SECTION 17
SUBSTATIONS

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CONTENTS

17.1 AIR-INSULATED SUBSTATIONS

17.1.1 Function of Substations

Transmission and Distribution Systems. In large, modern ac power systems, the transmission and distribution systems function to deliver bulk power from generating sources to users at the load centers. Transmission systems generally include generation switchyards, interconnecting transmission lines, autotransformers, switching stations, and step-down transformers. Distribution systems include primary distribution lines or networks, transformer banks, and secondary lines or networks, all of which serve the load area.

17.1.2 Design Objectives

As an integral part of the transmission or distribution systems, the substation or switching station functions as a connection and switching point for generation sources, transmission or subtransmission lines, distribution feeders, and step-up and step-down transformers. The design objective for the

substation is to provide as high a level of reliability and flexibility as possible while satisfying system requirements and minimizing total investment costs.

Voltage Levels. The selection of optimal system voltage levels depends on the load to be served and the distance between the generation source and the load. Many large power plants are located great distances from the load centers to address energy sources or fuel supplies, cooling methods, site costs and availability, and environmental concerns. For these reasons, the use of transmission voltages as high as 765 kV has occurred. Transmission system substations that provide bulk power operate at voltages from 69 to 765 kV. Common voltage classes used in the United States for major substations include 69, 115, 138, 161, and 230 kV (considered *high voltage* or *HV class*) and 345,500, and 765 kV (considered *extra high voltage* or *EHV class*). Even higher voltages which include 1100 and 1500 kV have been considered. These are referred to as *ultra high voltage* or *UHV class*. Distribution system substations operate at secondary voltage levels from 4 to 69 kV.

Design Considerations. Many factors influence the selection of the proper type of substation for a given application. This selection depends on such factors as voltage level, load capacity, environmental considerations, site space limitations, and transmission-line right-of-way requirements. While also considering the cost of equipment, labor, and land, every effort must be made to select a substation type that will satisfy all requirements at minimum costs. The major substation costs are reflected in the number of power transformers, circuit breakers, and disconnecting switches and their associated structures and foundations. Therefore, the bus layout and switching arrangement selected will determine the number of the devices that are required and in turn the overall cost. The choice of insulation levels and coordination practices also affects cost, especially at EHV. A drop of one level in basic insulation level (BIL) can reduce the cost of major electrical equipment by thousands of dollars. A careful analysis of alternative switching schemes is essential and can result in considerable savings by choosing the minimum equipment necessary to satisfy system requirements.

A number of factors must be considered in the selection of bus layouts and switching arrangements for a substation to meet system and station requirements. A substation must be safe, reliable, economical, and as simple in design as possible. The design also should provide for further expansion, flexibility of operation, and low maintenance costs.

The physical orientation of the transmission-line routes often dictates the substation's location, orientation, and bus arrangement. This requires that the selected site allow for a convenient arrangement of the lines to be accomplished.

For reliability, the substation design should reduce the probability of a total substation outage caused by faults or equipment failure and should permit rapid restoration of service after a fault or failure occurs. The layout also should consider how future additions and extensions can be accomplished without interrupting service.

Bus Schemes. The substation design or scheme selected determines the electrical and physical arrangement of the switching equipment. Different bus schemes can be selected as emphasis is shifted between the factors of safety, reliability, economy, and simplicity dictated by the function and importance of the substation.

The substation bus schemes used most often are

1. Single bus

2. Main and transfer bus

3. Double bus, single breaker

4. Double bus, double breaker

5. Ring bus

6. Breaker and a half

Some of these schemes may be modified by the addition of bus-tie breakers, bus sectionalizing devices, breaker bypass facilities, and extra transfer buses. Figures 17-1 to 17-6 show one-line diagrams for some of the typical schemes listed above.

Single Bus. The single-bus scheme (Fig. 17-1) is not normally used for major substations. Dependence on one main bus can cause a serious outage in the event of breaker or bus failure without the use of mobile equipment. The station must be deenergized in order to carry out bus maintenance or add bus extensions. Although the protective relaying is relatively simple for this scheme, the single-bus scheme is considered inflexible and subject to complete outages of extended duration.

