$X_s = 0.22\ \Omega$ $\quad R_r = 0.012\ \Omega$

$R_s = 0.04\ \Omega$ $\quad X_{br} = 0.063\ \Omega$

$R_c = 50.0\ \Omega$ $\quad N_s/N_r = 2.4:1$

$X_m = 3.5\ \Omega$

Calculate the following:

a. Stator current, apparent power, and power factor at starting
b. Stator current and power factor under normal running conditions

2.5. A 150-hp, 460-V, 1790-rpm, 60-Hz, four-pole, three-phase, code letter H, premium efficiency motor has a full-load current rating of 166 A and a NEMA nominal efficiency of 95.8%. Calculate the following:
a. Active, apparent, and reactive power input
b. Power factor
c. Inrush kVA and inrush current during full-voltage starting

2.6. A 5-hp, 230-V, single-phase, two-pole, 60-Hz, code letter G, capacitor start motor has a full-load current rating of 21.5 A. The NEMA nominal efficiency is 85%. Calculate the following:
a. Active, apparent, and reactive power input
b. Power factor
c. Inrush kVA and inrush current during full-voltage starting

2.7. A 200-hp, 600-rpm, 460-V, three-phase, 60-Hz, synchronous motor draws an armature current of 255 A when operating at rated load and 0.8 leading power factor. The synchronous reactance is 0.7 Ω/phase and the stator winding resistance is 0.2 Ω/phase. Calculate the following:
a. Armature current in complex form
b. Countervoltage
c. Torque angle

2.8. The motor in Problem 2.7 is disconnected from the load. Assume that the magnitude of the countervoltage $\mathbf{E}_f$ remains constant and that the torque angle at no load is $-5°$. Calculate the armature current and power factor under these conditions.

2.9. A 300-MVA, 14-kV, two-pole, 60-Hz, wye-connected, three-phase synchronous generator is supplying rated load at 0.85 lagging power factor. The synchronous reactance is 0.75 Ω/phase, and the stator resistance is negligible. Calculate the armature current, generated voltage and power angle for the specified load conditions.

2.10. The generator of Problem 2.9 is now operating at rated load and 0.9 leading power factor. Calculate the armature current, generated voltage, and power angle for this load condition. Compare the results to Problem 2.9.

3

Introduction to Electric Utility Power Systems

3-1 General

This chapter provides a general overview of the design and operation of electrical utility power systems. The development and operation of the interconnected systems in the United States are discussed. Typical generating plant, transmission, distribution, and substation topologies are presented.

3-2 Operating Voltage Levels

The electric power network is operated at several different voltage levels. Figure 3-1 is a diagram of a simple power system showing typical voltage levels from generation to utilization.

Generation at utility power plants is typically at voltage levels ranging from 14 to 24 kV for large three-phase synchronous generators. The source of mechanical power to drive the generators is primarily from hydraulic (water power) or steam turbines. Gas combustion turbines are also used to provide additional generation during peak load conditions.

The output voltage of the generator is stepped up to transmission levels in the generating plant substation. Transmission voltage levels typically range from 138 to 765 kV. The bulk transmission network is used to transmit power between utilities and from the generating plants to the major load centers.

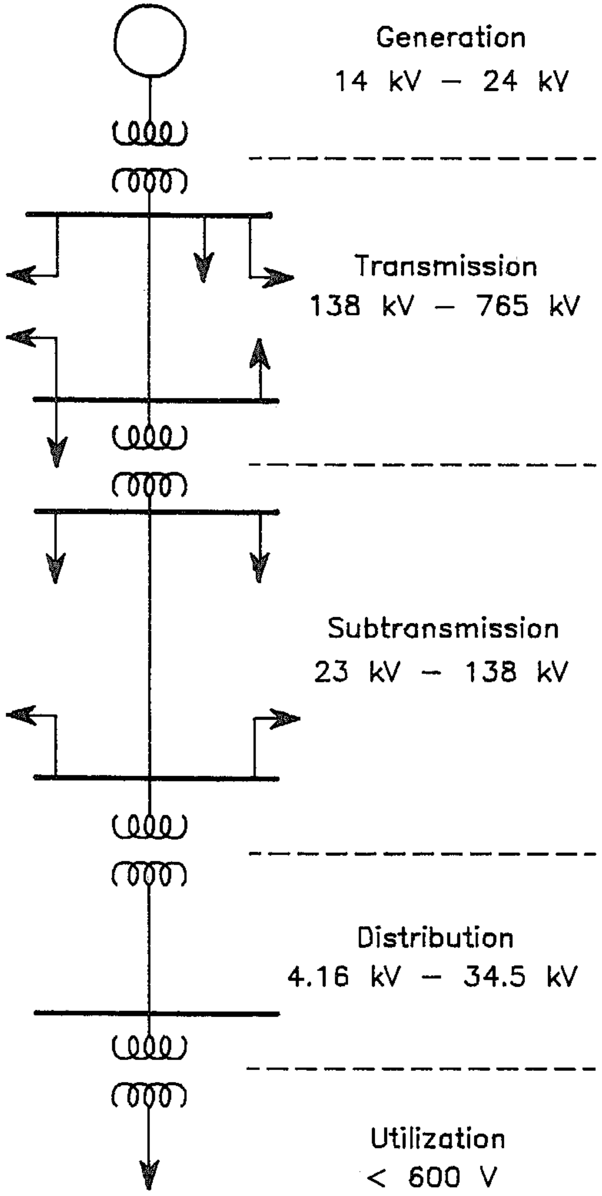


Figure 3-1 Operating voltage levels.

Table 3-1 Typical Power System Voltage Levels

Transmission	*Subtransmission*	*Distribution*	*Utilization*
765 kV	138 kV	34.5 kV 3Φ 4W	480 V 3Φ 4W
500 kV	115 kV	24.94 kV 3Φ 4W	208 V 3Φ 4W
345 kV	69 kV	22.86 kV 3Φ 4W	240 V 3Φ 4W
230 kV	23 kV	13.2 kV 3Φ 4W	600 V 3Φ 3W
		12.47 kV 3Φ 4W	480 V 3Φ 3W
		8.32 kV 3Φ 4W	240 V 3Φ 3W
		4.16 kV 3Φ 4W	120/240 V 1Φ 3W
		13.8 kV 3Φ 3W	
		4.16 kV 3Φ 3W	

The subtransmission network receives power from the bulk transmission network at various transmission substations. Typical voltage levels for the subtransmission network range from 23 to 138 kV. The subtransmission network is used to distribute power to the distribution substations throughout the system and to supply large industrial loads.

The distribution system is used to distribute power on a local level in urban and rural areas. Power is supplied to the distribution system at distribution substations. Typical voltage levels for distribution circuits are 4.16 to 34.5 kV. The most common distribution system voltage level is 12.47 kV line to line.

Utilization or secondary voltage is used to supply residential, commercial, and industrial systems. The utilization voltage for large commercial and industrial facilities may be at the medium voltage distribution levels previously discussed.

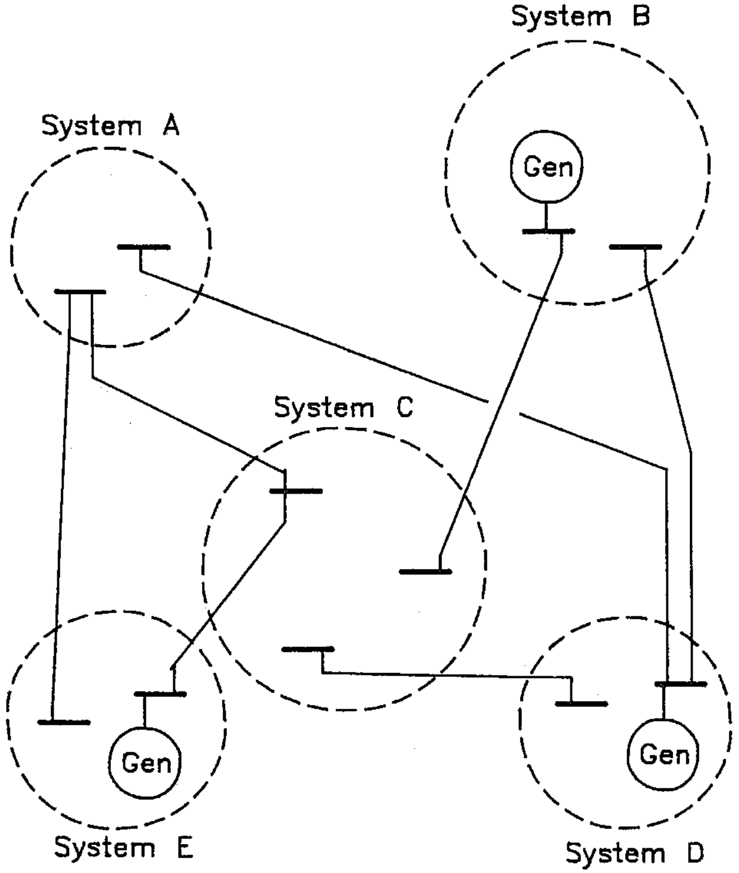
Some of the more common nominal voltage levels for electrical power systems are shown in Table 3-1. Generally, voltage levels exceeding 230 kV are classified as extra high voltage (EHV). Voltages between 100 and 230 kV are classified as high voltage (HV), and voltages between 1000 V and 100 kV are medium voltage (MV). Utilization voltages below 1000 V are generally classified as low-voltage (LV) systems.

