1

ELECTRIC POWER SYSTEMS

The purpose of the electric power system is to generate, transmit, and distribute electrical energy. Usually, a three-phase alternating current (ac) system is used for generation and transmission of the electric power. The frequency of the voltage and current is 60 Hz in the United States and some Asian countries, and is 50 Hz in Europe, Australia, and parts of Asia. Sometimes, exceptions are the rule, as in the case of Japan for which the western portion of the country is served by 60 Hz, whereas the eastern side operates at 50 Hz.

In the 1880s, during the development of electricity distribution, the pioneers' choice as to whether to use direct current (dc) or ac was contested. In particular, Thomas Edison favored dc, whereas both George Westinghouse and Nikola Tesla supported ac. AC transmission won this so-called War of the Currents due to the ability to convert ac voltages from higher to lower voltages using transformers and vice versa. This increased ac voltage permitted electric energy transport over longer distances with less power line losses than with dc.

The ac electrical system development started in the end of the 19th century, when the system frequency varied between 16.66 and 133 Hz. A large German company introduced 50 Hz frequency around 1891, after flickering was observed in systems

Electrical Energy Conversion and Transport: An Interactive Computer-Based Approach, Second Edition. George G. Karady and Keith E. Holbert.

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Figure 1.1. Overview of the electric power system.

operating at 40 Hz. In 1890, the leading U.S. electric company, Westinghouse Electric, introduced the 60 Hz frequency to avoid arc light flickering at lower frequencies.

The major components of the power system are:

- · power plants, which produce electric energy,
- transmission and distribution lines, which transport the electric energy,
- substations with switchgear, which transform voltages, provide protection, and form node points, and
- loads, which consume the energy.

Figure 1.1 shows the major components of the electric power system.

This chapter describes the construction of the electric transmission and distribution system; discusses the substation equipment, including circuit breakers (CBs), disconnect switches, and protection; and describes the low voltage distribution system, including residential electric connections.

1.1. ELECTRIC NETWORKS

Power plants convert the chemical energy in coal, oil, or natural gas, or the potential energy of water, or nuclear energy into electric energy. In fossil nuclear power plants, the thermal energy is converted to high-pressure, high-temperature steam that drives a turbine which is mechanically connected to an electric generator. In a hydroelectric plant, the water falling to a lower elevation drives the turbine-generator set. The



Figure 1.2. High- and extra-high-voltage transmission system in Arizona (power generation sites are shown in bold letters). (Data are from Western Systems Coordinating Council, 1999).

generator produces electric energy in the form of voltage and current. The generator voltage is around 15–25 kV, which is insufficient for long-distance transmission of the energy. To permit long-distance energy transportation, the voltage is increased and, simultaneously, the current is reduced by a transformer at the generation station. In Figure 1.1, the voltage is raised to 500 kV, and an extra-high-voltage (EHV) line carries the energy to a faraway substation, which is usually located in the outskirts of a large town or in the center of several large loads. For example, in Arizona, a 500 kV transmission line connects the Palo Verde Nuclear Generating Station to the Kyrene and Westwing substations, which supply a large part of Phoenix (see Fig. 1.2).

The electric power network is divided into separate transmission and distribution systems based on the voltage level. The system voltage is described by the

Name or Category	Nominal Voltage (kV)
Subtransmission	34.5
	46
	69
High voltage	115
	138
	161
	230
EHV	345
	400 (Europe)
	500
	765
Ultra-high voltage	1000 (China)

TABLE 1.1. Standard System Voltages (ANSI C84.1-1995^a and C92.2-1987^b)

^aANSI C84.1-1995, Voltage ratings for electric power systems and equipment (60 Hz).

^bANSI C92.2-1987, Alternating-current electrical systems and equipment operating at voltages above 230 kV nominal—preferred voltage ratings.

root-mean-square (rms) value of the *line-to-line* voltage, which is the voltage between phase conductors. Table 1.1 lists the standard transmission line and the subtransmission voltages. The line voltage of the transmission systems in the United States is between 115 and 765 kV. The ultra-high-voltage lines are generally not in commercial use; although in 2011 China started the operation of a 392 miles (630 km) long 1000 kV ultra-high-voltage ac line with a maximum capacity of 3000 MVA. The 345–765 kV transmission lines are the EHV lines, with a maximum length of 400–500 miles. The 115–230 kV lines are the high-voltage lines with a maximum length of 100–200 miles. The high-voltage lines are terminated at substations, which form the node points on the network. The substations supply the loads through transformers and switchgear. The transformer changes the voltage and current. The *switchgear* protects the system. The most important part of the switchgear is the *circuit breaker*, which automatically switches off (opens) the line in the event of a fault. Distribution line lengths are around 5–30 miles (8–48 km) with voltages at or below 46 kV.