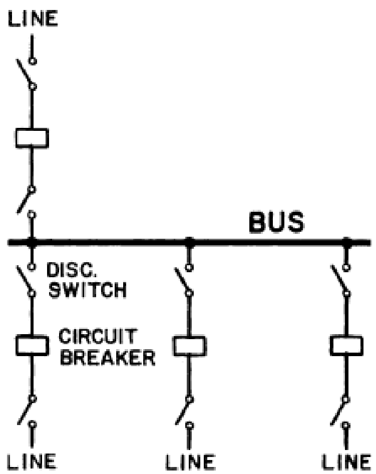


FIGURE 17-1 Single bus.

Main and Transfer Bus. The main- and transfer-bus scheme (Fig. 17-2) adds a transfer bus to the single-bus scheme. An extra bus-tie circuit breaker is provided to tie the main and transfer buses together.

When a circuit breaker is removed from service for maintenance, the bus-tie circuit breaker is used to keep that circuit energized. Unless the protective relays are also transferred, the bus-tie relaying must be capable of protecting transmission lines or generation sources. This is considered rather unsatisfactory because relaying selectivity is poor.

A satisfactory alternative consists of connecting the line and bus relaying to current transformers located on the lines rather than on the breakers. For this arrangement, line and bus relaying need not be transferred when a circuit breaker is taken out of service for maintenance, with the bus-tie breaker used to keep the circuit energized.

If the main bus is ever taken out of service for maintenance, no circuit breakers remain to protect any of the feeder circuits. Failure of any breaker or failure of the main bus can cause complete loss of service of the station.

Due to its relative complexity, disconnect-switch operation with the main- and transfer-bus scheme can lead to operator error and a possible outage. Although this scheme is low in cost and enjoys some popularity, it may not provide as high a degree of reliability and flexibility as required.

Double Bus, Single Breaker. This scheme uses two main buses, and each circuit includes two bus selector disconnect switches. A bus-tie circuit (Fig. 17-3) connects to the two main buses and, when closed, allows transfer of a feeder from one bus to the other bus without deenergizing the feeder circuit by operating the bus selector disconnect switches. The circuits may all operate from either the no. 1 or no. 2 main bus, or half the circuits may be operated off either bus. In the first case, the station

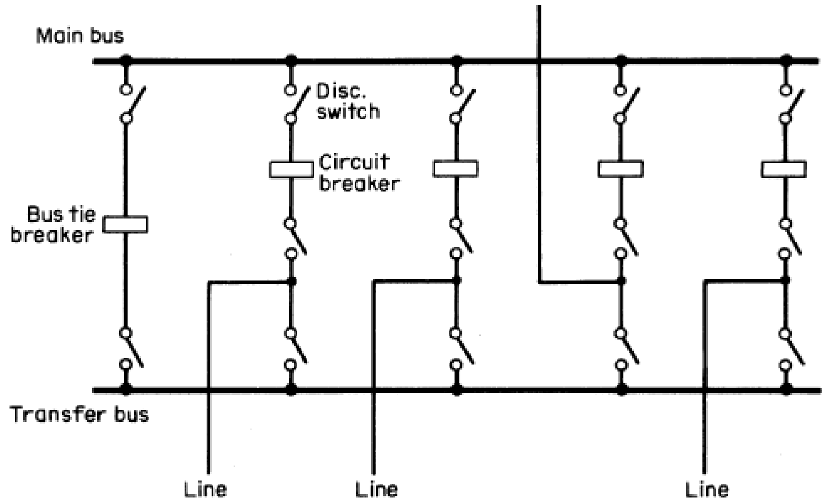
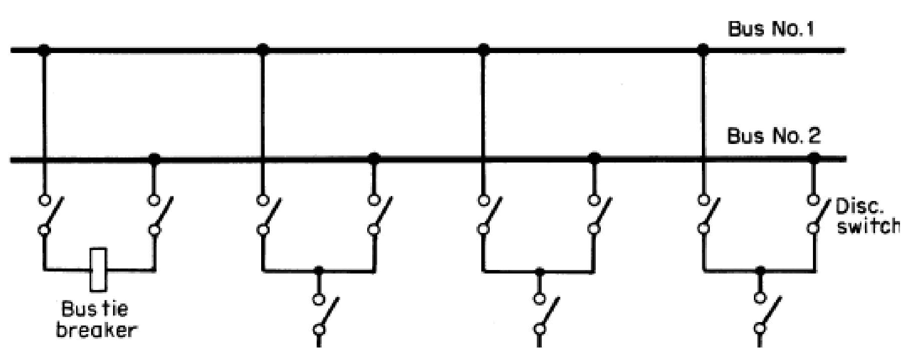


FIGURE 17-2 Main and transfer bus.



