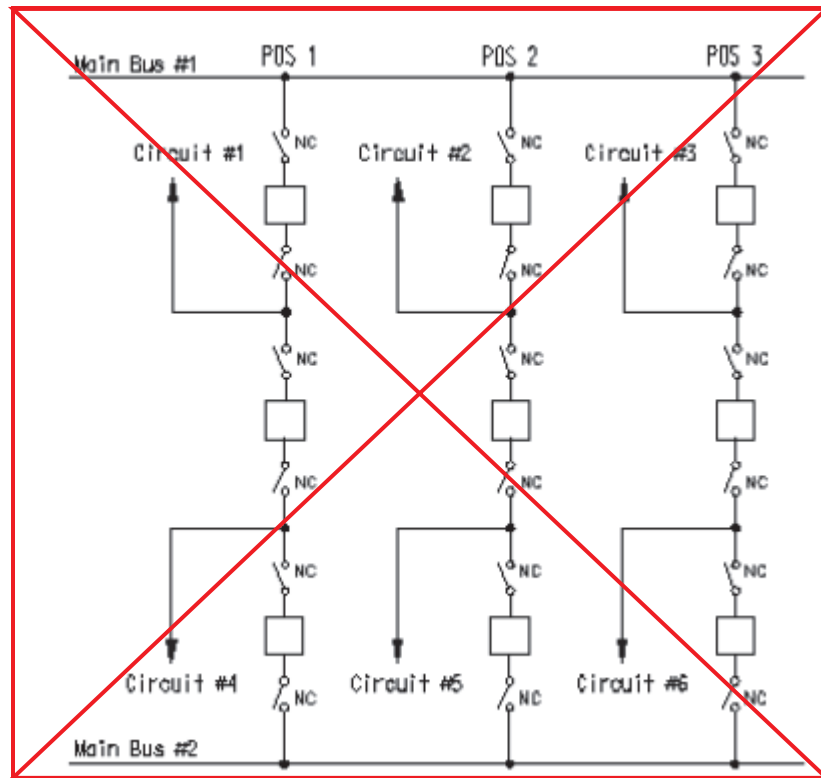
The breaker and half bus ([BAH](#)) arrangement shown in Figure 5 consists of two main buses that are normally energized. Three breakers are required to serve two [positions circuits](#). The middle breaker is common between two [positions circuits](#) and, hence, the name [BAH breaker-and-half-bus](#)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

This arrangement is costly due to the number of breakers and switches needed, and it requires a large ground area. However, it uses approximately 25% less equipment than the double bus double breaker (DBDB) arrangement for each position circuit.

This arrangement is used for substations where reliability and service continuity is important. This arrangement is used extensively for voltages from 15 ~~voltage levels above 345~~ kV and up. It is more frequently used at voltages from 115 ~~some 230~~ kV and up ~~substations due to the importance of these substations~~. Line switches can be added if required. See Table 1 for the advantages and disadvantages of a BAH arrangement.



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Figure 5—Breaker and half bus arrangement