1.1.1. Transmission Systems

The *transmission system* transfers three-phase power from the electric generating stations to the load centers. As an example, Figure 1.2 sketches a typical electrical network that supplies the metropolitan areas in Arizona and interconnects to the power systems of neighboring states. In this system 500, 345, 230, and 115 kV lines connect the loads and power plants. Note that the system in Figure 1.2 is a loop network, where at least two lines supply each load and the generating stations are connected to the network with three, or even four, lines. This arrangement assures that the failure of one line does not produce an outage. The electric system in the United States must withstand at least a single contingency, which means that loads and generators at a specific node are connected by at least two independent power system paths (e.g., power lines).

In addition, the map shows that 500, 345, and 230 kV lines interconnect the Arizona (AZ) system with California, Nevada, Utah, and New Mexico. These interconnections provide instantaneous assistance in cases of lost generation and line outages in the AZ system. Interconnection also permits the export or import of energy depending on the need of the area.

In open areas, overhead transmission lines are used. Typical examples are the interconnection between towns or a line running along a road within a city. In large, congested cities, underground cables are frequently used for electric energy transmission. An underground system has significantly higher costs but is environmentally and aesthetically preferable. Typically, the cost per mile of the overhead transmission lines is 6–10 times less than the underground cables.

At an EHV substation, transformers reduce the voltage to 230 or 345 kV. In Figure 1.1, a 230 kV high-voltage transmission line transports the energy to a high-voltage substation, typically located on the outskirts of the town. The voltage is further reduced at the high-voltage substation. Typically, 69 kV subtransmission lines connect the high-voltage substation to local distribution stations, which are located in the town. The subtransmission lines are built along larger streets.

In addition to the ac transmission system, high-voltage dc (HVDC) lines are used for long-distance, large energy transmission. Figure 1.3 depicts the main components of an HVDC system. The HVDC link contains two converters interconnected by a dc transmission line. The converters are electronic devices able to operate as a rectifier or as an inverter. Figure 1.3 shows that both converters are divided into two units connected in series. The middle point of the series-connected units is grounded. If the power is transferred from Converter 1 to Converter 2, then Converter 1 functions as a rectifier and Converter 2 acts as an inverter. The rectifier mode converts ac voltage to dc, and the inverter mode changes the dc voltage to ac. The dc transmission line typically has only two conductors, a positive (+) conductor and a negative (–) conductor.

HVDC is used to transport large amounts of energy over a long distance; typically, a dc line is not economical for less than around 300 miles (~500 km). A representative



Figure 1.3. Main components of a high-voltage dc (HVDC) transmission system.

example for HVDC transmission is the Pacific DC Intertie, which is an 846 miles (1362 km) long HVDC transmission line between the Celilo Converter Station at The Dalles, Oregon and the Sylmar Converter Station north of Los Angeles, California. The line has two conductors with a maximum operating voltage of ± 500 kV between the conductors and the ground; the maximum capacity of the Intertie is 3100 MW.

The large capacitance of the ac cables limits the power transfer through the cable, because the cable must carry both the load and the capacitive current. Using dc eliminates the capacitive current, which justified building HVDC underwater cable systems all over the world. One of the frequently discussed systems is the HVDC cable interconnection between the United Kingdom (UK) and France. This system is capable of transporting 2000 MW through a 45-km long HVDC underwater cable. Another advantage of the HVDC system is the elimination of the inductive voltage drop.

1.1.2. Distribution Systems

The *distribution system* uses both three-phase and single-phase networks. The larger industrial loads require a three-phase supply. A subtransmission line or a dedicated distribution line directly supplies large industrial plants and factories. A single-phase system delivers power to ordinary residences.

The voltage is reduced at the distribution substation, which supplies several distribution lines that deliver the energy along streets. The distribution system voltage is less than or equal to 46 kV. The most popular distribution voltage in the United States is the 15 kV class, but the actual voltage varies. Typical examples for the 15 kV class are 12.47 and 13.8 kV. As an example, in Figure 1.1, a 12 kV distribution line is connected to a 12 kV cable, which supplies commercial or industrial customers. The graphic also illustrates that 12 kV cables supply the downtown area in a large city.