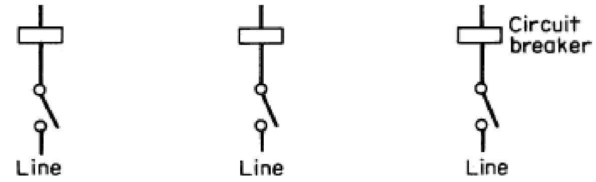


FIGURE 17-3 Double bus, single breaker.

will be out of service for bus or breaker failure. In the second case, half the circuits will be lost for bus or breaker failure.

In some cases circuits operate from both the no. 1 and no. 2 bus, and the bus-tie breaker is normally operated closed. For this type of operation, a very selective bus-protective relaying scheme is required to prevent complete loss of the station for a fault on either bus. Disconnect-switch operation becomes quite involved, with the possibility of operator error, injury, and possible outage. The double-bus, single-breaker scheme is relatively poor in reliability and is not normally used for important substations.

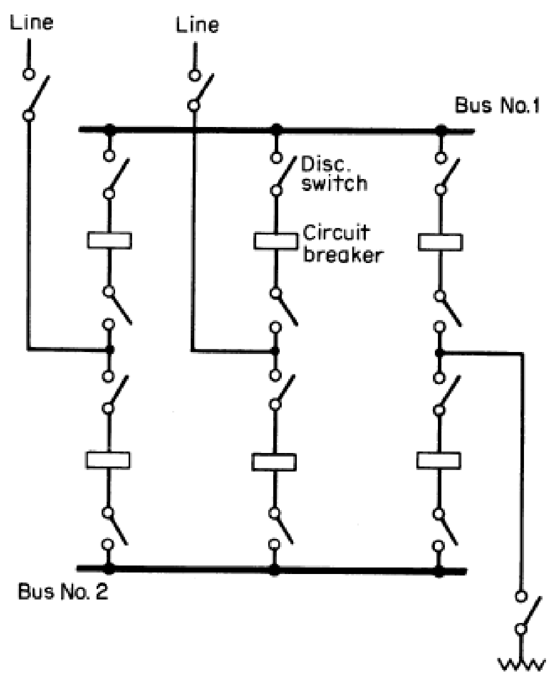


FIGURE 17-4 Double bus, double breaker.

Double Bus, Double Breaker. The double-bus, double breaker scheme (Fig. 17-4) requires two circuit breakers for each feeder circuit. Normally, each circuit is connected to both buses. In some cases, half the circuits operate on each bus. For these cases, a bus or breaker failure would cause loss of only half the circuits, which could be rapidly corrected through switching. The physical location of the two main buses must be selected in relation to each other to minimize the possibility of faults spreading to both buses. The use of two breakers per circuit makes this scheme expensive; however, it does represent a high degree of reliability.

Ring Bus. In the ring-bus scheme (Fig. 17-5), the breakers are arranged in a ring with circuits connected between breakers. There are the same number of circuits as there are breakers. During normal operation, all breakers are closed. For a circuit fault, two breakers are tripped, and in the event that one of the breakers fails to operate to clear the fault, an additional circuit will be tripped by operation of breaker-failure backup relays. During breaker maintenance, the ring is broken, but all lines remain in service.

The circuits connected to the ring are arranged so that sources are alternated with loads. For an extended circuit outage, the line-disconnect switch may be opened, and the ring can be closed. No changes to protective relays are required for any of the various operating conditions or during maintenance.

The ring-bus scheme is relatively economical in cost, has good reliability, is flexible, and is normally considered suitable for important substations up to a limit of five circuits. Protective relaying and automatic reclosing are more complex than for previously described schemes. It is common practice to build major substations initially as a ring bus; for more than five outgoing circuits, the ring bus is usually converted to the breaker-and-a-half scheme.