3-3 Interconnected Systems

In the early days of the electric utility industry, many systems were operated as isolated systems. These systems were located primarily in the larger urban areas of the country. Generation was often at low voltage utilization or medium voltage distribution voltage levels. As these systems expanded, it became necessary to provide additional generation capacity to supply the additional load and to provide reliability in the event of an outage. Many of these isolated systems grew to include several generating plants and several miles of distribution circuits.

Eventually, power systems in neighboring areas were interconnected with one another for reasons of reliability and economics. For example, if the generation in one area was lost due to an outage, power could be transmitted from another system to supply the load. Also, as newer power generating plants were constructed, the cost of generation decreased. In some instances, it became more economical to purchase power from a neighboring system that used newer, more efficient generation than to generate within the system. Figure 3-2 shows an example of interconnected power systems.

The operation of interconnected utility systems is much more complicated than that of an isolated system. Some of the problems associated with transmitting large amounts of power over long distances include excessive line I^2R power losses, excessive voltage drop, and maintenance of synchronization between systems. Many of these problems were minimized by transmitting power at higher voltage levels. Also, as computer technology developed, control of large-scale interconnected systems became feasible. Economic generation dispatch, control of area power interchanges, and regulation of voltage levels on the bulk transmission system are controlled by an energy management system (EMS). The EMS uses real-time measurements of voltage, active and reactive power flows, generation, load, and current to determine system operating conditions. Discussion of these control functions is beyond the scope of this text.



3-4 Three-Line, One-Line, and Impedance Diagrams

The three-line diagram is often used to represent each phase of a three-phase system. A representive three-line diagram for a circuit exit of a subtransmission substation is shown in Fig. 3-3. Major equipment, relaying, and conductor size for each phase of the three-phase system are shown on the three-line diagram.

The three-line diagram becomes rather cluttered for large substations and systems. A shorthand version of the three-line diagram is referred to as the one-line diagram. Similar to the three-line diagram, the one-line diagram shows all major equipment and relaying. A one-line diagram for the substation circuit exit of Fig. 3-3 is shown in Fig. 3-4.

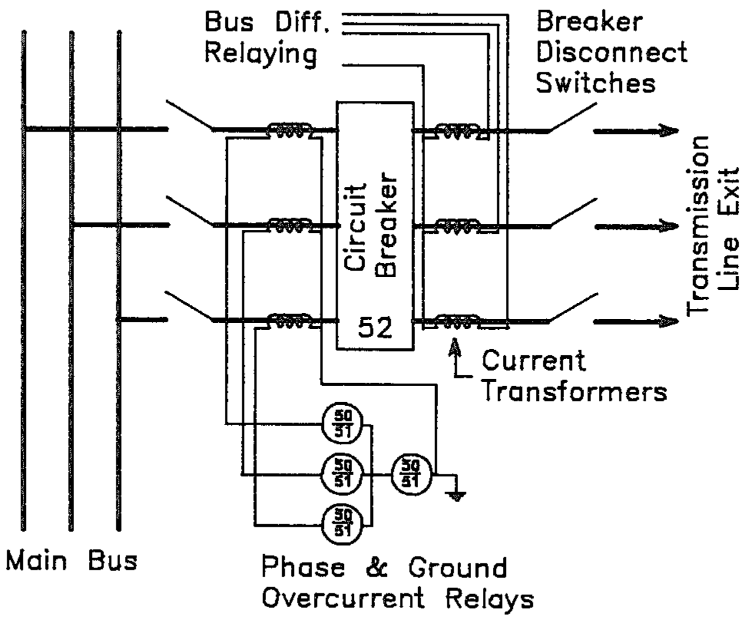
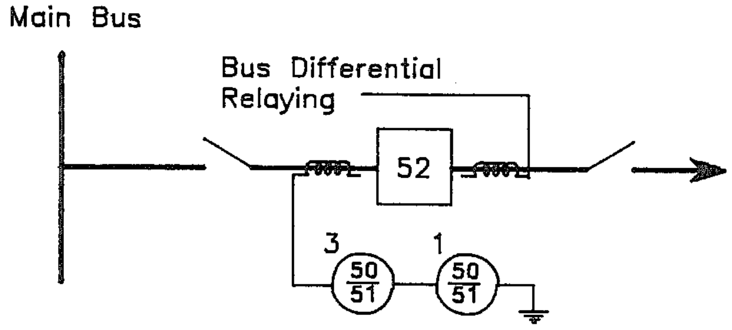


Figure 3-3 Three-line diagram.



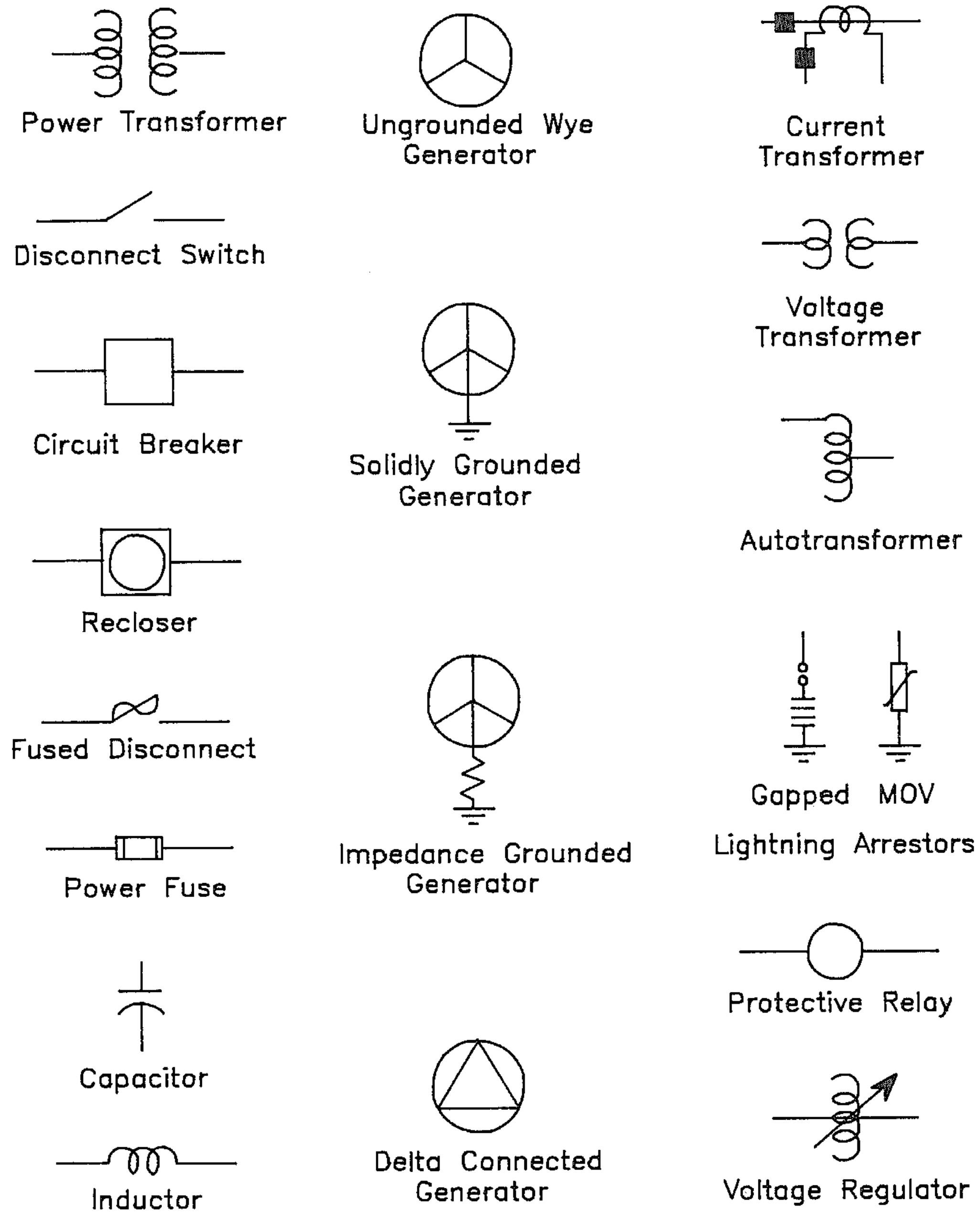


Figure 3-5 Common one-line diagram symbols.