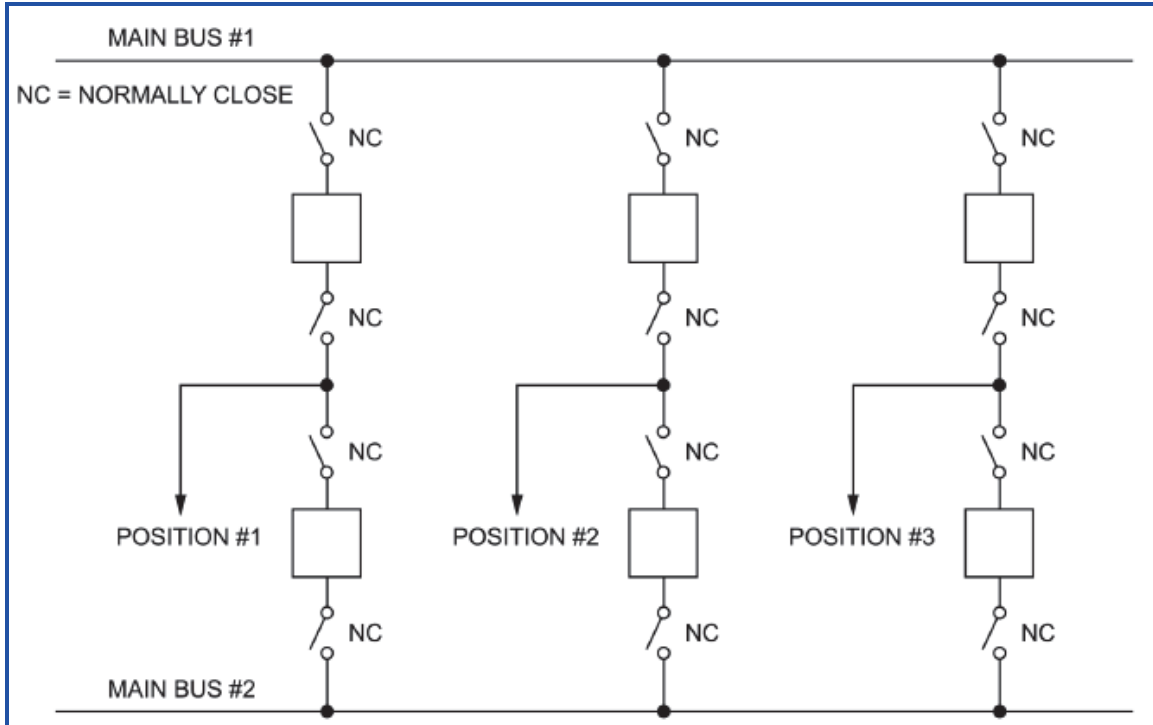
4.7 Double bus double breaker (DBDB) arrangement ~~(DBDB)~~

This bus arrangement, shown in Figure 6, consists of two main buses with two breakers and four switches per position ~~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.

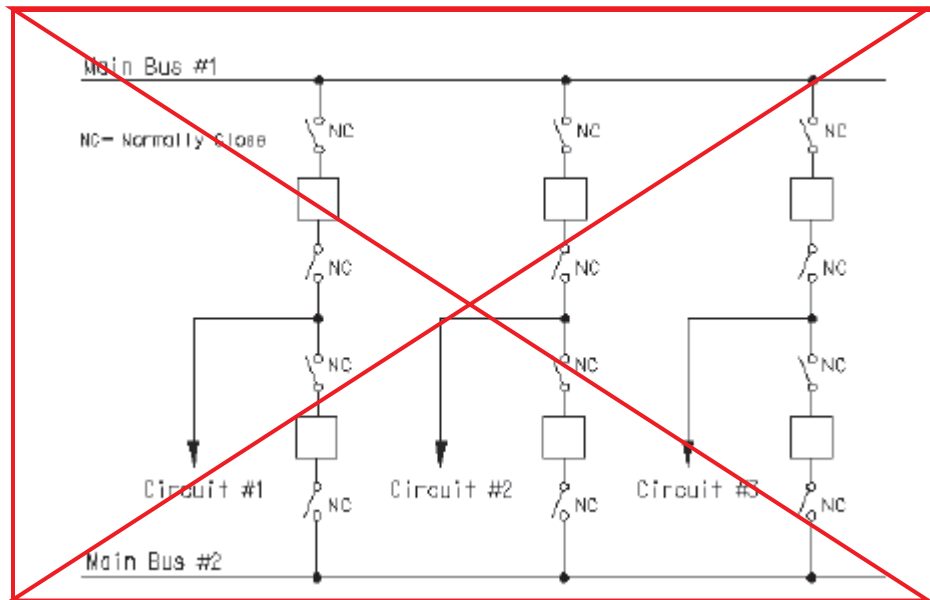
This arrangement requires a large ground area. It is the most expensive one because it requires the most equipment per position ~~circuit~~. This bus arrangement requires a considerable amount of material for mounting structures.