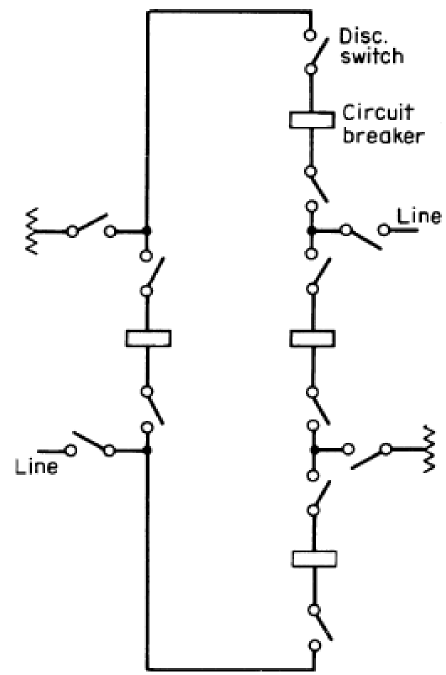
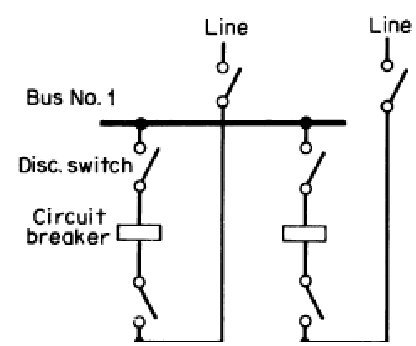


FIGURE 17-5 Ring bus.

Breaker and a Half. The breaker-and-a half scheme (Fig. 17-6), sometimes called the *three-switch scheme*, has three breakers in series between two main buses. Two circuits are connected between the three breakers, hence the term *breaker and a half*. This pattern is repeated along the main buses so that one and a half breakers are used for each circuit.

Under normal operating conditions, all breakers are closed, and both buses are energized. A circuit is tripped by opening the two associated circuit breakers. Tie-breaker failure will trip one additional circuit, but no additional circuit is lost if a line trip involves failure of a bus breaker. Either bus may be taken out of service at any time with no loss of service. With sources connected opposite to loads, it is possible to operate with both buses out of service. Breaker maintenance can be done with no loss of



service, no relay changes, and simple operation of the breaker disconnects.

The breaker-and-a-half arrangement is more expensive than the other schemes, with the exception of the double-breaker, double-bus scheme, and protective relaying and automatic reclosing schemes are more complex than for other schemes. However, the breaker-and-a half scheme is superior in flexibility, reliability, and safety.

17.1.3 Reliability Comparisons

The various schemes have been compared to emphasize their advantages and disadvantages. The basis of comparison to be employed is the economic justification of a particular degree of reliability. The determination of the degree of reliability involves an appraisal of anticipated operating conditions and the continuity of service required by the load to be served. Table 17-1 contains a summary of the comparison of switching schemes to show advantages and disadvantages.

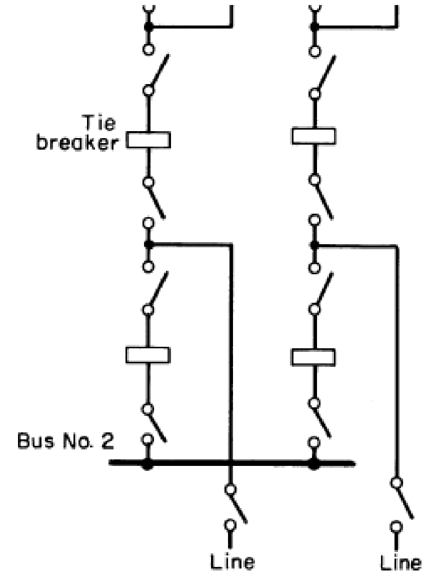


FIGURE 17-6 Breaker-and-a-half scheme.

TABLE 17-1 Summary of Comparison of Switching Schemes

Switching scheme	Advantages	Disadvantages
1. Single bus	1. Lowest cost.	1. Failure of bus or any circuit breaker results in shutdown of entire substation. 2. Difficult to do any maintenance. 3. Bus cannot be extended without completely deenergizing substation.