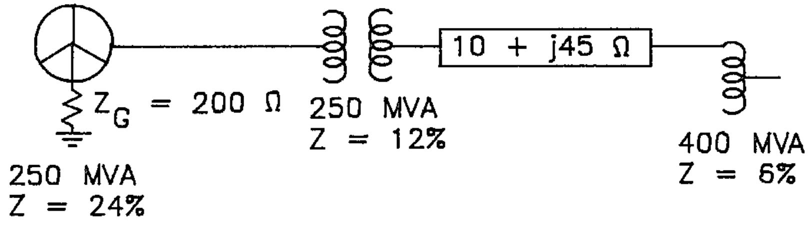


Figure 3-6 Impedance diagram.

The standard symbols used to represent various equipment will vary somewhat among different electric utility companies. Some of the standard symbols for one- and three-line diagrams are shown in Fig. 3-5.

The impedance diagram shown in Fig. 3-6 is used to record the impedance data of generators, lines, transformers, regulators, capacitors, cables, and the like. This impedance data are used for voltage-drop, short-circuit, load transfer, and circuit loading calculations. It is extremely important that these impedance data be kept up to date as system conditions are changed.

3-5 Generating Plant Layout

Generating plants represent the largest single portion of capital investment made by the electrical utility industry. Therefore, it is extremely important that provisions be made to ensure reliability and flexibility of operation to minimize outages and downtime. Although each generating plant has its own distinct electrical layout, a basic layout will be presented here. A one-line diagram for a typical generating plant is shown in Fig. 3-7.

In the majority of power plants, the generator windings are connected in a wye configuration. The neutral point of the wye-connected winding is usually connected to ground through an impedance. By grounding the neutral through an impedance, the short-circuit current for line to ground faults is minimized.

Typically, the stator of the generator is connected directly to the generator step-up transformer and auxiliary power transformers through isolated phase bus duct. Each phase of this bus duct consists of a single-phase conductor supported by insulators and surrounded by an enclosure. Since each phase is isolated from the other phases, the possibility of a short circuit involving two or more phases is minimized. The most probable short circuit that may occur is a line to ground fault between the bus conductor and the bus duct enclosure. Cooling air is typically forced through the enclosure to cool the bus conductor.

The main generator step-up transformer is either a single three-phase unit or three single-phase units connected in a three-phase configuration. The transformer is usually connected delta on the low-voltage side and solidly grounded wye on the high-voltage side. By connecting the low-voltage side of the generator step-up transformer in delta,

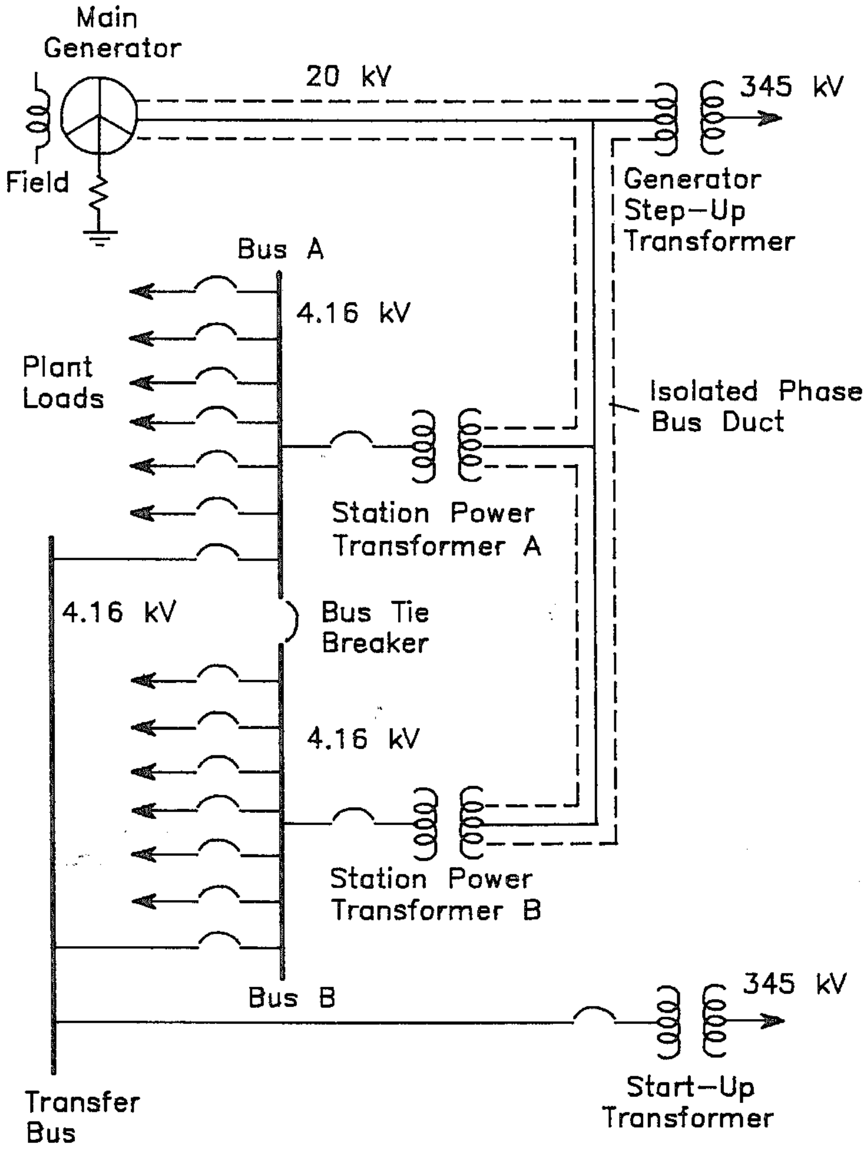


Figure 3-7 Typical generating plant one-line diagram.

the contribution of short-circuit current from the system in the event of a line to ground fault in the isolated phase bus duct will be zero. Also, the rated phase current of the low-voltage, delta-connected transformer winding will be less than that of a comparable wye-connected winding. (Recall that the phase current in a delta connection is equal to the line current divided by $\sqrt{3}$). Therefore, a smaller total cross-sectional area of coil conductor is required in the low-voltage delta connection as compared to the wye connection.

(However, the delta-connected winding will require $\sqrt{3}$ more turns as compared to a wye-connected winding of the same line to line voltage rating.)

The high-voltage winding is connected solidly grounded wye and connects to the high-voltage grounded wye transmission system through a set of power circuit breakers. The grounded wye-connected high-voltage winding is more economical to insulate than a delta-connected high-voltage winding having the same voltage rating. Thus, the delta grounded wye connection for the generator step-up transformer provides the most desirable electrical characteristics and may also be the most economical to construct.

The station power transformers are also connected directly to the stator terminals of the generator. These station power transformers may consist of a three-phase transformer, or three single-phase transformers connected in a three-phase bank. These transformers provide power to the auxiliary equipment, such as pumps, fans, and controls, required to operate the main generator. The windings of the station power transformers are usually connected delta on the high-voltage (generator) side and either delta or grounded wye on the low side. Typical low-voltage ratings are 4.16 and 13.8 kV. Notice in Fig. 3-7 that the low-voltage station power buses, *A* and *B*, are connected through transfer breakers to at least two different sources. This provides improved reliability in the event of a transformer failure. Note also that the station auxiliary power transformers are connected directly to the generator isolated phase bus duct.

The start-up, or cranking transformer as it is sometimes referred to, is used to provide power to the station auxiliary equipment during initial start-up of the main generator. The cranking transformer is usually grounded wye connected on the high- and low-voltage sides. The high-voltage side is connected to the transmission system, and the low-voltage side is connected to the station auxiliary buses.