[See Table 1 for the advantages and disadvantages of a DBDB arrangement.](#)

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



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Figure 6 – Double bus double breaker arrangement

4.8 Bus arrangements comparison

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

Table 1 — Bus arrangements comparison

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

(New)

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

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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 ~~positions~~ ~~circuits~~ in all bus arrangements is four (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 arrangement ~~arrangements~~ are installed costs, including cost of equipment, foundation, steel, design, engineering, construction supervision, control circuits, and so on.

5. Bus design considerations

5.1 General

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, capacitors 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 (EHV) substations (230 kV and higher) where either high-capacity or increased seismic withstand capability is required~~7~~, and the area is available. The gas-insulated bus is suitable for unique environmental or space-constrained applications. The gas-insulated 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, desert sandstorms, and areas where aesthetics are major concerns.

5.2 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~~7~~, and the reliability desired or required for these circuits

- b) Site location and size
- c) Seismic activity
- d) Conductor ampacity
- e) Maximum anticipated fault current
- f) Maximum operating voltage
- g) Fault clearing time
- h) Electrical and safe working clearances
- i) Phase spacing
- j) Bus conductor temperature
- k) Maximum and minimum ambient temperature
- l) Maximum anticipated wind speed
- m) Maximum anticipated icing conditions combined with wind
- n) Altitude and latitude of the substation
- o) Basic substation layout
- p) Standard design practices
- q) 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; [see IEEE Std 1127™ for additional information for community involvement.](#)

The bus design can begin after all of the design conditions are firmly established and the bus arrangement has been determined. Several factors [need consideration in determining](#) ~~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 [are discussed in 5.3 and 5.4](#) .

5.3 Construction type

5.3.1 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.

[The advantages and disadvantages of this type of bus construction are as follows:](#)

[a\) Advantages](#)

- [1\) Requires the least amount of land area.](#)
- [2\) Rigid or strain bus can be used.](#)

[b\) Disadvantages](#)

- ~~This construction is~~ Generally considered the least attractive and is predominantly installed in rural or industrial locations.

5.3.2 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:

[a\) Advantages](#)

- [1\) Uses](#) ~~Use~~ low-level mounting structures. This will result in a low profile bus, which is important in populated areas.

- 2) The conductors are not under strain, which improves the reliability by reducing the probability of breakage.
 - 3) The station post insulators are more accessible for cleaning in an area of high contamination.
 - 4) A rigid bus requires less area because the phase-to-phase clearance is less for the rigid bus than for the strain bus.
- b) Disadvantages
- 1) Due to the span length limitation, the rigid bus requires more mounting structures than the strain bus. As a result, more foundations and [structure](#) grounding will be required.
 - 2) Additional design features may be needed to allow access to equipment for maintenance.
 - 3) 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.

5.3.3 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-to-phase and phase-to-ground clearances required.

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

- a) Advantages

- 1) ~~Fewer~~ ~~Less~~ mounting structures are used, and, therefore, the substation area is open and clear to allow access to equipment for maintenance.
 - 2) Strain bus may be more ~~resistant~~ ~~effective~~ to earthquake loads.
 - 3) Fewer insulators and less hardware are used in the strain bus.
 - 4) Strain bus requires fewer man-hours to construct than the rigid bus.
- b) Disadvantages
- 1) 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.
 - 2) Strain bus requires a higher structure to allow for phase-to-ground clearance due to conductor sag.
 - 3) The strain bus uses a larger structure than rigid bus.
 - 4) 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 1527TM ~~-2006~~).