A 12 kV cable can also supply the residential areas through *step-down transformers*, as shown in Figure 1.1. Each distribution line supplies several step-down transformers distributed along the line. The distribution transformer, frequently mounted on a pole or placed in the yard of a house, reduces the voltage to 240/120 V. Short-length low-voltage lines power the homes, shopping centers, and other local loads. One distribution transformer can serve six to eight residential customers.

1.2. TRADITIONAL TRANSMISSION SYSTEMS

The North American electric power system is presently divided into four isolated systems referred to as interconnections. The interconnections, as indicated in Figure 1.4, are:

- 1. the Eastern Interconnection,
- 2. the Electric Reliability Council of Texas (ERCOT) Interconnection,
- 3. the Western Interconnection, and
- 4. the Québec Interconnection.



Figure 1.4. North American Electric Reliability Corporation (NERC) interconnections. FRCC, Florida Reliability Coordinating Council; MRO, Midwest Reliability Organization; NPCC, Northeast Power Coordinating Council; RFC, Reliability First Corporation; SERC, SERC Reliability Corporation; SPP, Southwest Power Pool, RE; TRE, Texas Reliability Entity (TRE). This image from the North American Electric Reliability Corporation's website is the property of the North American Electric Reliability Corporation and is available at http://www.nerc.com/page. php?cid=1%7C9%7C119. This content may not be reproduced in whole or any part without the prior express written permission of the North American Electric Reliability Corporation.

The four systems are connected through regulated back-to-back HVDC links, HVDC transmission lines, and regulated ac tie lines. A back-to-back HVDC link is an HVDC system without a transmission line, that is, it contains two directly interconnected converters. High-power electronic devices can regulate the power flow through the ac line. In the last two decades, the industry developed the flexible ac transmission system (FACTS), which is able to electronically control the operation of a high-voltage ac line. Chapter 11 discusses both HVDC and FACTS systems.

The regulated connections permit energy transfer in normal operation and in case of an emergency. They block system oscillations and cascading outages. As examples, ERCOT in Texas uses back-to-back HVDC links, and the Western Electricity Coordinating Council (WECC) connects to the Eastern Interconnection through powerful HVDC transmission ties.



Figure 1.5. IEEE 118 bus power flow test case network.

1.2.1. Substation Components

The connection diagrams for actual power networks are confidential material because of security concerns. Figure 1.5 presents the Institute of Electrical and Electronics Engineers (IEEE) published 118 bus power flow test case network, which is the oneline diagram of a typical three-phase system illustrating the nature of an actual power network. The diagram shows a loop network that should withstand at least a single contingency, but in most cases will withstand multiple contingencies. This implies that at least two transmission lines supply each bus.

Figure 1.6 details a portion of the system, where each transmission line is connected to a substation bus, which is a node point of the system. There are simple load buses, like the Pokagon bus, which is supplied by only two lines (i.e., meets singlecontingency requirement). Other buses have both load and generation like Twin Branch with seven connecting lines—it may withstand six outages. A third type of bus has load, generation, and parallel connected capacitor, or synchronous condenser, for example, New Carlisle. The capacitor is a switched unit, which is used at high load to produce reactive power and reduce voltage drop. Similarly, switched inductive load is connected in parallel to selected buses to reduce overvoltages in case of light loading. A *synchronous condenser* is a rotating device, like a generator, which produces or absorbs reactive power (vars). It can be permanently connected to the system and regulates voltage by producing or absorbing vars. A synchronous condenser can be used instead of a capacitor. At the Olive substation in Figure 1.6, a regulating autotransformer



Figure 1.6. Segment of the IEEE 118 bus power flow test case network.

interconnects the substation with the lower portion of the network. This transformer regulates the voltage within a $\pm 10\%$ range. The transformer neutral point may be grounded though a reactance to reduce the ground fault-produced short circuit current. Other components not shown include:

- switched or electronically controlled series capacitors that are inserted in selected transmission lines to compensate for the line inductance and reduce voltage drop, and
- CBs, which are protecting the system and switch off the line in case of short circuit.

1.2.2. Substations and Equipment

Substations form the node points of the electric system. Figure 1.7 pictures a typical distribution substation. The major role of substations is to distribute the electric energy and provide protection against faults on the lines and other equipment. Figure 1.1 reveals three types of substations that are used:

- 1. EHV substations (500/230 kV);
- 2. high voltage substations (230/69 kV); and
- 3. distribution substations (69/12 kV).



Figure 1.7. Aerial view of a three-bay distribution substation (courtesy of Salt River Project).