During start-up, the high-voltage side of the main generator step-up transformer is disconnected from the transmission system. In addition, all station auxiliary power transformers are disconnected from the station auxiliary power buses. The generator is brought up to speed and synchronized with the system. Once synchronized, the generator breaker(s) on the high-voltage side of the generator step-up transformer are closed to connect the generator to the system. The station power auxiliary transformers are now connected to the station power buses, and the cranking transformer is disconnected. The active power output and terminal voltage of the generator are adjusted to the desired operating conditions.

3-6 Transmission System Layout

Bulk Transmission System

The bulk transmission system is used to transmit large amounts of power from the generating plants to major load centers and to facilitate interchange of power between utilities. Similarly to the generating plants, the bulk transmission system is designed for maximum reliability and flexibility of operation. Several transmission lines connect between transmission substations, generating plant locations, and neighboring utility systems. The system is designed such that a single line outage will not adversely affect overall system operation. A representive one-line diagram of a bulk power transmission system is shown in Fig. 3-8. Notice that generator *A* is connected to the 345-kV transmission system, while generator *B* is connected to the 138-kV portion of the system. Figure 3-9 shows a 345-kV transmission line used to transmit bulk power from remote generating plants to the system load centers. Note that there are two conductors per phase.

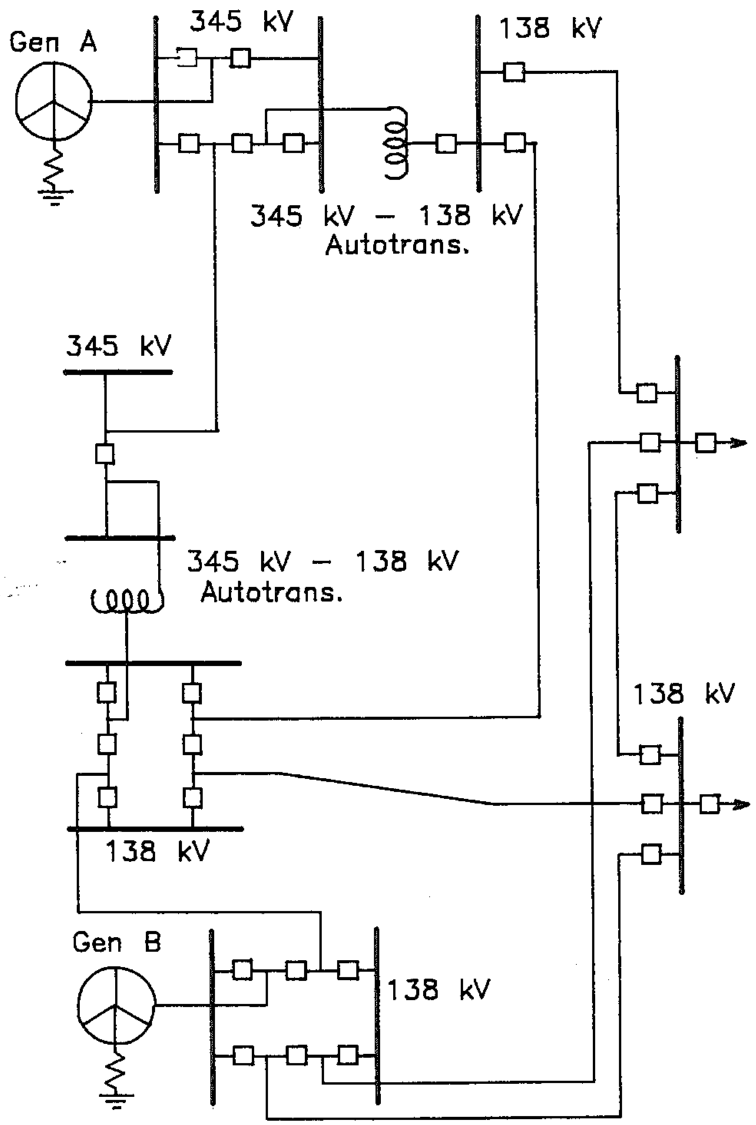


Figure 3-8 Bulk power transmission system.

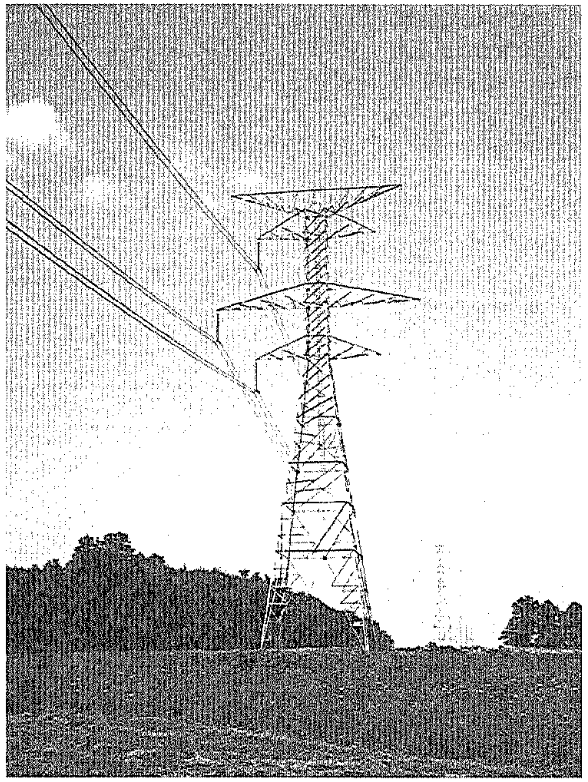


Figure 3-9 345-kV transmission line. (Photo Courtesy of Ohio Edison Company)

Subtransmission System

The subtransmission system may be designed in a network, loop, or radial configuration depending on the degree of reliability desired. The network configuration is the most reliable and most expensive to construct, while the simple radial system is the least expensive and least reliable. Many portions of the subtransmission system are designed in a loop configuration, but operated as a radial system. Figure 3-10 shows a 69-kV subtransmission line used for transmitting power from the subtransmission substations to the distribution substations.

Figure 3-11 shows the one-line diagram of a subtransmission line constructed in a loop configuration, with distribution substations located at various points along the line. The line in this figure is operating at a nominal voltage of 69 kV and is supplied from transmission substations *A* and *B*. At each distribution substation tap point, there is a set

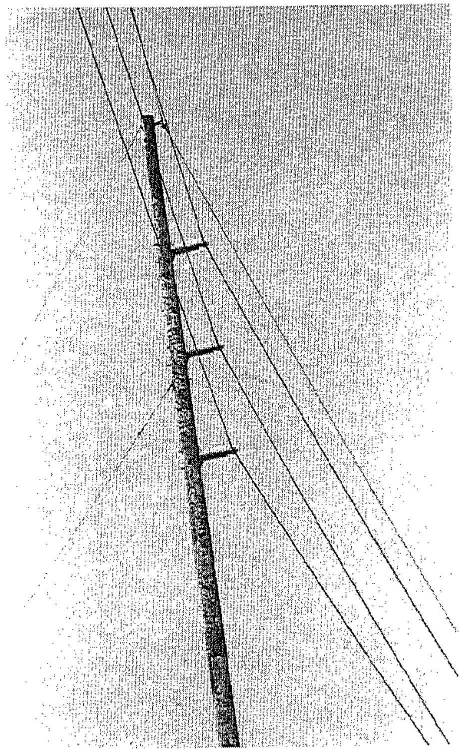


Figure 3-10 69-kV subtransmission line. (Photo Courtesy of Ohio Edison Company)

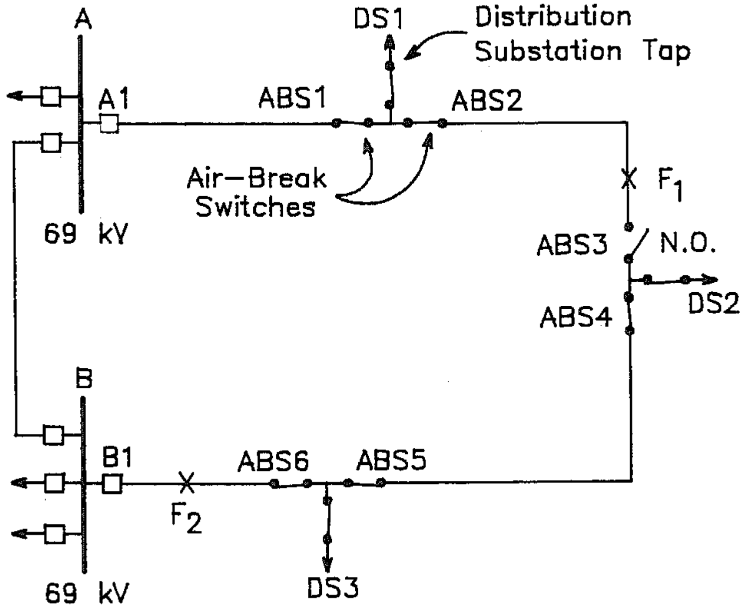


Figure 3-11 Subtransmission system one-line diagram.

of air-break switches to isolate the line sections and substation taps. Typically, these air-break switches are not designed to interrupt load or fault current. Their only purpose is to provide a means of isolating lines and equipment. Therefore, before attempting to operate any of these air-break switches, the circuit must be de-energized by tripping the respective circuit breaker or other load break device. A typical air-break switch installation is shown in Fig. 3-12.