5.3.4 Gas insulated bus

This type of bus construction consists of completely enclosed rigid bus conductors and equipment insulated with pressurized ~~SF₆~~-gas or gas mixture [traditionally sulfur hexafluoride (SF₆)]. Because of the excellent insulating properties of such gases, ~~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-insulated bus construction is typically used at EHV and UHV levels where land costs or environmental hazards offset the much higher gas-insulated ~~SF₆~~ equipment costs.

- a) Advantages
- 1) ~~Requires~~ ~~Require~~ minimum land area.
 - 2) Enclosed live parts not exposed to the environment.
 - 3) Modularized designs minimize construction man-hours.
- b) Disadvantages

- 1) Requires very expensive specialized equipment.
- 2) Pressurized bus may create potential safety issues.
- 3) The use of insulating gas may become restricted if considered a greenhouse gas (such as SF₆).

5.4 Disconnect switches

The clearance requirements for each switch must be determined. For example, if the available phase-to-phase clearance is 3 m (10 ft), a switch that requires 4.5 m (15 ft) 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 on the switch must be considered. The terminal loading requirements of high-voltage switches published in IEEE Std C37.30.1 are operational loads only (opening and closing of switch) and do not represent the mechanical loading limits on the switch terminals; seek loading information from the switch manufacturer for maximum nonoperational loading limits.

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 material to increase the strength of the overall conductor assembly.

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. [See ASTM B188 for additional information.](#)

Table 2—Properties of common bus materials

Metal	Alloy and temper	ASTM reference standard	Minimum tensile strength MPa (ksi)	Minimum yield strength MPa (ksi)	Minimum conductivity at 20 °C in % of IACS (NOTE 1)	Modulus of elasticity GPa (ksi)
Copper tube	H80 Hard (< 4 inch outer diameter)	B188	275 (40.0)	172 (25.0) (NOTE 6)	96.6 (NOTE 2)	110 (16 000)
	H80 Hard (> 4 inch outer diameter)	B188	260 (38.0)	163 (23.8) (NOTE 6)	97.4 (NOTE 2)	110 (16 000)
	O60 Soft	B188	—	—	100 (NOTE 2)	110 (16 000)
Copper wire	Hard	B1	430 (62.1) (NOTE 3)	—	96.16	110 (16 000)
	Medium-hard	B2	340 (49.0) (NOTE 3)	—	96.66	110 (16 000)
	Soft	B3	—	—	100	110 (16 000)
Aluminum tubes and shapes (NOTE 7)	6061-T6	B241	260 (38.0)	240 (35.0)	40 (typical)	69 (10 000)
	6063-T6	B241	205 (30.0)	170 (25.0)	53 (typical)	69 (10 000)
	6101-T6	B317	200 (29.0)	172 (25.0)	55.00	69 (10 000)
	6101-T61	B317	138 (20.0)	103 (15.0)	57.00	69 (10 000)
	6101-T63	B317	186 (27.0)	152 (22.0)	56.00	69 (10 000)
	6101-T64	B317	103 (15.0)	55 (8.0)	59.50	69 (10 000)
	6101-T65	B317	172 (25.0)	138 (20.0)	56.50	69 (10 000)
Aluminum wire	1350-H19 (NOTE 5)	B230	180 (26) (NOTE 4)	—	61.00	69 (10 000)
	6201-T81	B398	315 (46) (NOTE 4)	—	52.50	69 (10 000)

(New)