Although the circuit diagrams of these substations are different, the general circuit concept and major components are the same. Figure 1.8 presents a conceptual diagram for an EHV substation. That circuit is frequently called the "breaker-and-a-half bus scheme." The rationale behind the name is that two lines have three CBs.

The primary substation equipment is as follows:

The CB is a large switch that interrupts load and fault currents. The fault current automatically triggers the CB, but the CB can also be operated manually. A CB has a fixed contact and a moving contact placed in a housing that is filled with gas or oil. Sulfur hexafluoride (SF₆) gas is the most common. Figure 1.9 illustrates a simplified contact arrangement for a typical breaker. In the closed position, the moving contact is inside the tubular fixed contact. Strong spring loading assures low contact resistance in the closed position. The switch is operated by pulling the moving contact out of the tubular fixed contact. The opening of the switch generates arcing between the contacts. The simultaneous injection of high-pressure SF₆ blows out the arc. Figure 1.10 demonstrates the operating principle for an actual CB. The CB has two tubes serving as fixed contacts (marked 1, 2, and 9) placed in a porcelain housing and a moving part with sliding contacts (3, 8, and 5), which connect the two fixed parts when the breaker is closed (Scene 1). The breaker is filled with SF_6 gas, which has high dielectric strength. The opening of the breaker drives the moving part downward (Scene 2). First, contact 3 separates and the moving contact compresses the SF_6 gas in chamber 7. This is followed by the separation of the main contact 5. The opening of contact 5 produces arcing between 4 and 5, and simultaneously initiates the fast, jet-like flow of the compressed SF₆, as portrayed by the small arrows in Scene 3. The SF₆ jet blows out the arc and interrupts the current (Scene 4).

The industry uses two types of CBs: live-tank and dead-tank breakers. In a livetank breaker, insulators support the breaker, and the breaker is placed in a horizontal porcelain housing and insulated from the ground. Figure 1.11 presents a live-tank breaker. The switch is in the crossarm. The vertical porcelain column insulates the



Figure 1.8. Concept of an EHV substation electric circuit with a breaker-and-a-half configuration.



Figure 1.9. Simplified CB operation.



Figure 1.10. SF₆ CB operation sequence.



Figure 1.11. CBA with live-tank breaker in a 69 kV substation.

switch and houses the control rods. The dead-tank breaker has a grounded metal housing. The switch is placed in this grounded (dead) tank and insulated by oil or SF₆. Large bushings isolate the circuit conductor from the tank. Figure 1.12 pictures a 500 kV SF₆ dead-tank CB.

The *disconnect switch* provides circuit separation and facilitates CB maintenance. The CB position cannot be determined by observation. Nevertheless, the lineman needs to know that the breaker is open for safety reasons. Furthermore, in the event that CB



Figure 1.12. Dead-tank 500 kV SF₆ CB.

maintenance is required, a disconnect switch is required on each side of the CB to completely isolate the CB. A disconnect switch is a large device that provides visible evidence that the circuit is open, and it can be operated only when the CB is open. Figure 1.13 provides a typical disconnect switch with a vertically rotating bar that opens the switch. Figure 1.11 shows disconnect switches with horizontally moving bars.

The *current and voltage transformers* reduce the current to 5 A or less and the voltage to about 120 V, respectively. The current transformers (CTs) and potential transformers (PTs) insulate the instrumentation circuits from the high voltage and current, and as such, CTs and PTs are collectively known as *instrument transformers*. These signals trigger the protection relays, which operate the CB in the event of a fault. In addition, the low power quantities are used for metering and system control.

The *surge arresters* are used for protection against lightning and switching overvoltages. Figure 1.14 presents a surge arrester. The surge arrester contains a nonlinear resistor housed in a porcelain tube. The nonlinear resistor has very high resistance at normal voltage, but the resistance is greatly reduced when the voltage exceeds a specified level. This diverts high lightning or switching current to ground and protects the substation from *overvoltage*.

The major component of the substation is the circuit breaker assembly (CBA), which requires two disconnect switches and one or more CTs for proper operation. The right side of Figure 1.8 illustrates a CBA with a single CT. In the main diagram, the simplified box is used. The two disconnect switches in the CBA permit maintenance of any CB. In case of a CB failure, other breakers will provide backup to clear the fault.



Figure 1.13. Disconnect switch, 500 kV.



Figure 1.14. Surge arrester, 69 kV.

The opening of the two disconnect switches, after deenergization, permits breaker maintenance to be performed. The CT is used to measure the line current and activates protection in case of a line fault. The protection triggers the CB, which opens the line to stop current flow. Figure 1.11 shows the CBA on a 69 kV substation.