Note that opening the line at two or more points would leave a section of line de-energized during normal operation. If a fault occurs on this de-energized section of line, no fault current will flow, and none of the breakers will trip. Therefore, the system operator will not be aware of the fault until the de-energized section of line is energized. Thus, the faulted section of line will not be available for service when it is needed. It is common practice to keep all lines and buswork energized to enable detection of faulted conditions.

In the subtransmission loop shown in Fig. 3-11, if a fault occurs at point F_1, only breaker *A*1 will trip since the line is open at *ABS*3. Distribution substation *DS*1 is now without a source of power. Air break switch *ABS*2 could be opened since the line is already de-energized by the tripping of breaker *A*1. Breaker *A*1 can now be reclosed to restore power to distribution substation *DS*1. The faulted section of line between *ABS*2 and *ABS*3 has now been isolated, and power is restored to all distribution substations. Repair of the faulted line section can now be performed at a convenient time.

For a fault at F_2, only breaker *B*1 will trip since the loop is open at *ABS*3. Distribution substations *DS*2 and *DS*3 will now be without power. This faulted section of line can be isolated by performing the following switching order:

1. Open *ABS*6
2. Trip breaker *A*1

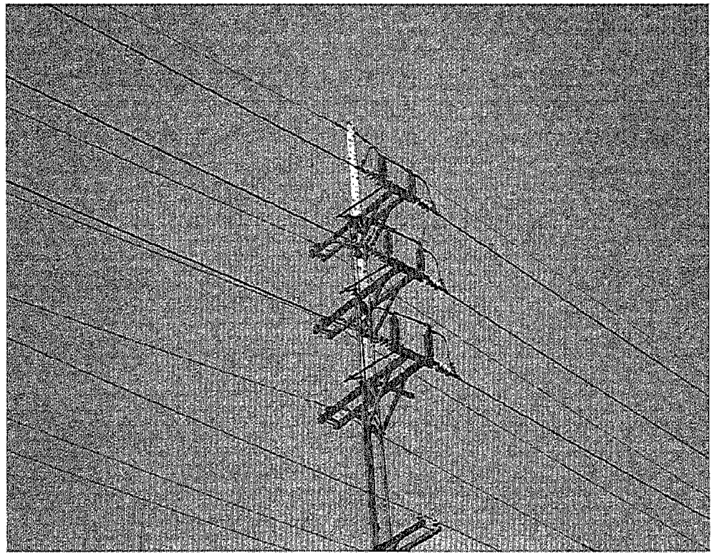


Figure 3-12 69-kV air-break switch installation. (Photo Courtesy of Ohio Edison

3. Close *ABS*3
4. Reclose breaker *A*1

Note that it is necessary to trip breaker *A*1 *before* closing *ABS*3, since the air-break switches must *not* be operated under load conditions. Under these operating conditions, all three distribution substations are supplied from substation *A* through breaker *A*1.

3-7 Substation Layout

Transmission and distribution substations are also designed for maximum reliability and flexibility of operation. The ability to switch equipment out of service for either scheduled or unscheduled outages while maintaining service is essential for reliable system operation. Several different substation bus layouts are used by electric utilities to accomplish reliable and flexible system operation. Some of these same layouts are also used in large commercial and industrial power systems. Figure 3-13 is an overall view of a large power substation supplying both transmission and subtransmission circuits.

Breaker and a Half

The breaker and a half scheme shown in Fig. 3-14 is used primarily in bulk transmission substations at voltage levels above 100 kV. In this substation bus layout, there are two main buses, with three breakers connecting the two buses as shown. The transmission lines terminate at a point electrically between any two of the breakers.

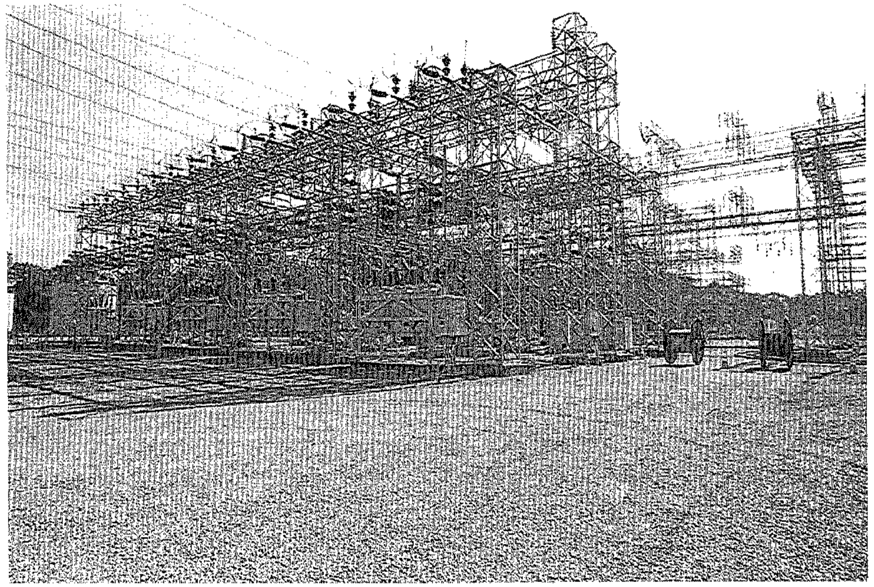


Figure 3-13 Overall view of transmission substation. (Photo Courtesy of Ohio Edison

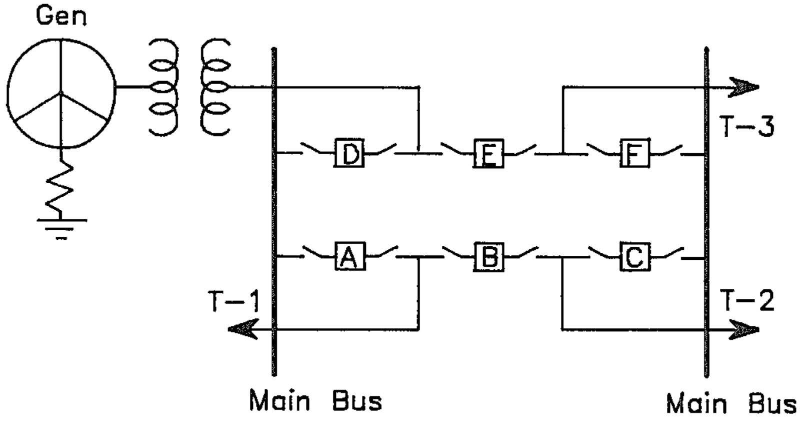


Figure 3-14 Breaker and a half scheme.

A high degree of reliability is achieved since any one breaker may be removed from service while keeping all transmission lines energized. For example, if breaker *A* fails or is removed from service for scheduled maintenance, transmission line *T*-1 will remain energized through breaker *B*. If breaker *B* is removed from service, line *T*-1 will be energized through breaker *A*, line *T*-2 will remain energized through breaker *C*, and so on. Note also that the generator is connected to the transmission substation in the same manner as the transmission lines. Again, this is for reasons of reliability. If either breaker *D* or *E* is removed from service, the generator will remain connected to the power grid. Synchronization of the generator to the power grid is accomplished through breakers *D* or *E*, or both.

It is common practice to install disconnect switches on both sides of each breaker in the substation as shown. As in the case of the transmission line air-break switches, these disconnect switches are not designed for load breaking duty. The breaker must first be tripped out of service; then the disconnects on each side of the breaker are opened to isolate the breaker. Once the breaker is isolated, *each* pole of the breaker is grounded on *both sides* of the breaker for safety purposes. The desired maintenance can now be performed on the breaker.