		4. Can be used only where loads can be interrupted or have other supply arrangements.
2. Double bus, double breaker	1. Each circuit has two dedicated breakers. 2. Has flexibility in permitting feeder circuits to be connected to either bus. 3. Any breaker can be taken out of service for maintenance. 4. High reliability.	1. Most expensive. 2. Would lose half of the circuits for breaker failure if circuits are not connected to both buses.
3. Main and transfer	1. Low initial and ultimate cost. 2. Any breaker can be taken out of service for maintenance. 3. Potential devices may be used on the main bus for relaying.	1. Requires one extra breaker for the bus tie. 2. Switching is somewhat complicated when maintaining a breaker. 3. Failure of bus or any circuit breaker results in shutdown of entire substation.
4. Double bus, single breaker	1. Permits some flexibility with two operating buses. 2. Either main bus may be isolated for maintenance. 3. Circuit can be transferred readily from one bus to the other by use of bus-tie breaker and bus selector disconnect switches.	1. One extra breaker is required for the bus tie. 2. Four switches are required per circuit. 3. Bus protection scheme may cause loss of substation when it operates if all circuits are connected to that bus. 4. High exposure to bus faults. 5. Line breaker failure takes all circuits connected to that bus out of service. 6. Bus-tie breaker failure takes entire substation out of service.
5. Ring bus	1. Low initial and ultimate cost. 2. Flexible operation for breaker maintenance. 3. Any breaker can be removed for maintenance without interrupting load. 4. Requires only one breaker per circuit. 5. Does not use main bus. 6. Each circuit is fed by two breakers. 7. All switching is done with breakers.	1. If a fault occurs during a breaker maintenance period, the ring can be separated into two sections. 2. Automatic reclosing and protective relaying circuitry rather complex. 3. If a single set of relays is used, the circuit must be taken out of service to maintain the relays. (Common on all schemes.) 4. Requires potential devices on all circuits since there is no definite potential reference point. These devices may be required in all cases for synchronizing, live line, or voltage indication. 5. Breaker failure during a fault on one of the circuits causes loss of one additional circuit owing to operation of breaker-failure relaying.
6. Breaker and a half	1. Most flexible operation. 2. High reliability. 3. Breaker failure of bus side breakers removes only one circuit from service. 4. All switching is done with breakers. 5. Simple operation; no disconnect switching required for normal operation. 6. Either main bus can be taken out of service at any time for maintenance. 7. Bus failure does not remove any feeder circuits from service.	1. $1\ ^1/_2$ breakers per circuit. 2. Relaying and automatic reclosing are somewhat involved since the middle breaker must be responsive to either of its associated circuits.

17.1.4 Arrangements and Equipment

Once a determination of the switching scheme best suited for a particular substation application is made, it is necessary to consider the station arrangement and equipment that will satisfy the many physical requirements of the design. Available to the design engineer are the following:

1. Conventional outdoor air-insulated open-type bus-and-switch arrangement substations (using either a strain bus or rigid bus design)
2. Metal-clad or metal-enclosed substations
3. Gas (sulfur hexafluoride)–insulated substations

Outdoor open-type bus-and-switch arrangements generally are used because of their lower cost, but they are larger in overall physical size. Metal-clad substations generally are limited to 38 kV. Gas-insulated substations are generally the highest in cost but smallest in size.

Substation Components. The electrical equipment in a typical substation can include the following:

Circuit breakers
Disconnecting switches
Grounding switches
Current transformers
Voltage transformers or capacitor voltage transformers
Coupling capacitors
Line traps
Surge arresters
Power transformers
Shunt reactors
Current-limiting reactors

Station buses and insulators

Grounding systems

Series capacitors

Shunt capacitors

Support Structures. In order to properly support, mount, and install the electrical equipment, structures made of steel, aluminum, wood, or concrete and associate foundations are required. The typical open-type substation requires strain structures to support the transmission-line conductors; support structures for disconnecting switches, current transformers, potential transformers, lightning arresters, and line traps, capacitor voltage transformers; and structures and supports for the strain and rigid buses in the station.

When the structures are made of steel or aluminum, they require concrete foundations; however, when they are made of wood or concrete, concrete foundations are not required. Additional work is required to design concrete foundations for supporting circuit breakers, reactors, transformers, capacitors, and any other heavy electrical equipment.