The breaker-and-a-half bus scheme is a redundant system where a fault of any of the components does not jeopardize operation. Figure 1.8 reveals that power entering through the supply transformer may flow directly through CBA 5 and supply transmission line T3. However, a part of the power can flow through CBA 4, Bus 1, and CBA 1 to supply T1. Transmission line T2 is supplied through CBA 5, CBA 6, Bus 2, and CBA 3, and/or through CBA 4, Bus 1, CBA 1, and CBA 2.

EXAMPLE 1.1: Failure analysis of the breaker-and-a-half substation configuration

It is an interesting exercise to analyze the operation when one of the components fails. It can be seen that any CBA can be removed without affecting service integrity.

Normal Operation: Referring to Figure 1.8, there are two independent current paths between the supply (S) and each of the transmission lines (T1, T2, and T3). For instance, the supply S can feed T3 directly through CBA 5, or through the series combination of CBA 4, Bus 1, CBA 1, 2, 3, Bus 2, and CBA 6.

Fault Operation: The substation electric circuit of Figure 1.8 is analyzed here for three cases: (a) short circuit on transmission line T1, (b) short circuit on Bus 1, and (c) CB failure of CBA 5.

- (a) Short Circuit on Transmission Line T1. The protective response to a short circuit on a transmission line is to isolate the affected line using the adjoining CBs. For instance, a short circuit on line T1 triggers the protection that opens the two CBs, CBA 1 and CBA 2, thus separating T1 from the substation. In this case, the supply S feeds T3 directly through CBA 5, and S serves T2 through CBA 5, 6, Bus 2, and CBA 3. Figure 1.15 shows the resultant current paths.
- (b) Short Circuit on Bus 1. Likewise, a short circuit on a bus initiates isolation of the bus from the remainder of the circuit. A short circuit on Bus 1 triggers the opening of both CBA 4 and CBA 1. In this case, T1 is supplied through CBA 5, 6, Bus 2, and CBA 3 and 2; T2 is powered through CBA 5, 6, Bus 2, and CBA 3; and T3 is supplied directly through CBA 5. Figure 1.16 indicates the current pathways.
- (c) *CB Failure*. The two CB failure modes are *fail open* and *fail close*. If a CB cannot be closed, it fails in the open position. Similarly, if the CB cannot be opened (i.e., current switched off), then it has failed closed. In the following, we analyze CBA 5 for each of the two failure modes.

Case 1: CBA 5 Fails Open. If CBA 5 cannot be closed, it has failed in the open position. Consequently, T1 is supplied through CBA 4, Bus 1, and CBA 1. T2 is powered through CBA 4, Bus 1, and CBA 1 and 2; and T3 is supplied through CBA 4, Bus 1, CBA 1, 2, 3, Bus 2, and CBA 6. Figure 1.17



Figure 1.15. Current paths in the case of a short circuit on transmission line T1.



Figure 1.16. Current paths in the case of Bus 1 fault.

provides the current paths. It is observed from this scenario that the CBs and buses must be specified to carry all three load currents simultaneously. Specifically in this case the full supply current passes through CBA 4 and 1, and Bus 1.

Case 2: CBA 5 Fails Closed. If CBA 5 fails in the closed position (that is, the CB cannot be opened), then a short circuit in T3 cannot be isolated



Figure 1.17. CB CBA 5 fails in open position.

locally because the faulty CBA 5 directly connects the source to the shorted line. Backup protection at the sources (not shown) is required to switch off the supply. Similarly, if a CBA that is directly connected to a bus fails closed, then a short circuit on that bus cannot be locally isolated.

1.2.3. Gas Insulated Switchgear

Most high-voltage substations use open-air switchgear as seen in Figure 1.7. However, modern cities with high-rise buildings consume large amounts of power, requiring high-voltage supplies and a substation located in an area with limited space. The industry developed the SF_6 gas insulated switchgear (GIS) that can be placed in constrained spaces, even underground. Figure 1.18 shows a typical GIS.

All components are placed in an aluminum tube that is filled with SF_6 gas. The high dielectric strength of the gas permits the use of short distances between the conductors, which in turn reduces the size of the switchgear. Figure 1.19a exhibits the cross section of a GIS unit, which contains the bus bars, a CB, disconnect switch, grounding switch, and current and voltage transformers. Figure 1.19b provides the connection diagram of the GIS unit.