The name ''breaker and a half'' probably comes from the fact that there are three breakers for every two transmission lines, or one and a half breakers per line. The middle breaker is actually shared by the two lines. For substations with more than four transmission line terminations, additional rows or *bays* of breakers are installed, with the lines terminated similarly to Fig. 3-14.

Ring Bus

In the ring bus scheme shown in Fig. 3-15, the number of breakers is equal to the number of lines terminating in the station. The ring bus is a more economical design than the

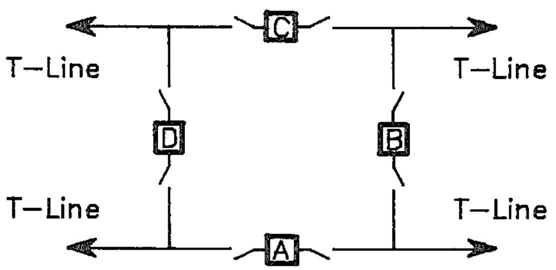


Figure 3-15 Ring bus.

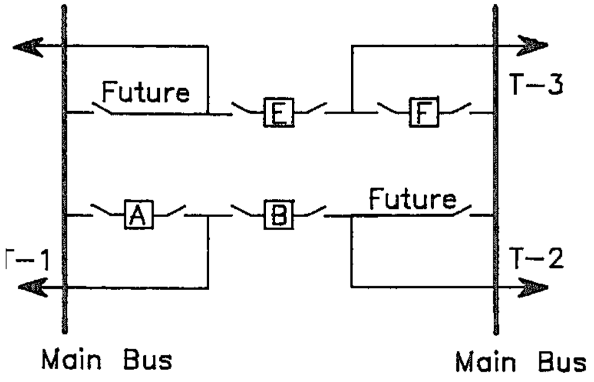


Figure 3-16 Future breaker and a half operating as a ring bus.

name ''ring bus'' comes from the fact that the breakers and buswork form a ring electrically. The transmission lines terminate at the buswork between the breakers as shown.

In some instances, a substation may be designed for a breaker and a half scheme and operated as a ring bus by leaving out two of the breakers, as shown in Fig. 3-16. When system conditions require additional reliability, the other two breakers can be added.

Transfer Bus

In the transfer bus arrangement, each transmission line is connected to the main bus through a breaker, as shown in Fig. 3-17. In addition, the line side of each line breaker is connected to the transfer bus by means of a disconnect switch. The transfer bus is connected to the main bus via the transfer breaker. The transfer bus and breaker thus serve as the alternative supply for any one of the transmission lines. Under normal operation, the transfer bus and main bus are energized.

If it is required to remove one of the line breakers from service, the following switching order may be performed:

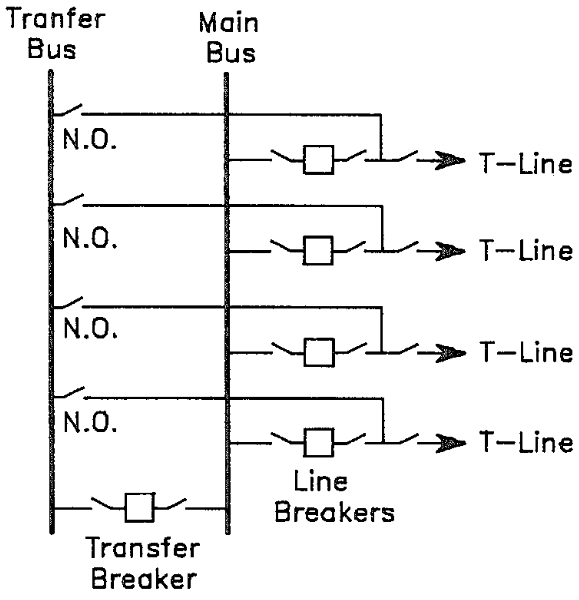


Figure 3-17 Transfer bus scheme.

1. Trip transfer breaker.
2. Close transfer bus switch on affected line.
3. Reclose transfer bus breaker.
4. Trip line breaker on affected line.
5. Open line breaker disconnect switches to isolate breaker.

The actual switching order to be performed depends on the substation layout and utility operating procedures. This switching order is only one possibility.

Radial

The radial scheme shown in Fig. 3-18 is the most economical layout in terms of equipment requirements. Note that there is only one breaker for each line termination, with no provision for supplying a line from another bus within the substation. Thus, the radial configuration offers the lowest operating flexibility. Most subtransmission substations have the radial bus configuration.

Distribution Substation Layout

An overall view of a distribution substation with circuit exits at 4.16 and 12.47 kV is shown in Fig. 3-19. The bus configuration of a typical distribution substation is shown

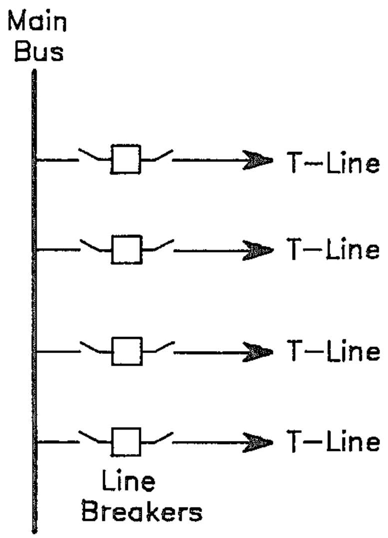


Figure 3-18 Radial bus scheme.

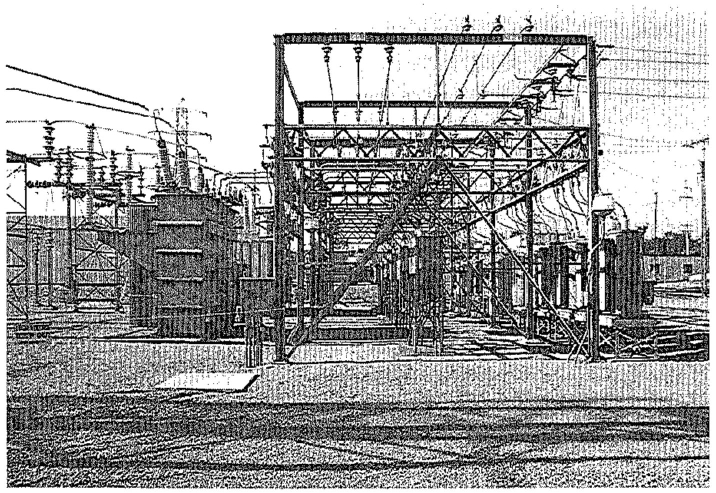


Figure 3-19 Overall view of distribution substation. (Photo Courtesy of Ohio Edison Company)

in Fig. 3-20. Also included is a portion of the subtransmission system feeding the distribution substation, indicating the location of the high-voltage air-break switches. These air-break switches may be mounted on transmission line structures outside the substation or located on the substation structure itself. The high-voltage substation disconnect switch is usually located on the substation structure. The substation disconnect provides a means to de-energize and isolate the entire substation from the system.