Substation-equipment support structures fabricated of steel or aluminum may consist of single wide-flange or tubular-type columns, rigid-frame structures composed of wide flanges or tubular sections, or lattice structures composed of angle members. Substation strain structures can be wood or concrete pole structures, aluminum or steel lattice-type structures, or steel A-frame structures. Aluminum, weathering steel, and concrete pole structures can be used in their natural unfinished state. Normal carbon-steel structures should have galvanized or painted finishes. Wood structures should have a thermal- or pressure-process-applied preservative finish.

Aluminum structures are lightweight, have an excellent strength-to-weight ratio, and require little maintenance but have a greater initial cost than steel structures. Weathering-steel structures can be field-welded without the special surface preparation and touch-up work required on galvanized or painted steel structures, and the self-forming protective corrosion oxide eliminates maintenance. In addition, the weathering-steel color blends well in natural surroundings. Galvanized- or painted-steel structures have a slightly lower initial cost than weathering-steel structures; however, they require special treatment before and after field welding and require more maintenance.

Lattice-type structures are light in weight, have a small wind-load area, and are low in cost. Single-column support structures and rigid-frame structures require little maintenance, are more aesthetically pleasing, and can be inspected more quickly than lattice structures, but they have a greater initial cost. In order to reduce erection costs, rigid-frame structures should be designed with bolted field connections.

The design of supporting structures is affected by the phase spacings and ground clearances required, by the types of insulators, by the length and weight of buses and other equipment, and by wind and ice loading. For data on wind and ice loadings, see National Electric Safety Code©, IEEE Standard C2-2002, or latest edition. For required clearances and phase spacings, see Part I, Secs. 11 and 12.

Other structural and concrete work required in the substation includes site selection and preparation, roads, control houses, manholes, conduits, ducts, drainage facilities, catch basins, oil containment, and fences.

17.1.5 Site Selection

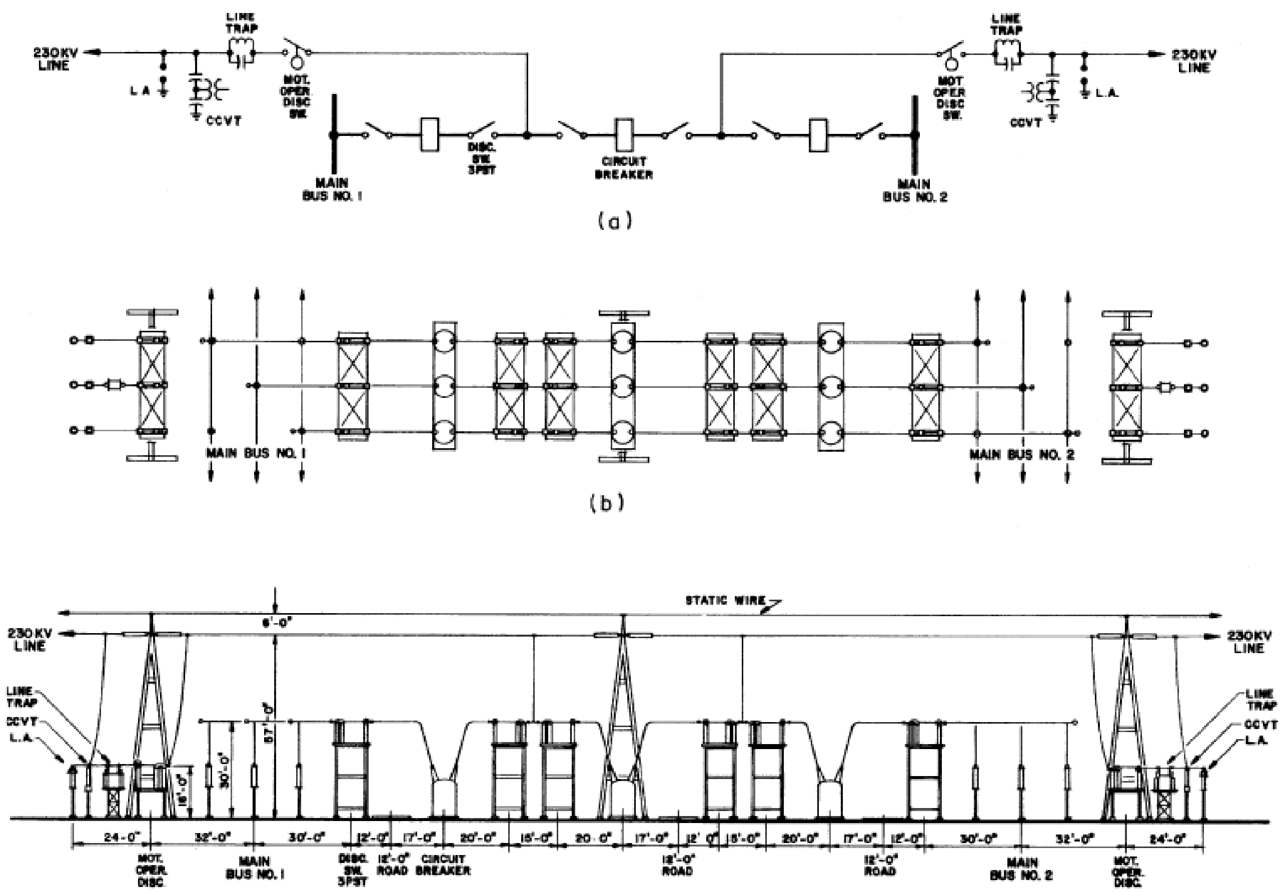
Civil engineering work associated with the substation should be initiated as early as possible in order to ensure that the best available site is selected. This work includes a study of the topography and drainage patterns of the area together with a subsurface soil investigation. The information obtained from the subsurface soil investigation also will be used to determine the design of the substation foundations. For large substations or substations located in area with poor soils, it may be necessary to obtain additional subsurface soil tests after final selection of the substation site has been made. The additional information should fully describe the quality of the soil at the site, since the data will be used to design equipment foundations.