Although GIS significantly reduces the size of the high-voltage switchgear, its high price and the adverse environmental effects of SF₆ gas limit the use of this switchgear. The International Electrotechnical Commission (IEC) 60694 standard permits 1-3% in SF₆ gas emission per year. SF₆ is an anthropogenically produced compound, which, in addition to being a greenhouse gas, can also decompose under electrical stress, forming toxic by-products that are a health threat for workers in the event of exposure.



Figure 1.18. GIS placed inside building (courtesy of Siemens, Erlangen, Germany).

1.2.4. Power System Operation in Steady-State Conditions

Synchronous generators supply the power system. All synchronous generators rotate with the same speed and produce 60 Hz voltage in the United States. An increase in load changes the angle between the induced voltage and terminal voltage. In steady-state conditions, this power angle must be much less than 90°. The operation with constant synchronous speed maintains the frequency at a constant level. The permitted frequency deviation is less than ± 0.5 Hz.

The electric power system practically has no storage capacity, which implies that the generated power must equal the power consumed by the loads plus the system losses. The power system load is continuously changing. Typically, the load is very low at night, higher during the day, and the maximum load occurs in the early evening or late afternoon. Most of the time, the load changes gradually.

The system must be able to supply the load at any instant and simultaneously maintain the system voltage on each bus near the rated value. Standards require that the voltage on each bus must be within the range of $\pm 5-8\%$.

The load is forecast and most of the generators follow a predetermined schedule. However, selected generators provide the necessary power to balance the system. The system power limitations are based on keeping voltages within range and equipment loading within the current carrying capability. The corrective measures are to shift generation between power plants to unload the heavy loaded equipment. The system voltage, in practice, is maximized to reduce transmission line losses. System voltage is controlled by producing or absorbing reactive power.

Utilities perform studies to anticipate the power system conditions at specific load levels. This is usually done with the use of a power flow program that simulates the actual power system. The generator terminal voltages in the power flow study are selected to minimize losses in the system and have voltages within equipment rating.







Figure 1.19. Gas insulated switchgear. (a) Cross section; (b) Electrical connection diagram. (1) Circuit breaker (CB) interrupter unit; (2) spring-stored energy mechanism with CB control unit; (3) and (5) busbar disconnector; (4) and (6) busbar; (7) outgoing feeder disconnector; (8), (9), and (10) earthing switch; (11) CT; (12) voltage transformer; (13) cable sealing end; (14) integrated local control cubicle. Courtesy of Siemens, Erlangen, Germany.

Generator power levels are defined at each generator bus except one. This one is called the slack bus. The power flow program causes the real power at the slack bus to be adjusted to balance generation, load, and losses.

The power flow program is a powerful tool for planning the future power system and anticipating operating problems by studying contingencies.

1.2.5. Network Dynamic Operation (Transient Condition)

A short circuit produces large current, typically 5–10 times the rated current. The system protection detects the short circuit and triggers the operation of the CB, which opens and interrupts the current after a few cycles. The large short circuit current produces severe voltage drop. Actually, the voltage at the fault location is practically zero.

This short duration voltage dip produces a sudden reduction of load near the fault. However, the generator input power remains practically constant, but the output power is reduced significantly. The larger input power than output power accelerates the generators near the fault. If the fault clears in a short time (the critical clearing time), the system restores voltage and loads, which stops the generator acceleration and the generator returns to normal operation.

However, if the fault clearing is delayed, the generator acceleration causes the affected generators to fall out of synchronism with the other generators of the system. The outage of several generators can collapse the system and require lengthy restart procedures. The described event is called a transient stability-caused outage. In addition to the fault transient instability, an outage can be initiated by switching operations and other disturbances. There have been cases where switching created a system configuration, resulting in undamped oscillations at a frequency around 0.5 Hz. These oscillations can cause lines to open and generators to trip. This can result in a system blackout. This is referred to as steady-state instability due to insufficient damping.

1.3. TRADITIONAL DISTRIBUTION SYSTEMS

Figure 1.20 depicts the structure of the electrical system. The transmission system contains three looped networks: (1) EHV network, (2) high-voltage network, and (3) subtransmission line network. These electrical networks connect the power plants and load centers together and thus bring electricity to towns and other loads. However, the medium voltage distribution systems, which supply the residential and industrial customers, are radial networks which may not withstand a contingency.