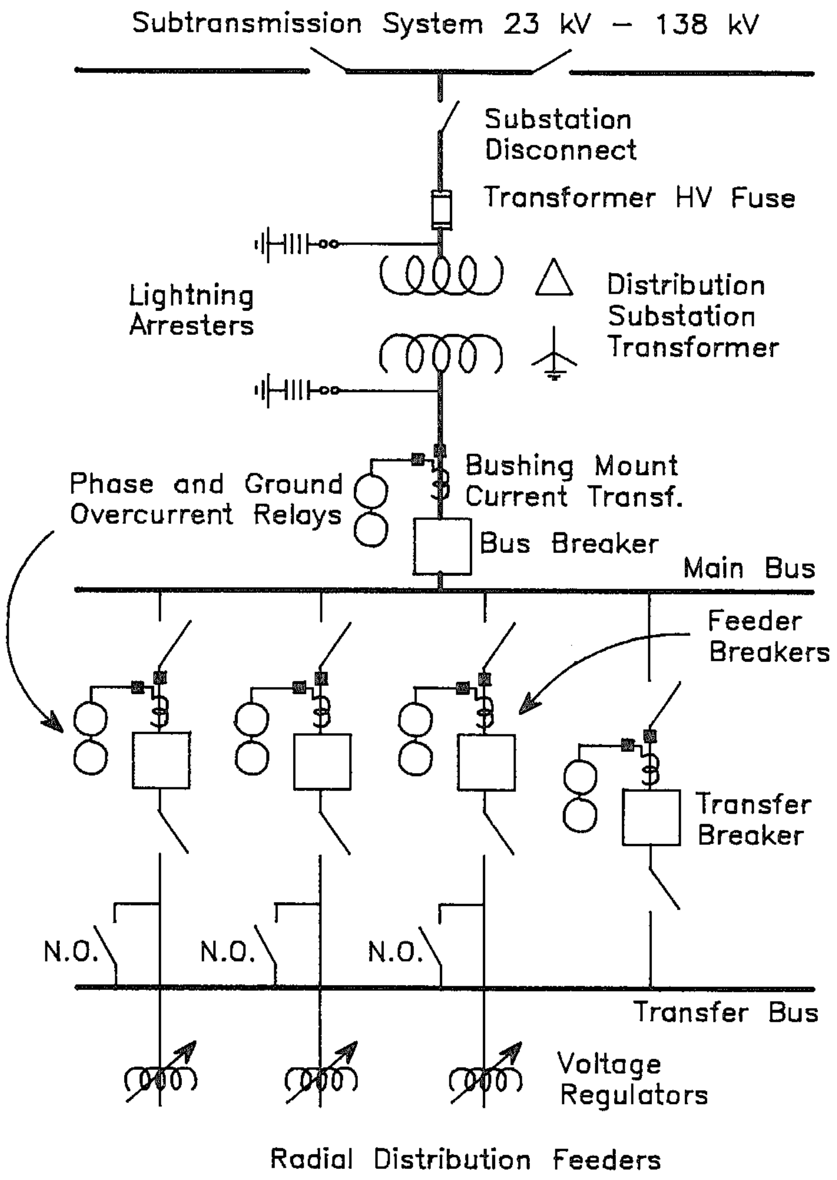


Figure 3-20 Distribution substation one-line diagram.

The distribution substation transformer steps down the voltage from subtransmission levels to distribution levels. The transformer may be protected by fuses or circuit breakers on the high-voltage side. Lightning arresters are applied on both the high- and low-voltage sides of the transformer to protect against overvoltages. The transformer windings are usually connected in delta on the high-voltage side and in solidly grounded wye on the low-voltage side. Taps are generally provided on the high-voltage side to allow adjustment of the bus voltage on the low side. These taps may be fixed or adjusted by an automatic load tap changing mechanism. The more common application is to use fixed taps at nominal, ±2.5%, and ±5% levels.

The low-voltage side of the transformer may be connected to the substation bus directly or through a circuit breaker, as shown in Fig. 3-20. Distribution feeders are tapped from the low-voltage bus and protected by reclosers or circuit breakers. In some designs, a bypass fuse is used to allow for the removal of the recloser or breaker. In other designs, a transfer bus scheme may be used to allow bypassing the recloser or breaker.

Voltage regulators are used to regulate the voltage on the distribution circuit. These regulators are typically tapped autotransformers that provide a certain amount of increase or decrease in the voltage in discrete steps. In some utilities, the entire substation bus is regulated, rather than the individual feeders, as shown in Fig. 3-20. The subject of voltage regulation will be discussed in more detail in Chapter 8.

3-8 Distribution System Layout

The distribution system consists of the overhead lines, underground cables, and distribution transformers used to distribute power from the distribution substations to the user. The distribution system typically operates as a multigrounded neutral system, with the neutral solidly grounded at the distribution substation transformer low-voltage side. In addition, the neutral is grounded at each major equipment location and at regular intervals along the line. The vast majority of distribution feeders are operated in a radial configuration, with provisions for transferring load between substations if required.

A representive distribution circuit one-line diagram is shown in Fig. 3-21. The distribution feeders originate from the distribution substation as a three-phase, four-wire system. The hash marks indicate the number of phase conductors. The phase designations, along with the number, size, and type of phase conductor or cable, are also indicated on the one line. The size of the neutral conductor may also be indicated. One-, two-, or three-phase conductors and the neutral may be tapped from the main feeder at various points to supply loads. At locations where there is a change in conductor size, or number of phases, an × is placed. The sizes and locations of all distribution transformers, capacitors, fuses, reclosers, and switches are indicated on the one-line diagram. Note also that in some configurations it is possible to provide a tie to another distribution feeder to allow for switching between circuits if required.

3-9 Secondary System Layout

The secondary system is used to distribute power at utilization voltage from the distribution transformers to the end users. The radial, network, and spot network secondary systems are the most common types of secondary systems in use.

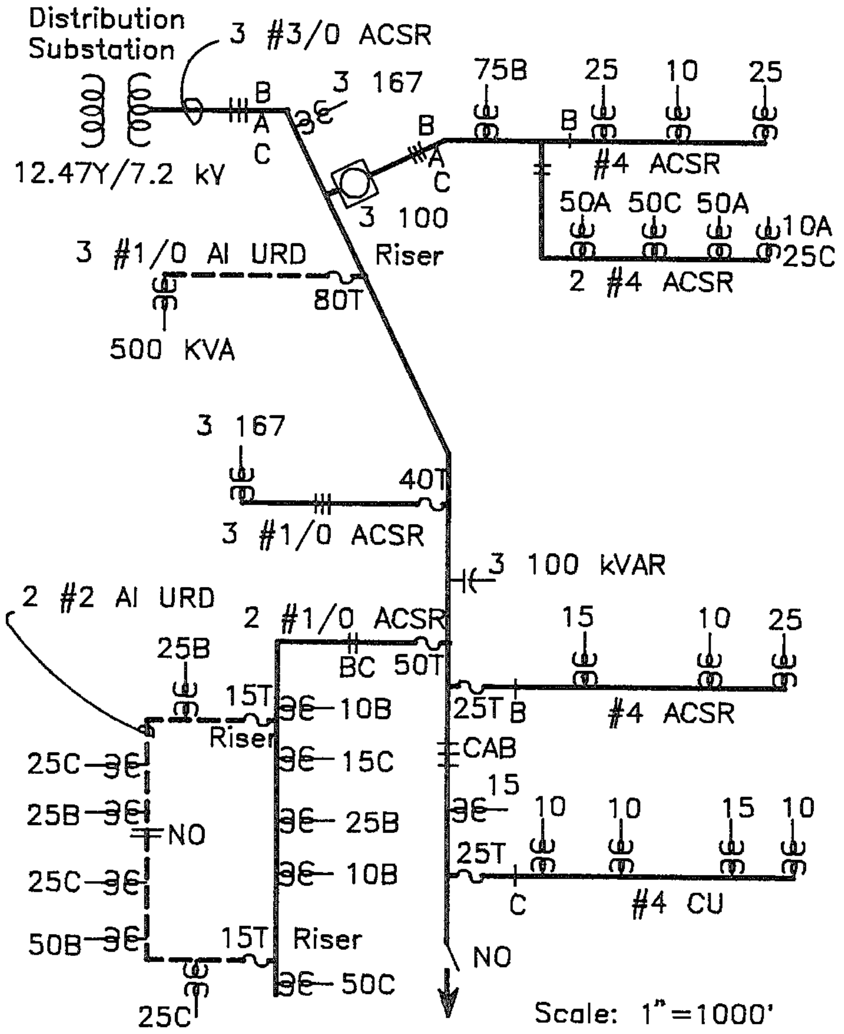


Figure 3-21 Distribution circuit one-line diagram.

Radial Secondary System

The most common form of secondary distribution system is the radial system. A representive secondary layout for a residential development is shown in Fig. 3-22. Low-voltage secondaries and service drops are made to each user in a radial manner, with no provision for alternative sources. Radial secondary systems are installed either overhead or underground.