Metal	Alloy and temper	ASTM reference standard	Minimum tensile strength MPa (ksi)	Minimum yield strength MPa (ksi)	Minimum Conductivity at 20 °C in % of IACS (NOTE 1)	Modulus of elasticity GPa (ksi)
Copper tube	H80 Hard (<4" OD)	B-188	275 (40.0)	172 (25.0) (NOTE 6)	96.6 (NOTE 2)	110 (16 000)
	H80 Hard (>4" OD)	B-188	260 (38.0)	163 (23.8) (NOTE 6)	97.4 (NOTE 2)	110 (16 000)
	O60 Soft	B-188	—	—	100 (NOTE 2)	110 (16 000)
Copper wire	Hard	B-1	430 (62.1) (NOTE 3)	—	96.16	110 (16 000)
	Medium-hard	B-2	340 (49.0) (NOTE 3)	—	96.66	110 (16 000)
	Soft	B-3	—	—	100	110 (16 000)
Aluminum tubes and shapes	6061-T6	B-241	260 (38.0)	240 (35.0)	40 (typical)	69 (10 000)
	6063-T6	B-241	205 (30.0)	170 (25.0)	53 (typical)	69 (10 000)
	6101-T6	B-317	200 (29.0)	172 (25.0)	55.00	69 (10 000)
	6101-T61	B-317	138 (20.0)	103 (15.0)	57.00	69 (10 000)
	6101-T63	B-317	186 (27.0)	152 (22.0)	56.00	69 (10 000)
	6101-T64	B-317	103 (15.0)	55 (8.0)	59.50	69 (10 000)
	6101-T65	B-317	172 (25.0)	138 (20.0)	56.50	69 (10 000)
Aluminum wire	1350-H19 (NOTE 5)	B-230	180 (26) (NOTE 4)	—	61.00	69 (10 000)
	6201-T81	B-398	315 (46) (NOTE 4)	—	52.50	69 (10 000)

(Deleted)

NOTE 1—_The international standard for the resistivity of annealed copper is 0.15328 Ω -g/m² at 68 °F (20 °C). This value represents 100% of the International Annealed Copper Standard (IACS).

NOTE 2—_Applicable to copper [Unified Numbering System \(UNS\) numbers](#) ~~nos.~~ C10200, C10400, C10500, C10700, C11000, C11300, C11400, and C11600.

NOTE 3—_Nominal value, see ASTM [B1 \[B11\]](#), ASTM B2 [B12] ~~B-1, B-2~~, or [ASTM B3 \[B13\]](#) ~~B-3~~ as applicable.

NOTE 4—_Nominal value, see ASTM [B230 \[B14\]](#) ~~B-230~~ or [ASTM B398 \[B16\]](#) ~~B-398~~ as applicable.

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

NOTE 6—_The Chase Electrical Handbook [[B22](#) ~~B44~~] 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 ½ of one percent.” The yield strength values listed in ~~this the~~ [table 4](#) are based on 62.5% of the ASTM minimum tensile strength as indicated in [Table Tables](#) 8 and [Table](#) 9 of the Chase Electrical Handbook [[B22](#)].

[NOTE 7— Welding of aluminum leads to annealing of the base metal in the Heat Affected Zone, which lowers the yield and tensile strength. See 6.6.1.5 for further discussion.](#)

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 [International Annealed Copper Standard \(IACS\)](#). 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 [are](#) ~~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.

[See ASTM B241 for additional information.](#)

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. [Rigid bus may subject equipment to undesirable stresses that may be mitigated by the use of flexible conductors](#)
~~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
- e) [Have a lower drag coefficient for wind loading, resulting in lower wind loads](#)

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 B317 [B15]. 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 or 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.

Table 3—Minimum flatwise bending radius of rectangular aluminum bus

Alloy and temper	Maximum bar width mm (in)	Bar thickness mm (in)	Minimum bending radius
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 Electrical connectors

6.6.1.1 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 [ANSI/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.

6.6.1.2 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

Bus bar materials to be joined	Bolting hardware
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.

To provide a good mechanical and electrical connection and to prevent the backing off of nuts due to wind and operation vibrations, nuts are tightened to develop a pretension within the bolt. Typically, this pretension is correlated to an associated torque value dependent on the hardware material and size. It should be cautioned that pretension to torque correlations can vary substantially depending on hardware finish and manufacturing tolerances, contaminations such as dust, dirt, or corrosion, and the application and condition of lubricants.

If the 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.~~