Open-Bus Arrangement. An air-insulated, open-bus substation arrangement consists essentially of open-bus construction using either rigid- or strain-bus design such as the breaker-and-a-half arrangement shown in Fig. 17-7; the buses are arranged to run the length of the station and are located toward the outside of the station. The transmission-line exits cross over the main bus and are dead-ended on takeoff tower structures. The line drops into the bay in the station and connects to the disconnecting switches and circuit breakers.

Use of this arrangement requires three distinct levels of bus to make the necessary crossovers and connections to each substation bay. Typical dimensions of these levels at 230 kV are 16 ft for the first level above ground, 30 ft high for the main bus location, and 57 ft for the highest level of bus (see Fig. 17-7).

This arrangement, in use since the mid-1920s and widely used by many electric utilities, has the advantage of requiring a minimum of land area per bay and relative ease of maintenance, and it is ideally suited to a transmission-line through-connection where a substation must be inserted into a transmission line.

Inverted Bus. An alternate arrangement is the inverted-bus, breaker-and-a-half scheme for EHV substations. A typical layout is outlined in Fig. 17-8. A one-line diagram of a station showing many variations of the inverted-bus scheme is presented in Fig. 17-9. With this arrangement, all outgoing circuit takeoff towers are located in the outer perimeter of the substation, eliminating the crossover of line or exit facilities. Main buses are located in the middle of the substation, with all disconnecting switches, circuit breakers, and bay equipment located outboard of the main buses. The end result of


230KV LINE
LINE TRAP
L.A.
CCVT
MOT. OPER. DISC SW.
DISC. SW. 3PST
CIRCUIT BREAKER
MAIN BUS NO. 1
MAIN BUS NO. 2
230KV LINE
(a)
MAIN BUS NO. 1
MAIN BUS NO. 2
(b)
STATIC WIRE
230 KV LINE
LINE TRAP
CCVT
L.A.
6'-0"
57'-0"
30'-0"
16'-0"
24'-0"
32'-0"
30'-0"
12'-0"
17'-0"
20'-0"
15'-0"
20'-0"
17'-0"
12'-0"
15'-0"
20'-0"
17'-0"
12'-0"
30'-0"
32'-0"
24'-0"
MOT. OPER. DISC.
MAIN BUS NO. 1
DISC. SW. 3PST
12'-0" ROAD
CIRCUIT BREAKER
12'-0" ROAD
12'-0" ROAD
MAIN BUS NO. 2
MOT. OPER. DISC.