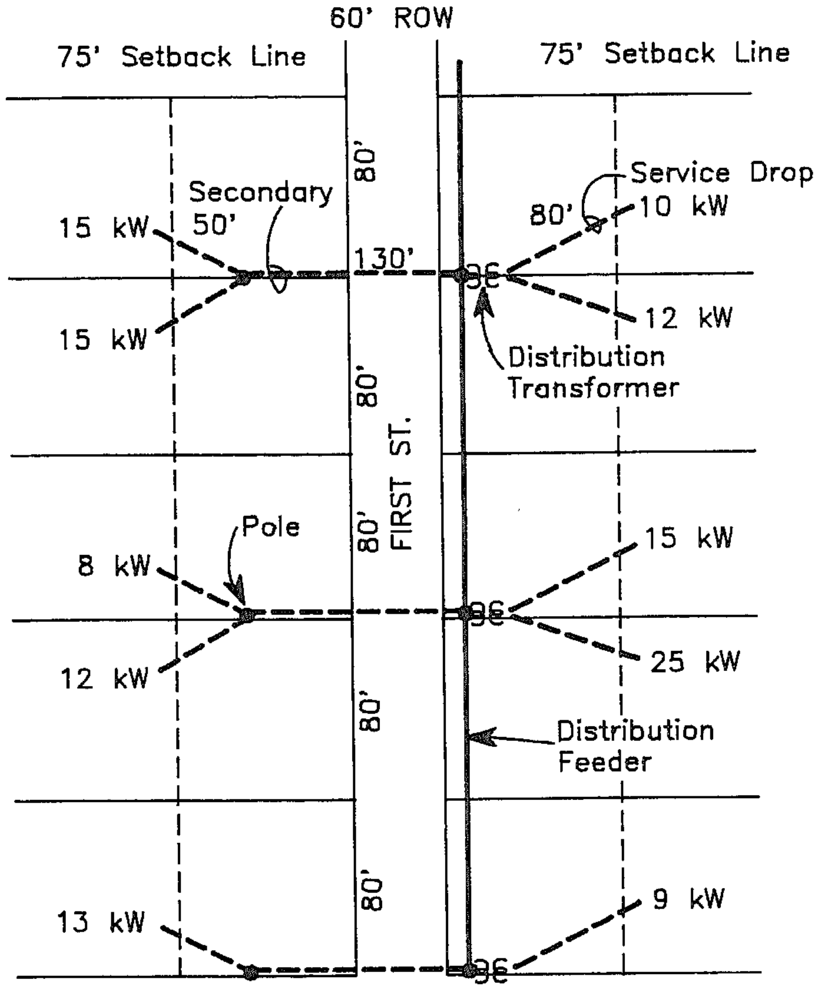
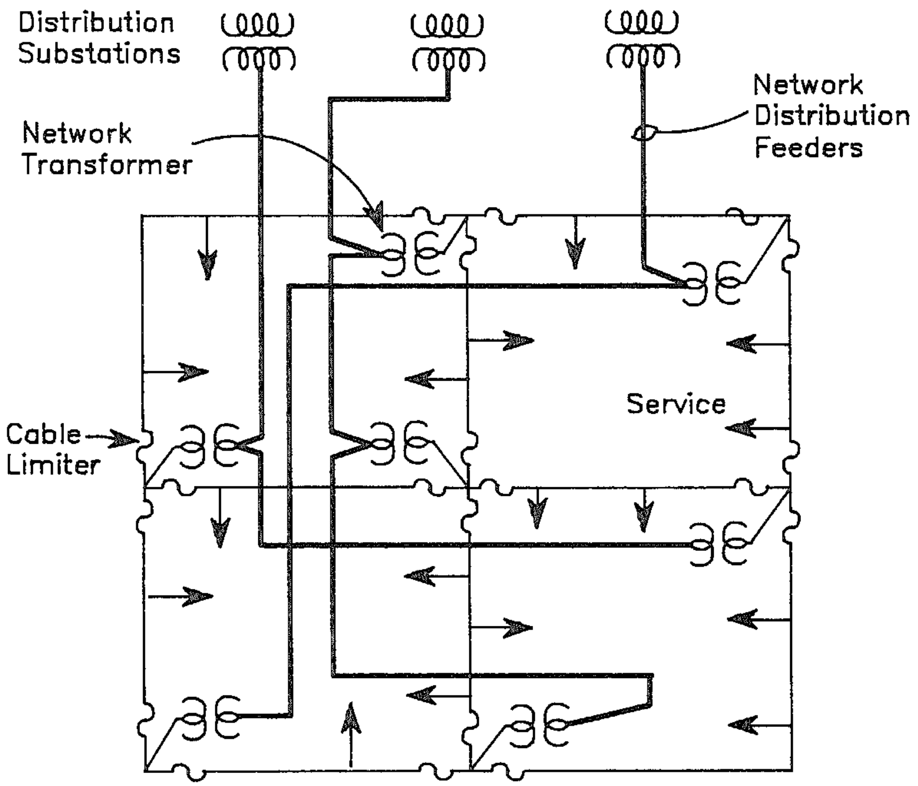


Figure 3-22 Overhead secondary distribution system one-line diagram.

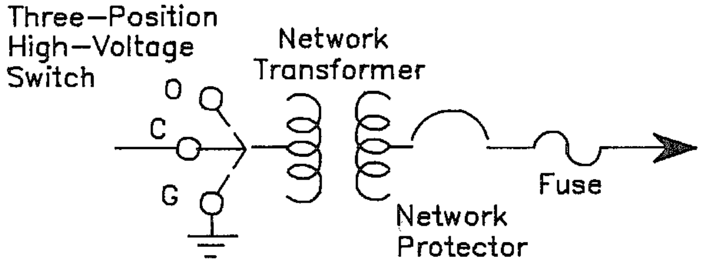
Secondary Network System

The secondary network system is used primarily in large urban areas to supply commercial loads. A one-line diagram of a typical network system is shown in Fig. 3-23a. A distinguishing feature of the network system is that the secondary cables are connected in the form of a grid or network. A special type of fuse referred to as a *cable limiter,* is used to protect and isolate the secondary cables in the event of a fault. These cable limiters are installed in each conductor at major junction points in the secondary network system. The cable limiter will isolate only the faulted cable, thereby allowing service to be maintained. Individual services are tapped from the network at various points to supply loads in the area. Typical nominal voltage levels for network systems are 208Y/120 V and 480Y/277 V, three phase, four wire.

The secondary network is supplied at various points by means of network transformers. Figure 3-23b shows a one-line diagram of a typical network transformer in-



(a) One–Line Diagram.



(b) Network Transformer.

Figure 3-23 Secondary network system.

stallation. The functions of the various network transformer components will be discussed in Chapter 6. These network transformers receive power from the primary distribution feeders at voltages between 4.16 and 34.5 kV. These feeders are usually dedicated network feeders that supply power only to the network transformers from one or more distribution substations. Since the network is typically supplied from several distribution substations, the loss of any one distribution substation, feeder, or network transformer will not cause an outage on the network.

Spot Network System

Spot network systems are similar in nature to the network systems previously described, but supply isolated load centers in a particular location. For example, individual spot networks may be designed to supply several floors of a high-rise building. In the spot network system, several network transformer secondaries are connected to the spot network bus. The network transformer primaries are connected to various feeders in a manner similar to the secondary network system previously discussed. Individual loads or feeders are tapped off this network bus. Figure 3-24 shows a one-line diagram of a typical spot network installation supplying several floors of a high-rise building.

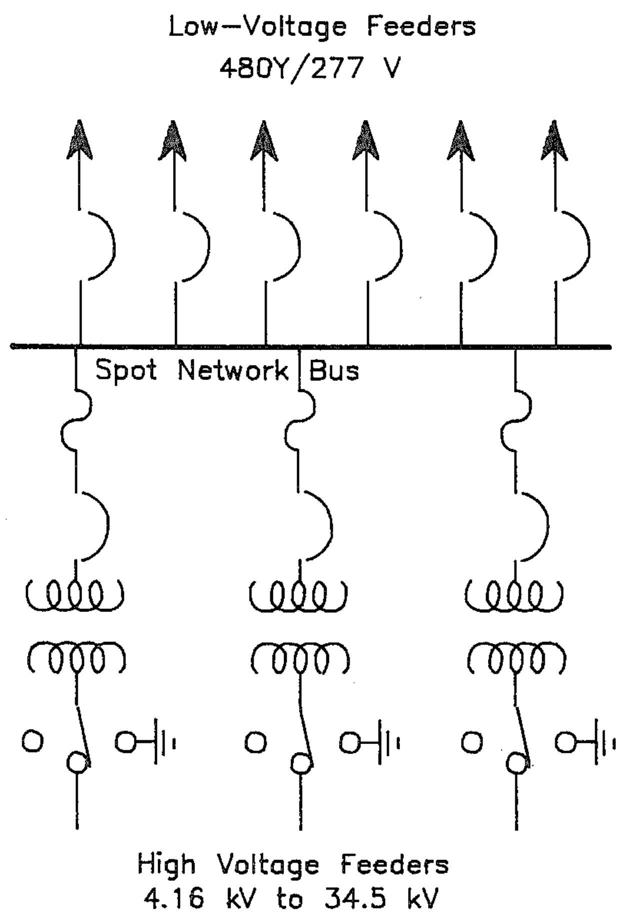


Figure 3-24 Spot network system.