The American National Standards Institute (ANSI) standard C84.1 for 60 Hz electric power systems and equipment in North America limits the voltage magnitude deviation at the service entrance to $\pm 5\%$ for normal conditions and from -8.3% to +5.8% for short durations or unusual conditions. There is not an established standard concerning the frequency deviation from nominal, but the frequency does not deviate more than 0.1 Hz, from 60 Hz, 99% of the time. Continuity of service is another important consideration since an unacceptable number of interruptions prompts customers to complain to the utility and the regulatory agency. The SAIFI (System Average



Figure 1.20. Structure of a modern electric system.

Interruption Frequency Index) is a measure of system reliability—the SAIFI is generally in the range of one to five interruptions per year.

1.3.1. Distribution Feeder

The distribution system is a radial system, without loops. Figure 1.21 illustrates the concept of a typical distribution system, where a main three-phase feeder is positioned along a major thoroughfare. The voltage of this primary distribution system is around 15 kV. In Arizona, the nominal voltage for most urban distribution is 12.47 or 13.8 kV.



Figure 1.21. Concept of radial distribution system.

The main feeder is protected by a reclosing CB that switches off the feeder in case of a fault, and after a few cycles, the breaker recloses and restores the energy supply. This is an effective way of protection for overhead distribution circuits because most faults on an overhead line are temporary—originating from a weather-related event. However, if the reclosing is unsuccessful, the breaker opens the line permanently. For an underground system, most faults are permanent, so reclosing is not used.

Many commercial customers (e.g., grocery stores, office buildings, and schools) are supplied with three-phase power due to heavy loads such as fan motors and air conditioning. Residential and light commercial customers are powered by single-phase subfeeders, which are protected by fuses. Close to the residential and light commercial loads, distribution transformers are connected to the single-phase subfeeders. Low voltage (120/240 V) secondary circuits, called *consumer service drops*, supply the



Figure 1.22. Overhead line and cable connections.

individual customers. The distribution transformers are protected on the primary side by fuses. This fuse operates in case of transformer fault or short on the service drop cable. The consumer is protected by CBs on the service panel.

Figure 1.22 shows the interconnection of a distribution line with a distribution cable. This connection is used to supply residential areas with underground distribution. The figure shows the cable termination, the surge arrester that is used for overvoltage protection, and the fuse cutout, which is used for *overcurrent* protection. The fuse cutout contains a fuse mounted on a pivoted insulator and it serves as a disconnect switch that can be opened using an insulated rod—commonly known as a *hot stick*. A metal conduit attached to the wooden pole protects the cable.

Figure 1.23 presents a typical consumer service drop, where a step-down transformer mounted on the distribution pole supplies an individual house or a group of homes. For aesthetic purposes, underground cables have replaced overhead distribution lines in some residential areas. In such cases, the transformer is housed in a groundlevel metal casing, which is placed on a concrete slab, as seen in Figure 1.24. Figure 1.23 shows a typical single-phase pole-mounted transformer that supplies a few (one to eight) houses. A surge arrester and a fuse cutout protect the pole-mounted oilinsulated transformer. The secondary of the transformer supplies a 240/120 V insulated conductor that is attached to a carrier steel wire, leading the electricity to the houses. Such transformers may supply a 240/120 V low voltage line.



Figure 1.23. Consumer service drop.

1.3.2. Residential Electrical Connection

A low-voltage secondary feeder supplies individual houses. A distribution transformer has a three-wire electrical system, which accommodates both 120 and 240 V loads. Figure 1.25 draws the electrical connection of a typical household supply.

The step-down transformer has one neutral and two phase wires. The neutral is grounded at the transformer secondary side. The three wires are connected to the kilowatt and kilowatt-hour meter at the house. The residence has a four-wire system, which consists of three insulated wires and one bare ground wire. The ground wire and insulated neutral wire are grounded at the house service entrance.

The kilowatt and kilowatt-hour meters measure and record the kilowatt-hour energy consumption, and in some cases the maximum 15-minute kilowatt demand. Figure 1.26 pictures a typical kilowatt-hour meter and service panel with the main CBs.

The power company is responsible for the system up to the secondary terminals of the meter. The service panel and the house wiring are the homeowner's responsibility. The service panel is equipped with the main CB, which protects the house against short circuit and overload. Lighting and small appliances are supplied by the 120 V lines, which are also protected by CBs. In older installations, fuses have been used instead of CBs. The load is connected between the phase and neutral conductors. The



Figure 1.24. Ground-level transformer in a residential area.

Figure 1.25. Residential electrical connection.

Figure 1.26. Typical residential kilowatt-hour meter and service panel.

housing of appliances and lamps is grounded by the ground wire. Larger appliances, such as the cooking stove and clothes dryer, are powered by 240 V circuits.