(c)

FIGURE 17-7 Typical conventional substation layout, breaker-and-a-half scheme. (*a*) Main one-line diagram; (*b*) plan; (*c*) elevation.

the inverted-bus arrangement presents a very low profile station with many advantages in areas where beauty and aesthetic qualities are a necessity for good public relations. The overall height of the highest bus in the 230-kV station just indicated reduces from a height of 57 ft above ground in the conventional arrangement to a height of only 30 ft above ground for the inverted-bus low-profile scheme.

17.1.6 Substation Buses

Substation buses are an important part of the substation because they carry electric currents in a confined space. They must be carefully designed to have sufficient structural strength to withstand the maximum stresses that may be imposed on the conductors, and in turn on the supporting structures, due to short-circuit currents, high winds, and ice loadings.

During their early development, HV class substations were usually of the strain-bus design. The strain bus is similar to a transmission line and consists of a conductor such as ACSR (aluminum cable steel reinforced), copper, or high-strength aluminum alloy strung between substation structures. EHV substations normally use the rigid-bus approach and enjoy the advantage of low station profile and ease of maintenance and operation (see Fig. 17-8). The mixing of rigid- and strain-bus construction is normally employed in the conventional arrangement shown in Fig. 17-7. Here, the main buses use rigid-bus design, and the upper buses between transmission towers are of strain-bus design. A typical design at 765 kV uses a combination of both rigid and strain buses (Fig. 17-10).

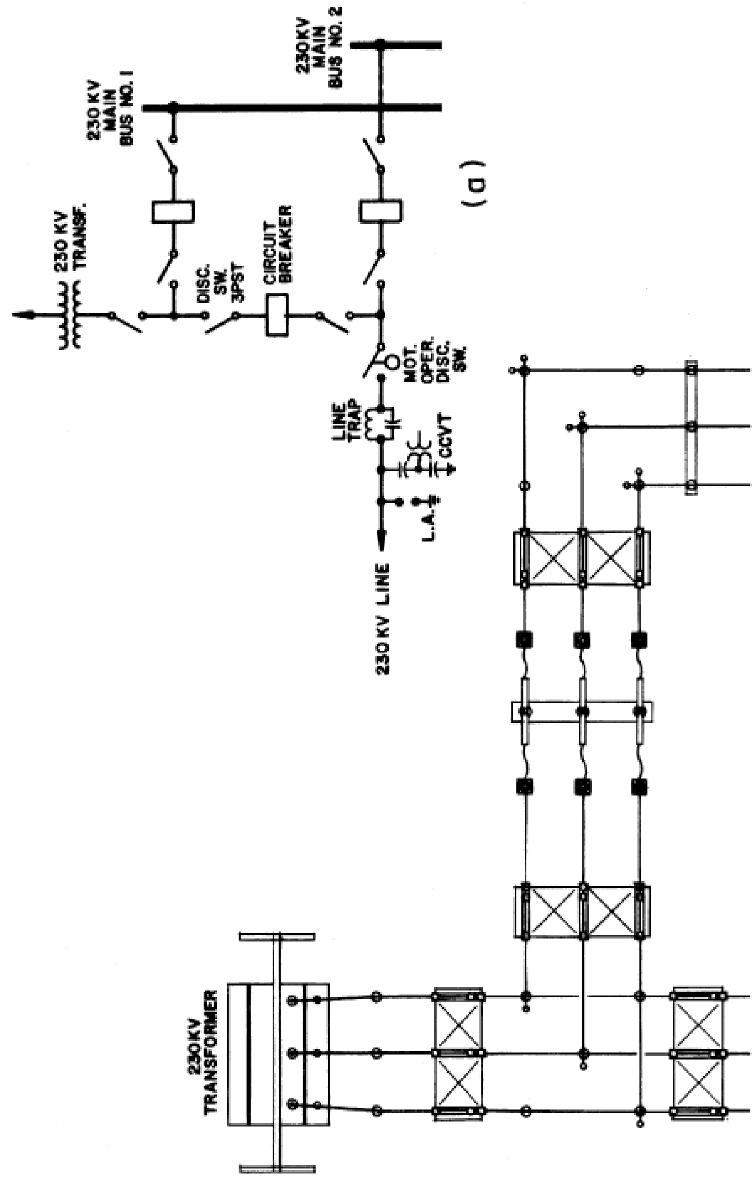


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FIGURE 17-8