1.4. INTELLIGENT ELECTRICAL GRIDS

The U.S. Energy Independence and Security Act of 2007 describes the smart grid as the modernization of the electricity infrastructure to maintain a reliable and secure system that can meet future growth. Figure 1.27 shows a conceptual model of the intelligent grid. The diagram depicts the electricity flow within the electric power system (generation, transmission, distribution, and customer) and the communication links between the individual components and the operations, service provider, and market domains. These require monitoring the electric system operation parameters at each level using an advanced sensor system, the communication of the measured data through a secure and fast system, and evaluation of the obtained information using advanced computer software. The goal is a more reliable electrical power system.

1.4.1. Intelligent High-Voltage Transmission Systems

The cascading outages observed in the last decade demonstrated that the electrical power grid remains vulnerable. Unexpected small faults can initiate a large-scale

Figure 1.27. Smart grid conceptual model. Source: National Institute of Standards and Technology.

network outage. The electrical network did not keep pace with the advancements in digital technology and communication. Because of the importance of the power grid to the national infrastructure, the modernization of the power grid became a high priority. The smart grid concept emerged at the end of the 1990s, when the application of digital processing and communications to the power grid began.

One of the first and most important innovations was the phasor measurement unit (PMU). Using PMUs, Bonneville Power Administration introduced the wide area measurement system (WAMS) in 2000. In this system, the Global Positioning System (GPS) time signal synchronizes a large number of sensors distributed throughout the network. The PMU sensors measure the magnitude and phase angle of the current or both current and voltage. The phasor data (magnitude, phase angle, and time stamp) obtained at different locations of the power system are sent to a computer called a phasor data concentrator, which compares and evaluates the data. The power system condition is assessed using the data. The combination of phasor measurement data with dynamic line ratings has emerged to monitor more accurately the transmission system operation and integrate renewable energy sources.

Large-scale solar- and wind generation-produced power is variable, depending upon meteorological conditions. Application of these electric power generation methods requires real-time monitoring of operational parameters and continuous analysis of the obtained data to assure reliable operation and foresee emerging operation problems as well as initiate remedial actions in case of equipment failure.

1.4.2. Intelligent Distribution Networks

Some of the renewable generation, like residential and commercial solar generation, is connected directly to the distribution system, and is referred to as distributed generation. The increasing use of electrical cars will increase the load on the distribution system. The present radial distribution system must be upgraded to an electric network, with at least a single contingency to handle distributed generation and increased loading.

The introduction of advanced metering infrastructure permits two-way communication between the individual customers and the utility. This permits dynamic electricity pricing. The utility will be able to control the voltage to minimize losses, and curtail customer usage in the event of generation shortage. The customer will be able to reduce costs by using appliances when the price of electricity is low. Furthermore, smart appliances, which acquire pricing signals from a smart meter, are programmed to reduce energy use during peak periods.

Simultaneously, the utility will instantaneously detect customer outages and initiate remedial actions. Smart meters will report voltage reduction or zero voltage, which is a sign of an outage. The low voltage network will automatically reconfigure the system to reduce the number of customers affected by a short circuit. The smart distribution grid was in an early stage of development in 2011, but most utilities in the United States are working toward its deployment.

1.5. EXERCISES

- 1. Draw a sketch and explain the concept of electric energy transmission. What are the advantages of the multilevel voltages?
- 2. What are the typical voltages for subtransmission, high-voltage, extra-high-voltage, and ultra-high-voltage systems?
- 3. What are the typical voltages for the distribution system?
- 4. Draw the connection diagram of a high-voltage substation using the breaker-anda-half configuration. Identify the components.
- 5. What is a circuit breaker? Discuss its role and operating principle.
- 6. What are current and voltage transformers?
- 7. What is the disconnect switch and its purpose?
- 8. What is a surge arrester? Why is it important?
- 9. Draw a diagram of a typical radial distribution system. Describe briefly its operation.
- 10. Describe the residential electric connection. Draw the connection diagram.

1.6. PROBLEMS

Problem 1.1

Using the one-line diagram of Figure 1.8, determine the protective response of the circuit breakers due to a short circuit (a) solely on transmission line T2 and (b) only on transmission line T3.

Problem 1.2

Substations frequently use the connections shown in the one-line diagram of Figure 1.8. Analyze the circuit operation for the cases of when CBA 4 (a) fails open and (b) fails close.

Problem 1.3

For the breaker-and-a-half configuration of Figure 1.8, determine the circuit breaker positions (open or closed) needed to supply power to the three lines, if a short circuit occurs on Bus 2.