CHAPTER 1

ELECTRIC POWER SYSTEM

The purpose of the electric power system is to generate, transmit and distribute electrical energy. Frequently 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.

The major components of the power system are:

- power plants, which generate the electricity,
- transmission lines, which transport and distribute the energy,
- substations with switchgear, which 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; provides short descriptions of fossil, nuclear and hydropower plants; discusses the substation equipment including circuit breaker disconnect switch, and so forth; and describes the low voltage distribution system including residential electrical connection.

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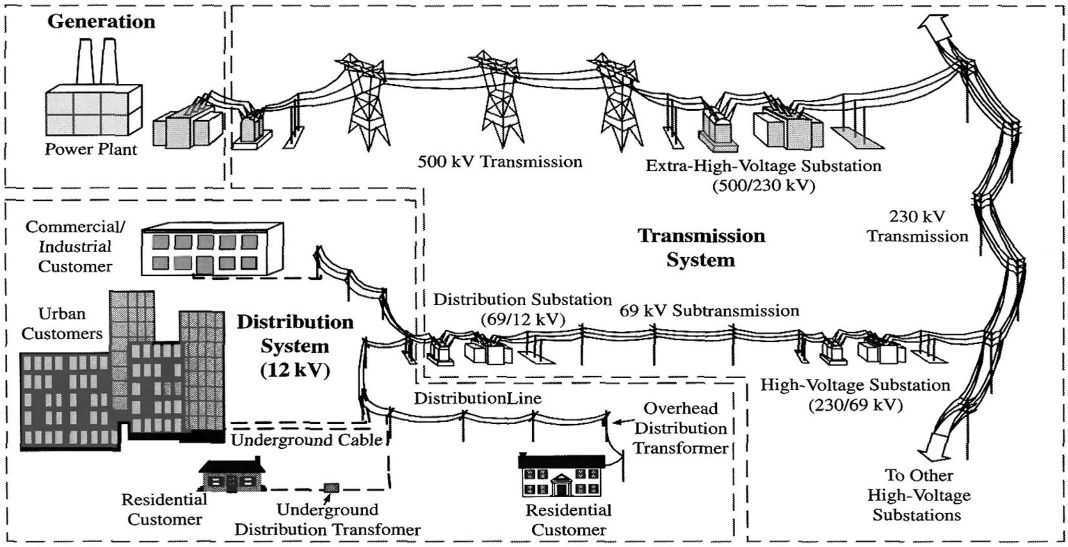


Figure 1.1 Overview of the electric power system.

1.1 ELECTRICAL NETWORK

Power plants convert the chemical energy in coal, oil or natural gas, or the potential energy of water, or nuclear energy into electrical energy. In fossil and nuclear power plants, the thermal energy is converted to high-pressure high-temperature steam that drives a turbine that is mechanically connected to an electric generator. In a hydroelectric plant, the water falling through a head drives the turbine-generator set. The 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 power. The voltage is increased and simultaneously the current is reduced by a transformer at the generation station to permit long-distance energy transportation. In Figure 1.1, the voltage is increased to 500 kV, and an extra-high-voltage line carries the energy to a faraway substation, which is usually located on 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 substation, which supplies a large part of Phoenix (see Figure 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 root-mean-square (rms) value of the *line-to-line* voltage, which is the voltage between phase conductors. The standard transmission line and sub-transmission voltages are listed in Table 1.1. The line voltage of the transmission system in the United States is between 115 kV and 765 kV. The ultra-high voltage lines of 1100 kV are not in commercial use although experimental lines were built. The 345 kV to 765 kV transmission lines are the extra-high-voltage (EHV) lines,

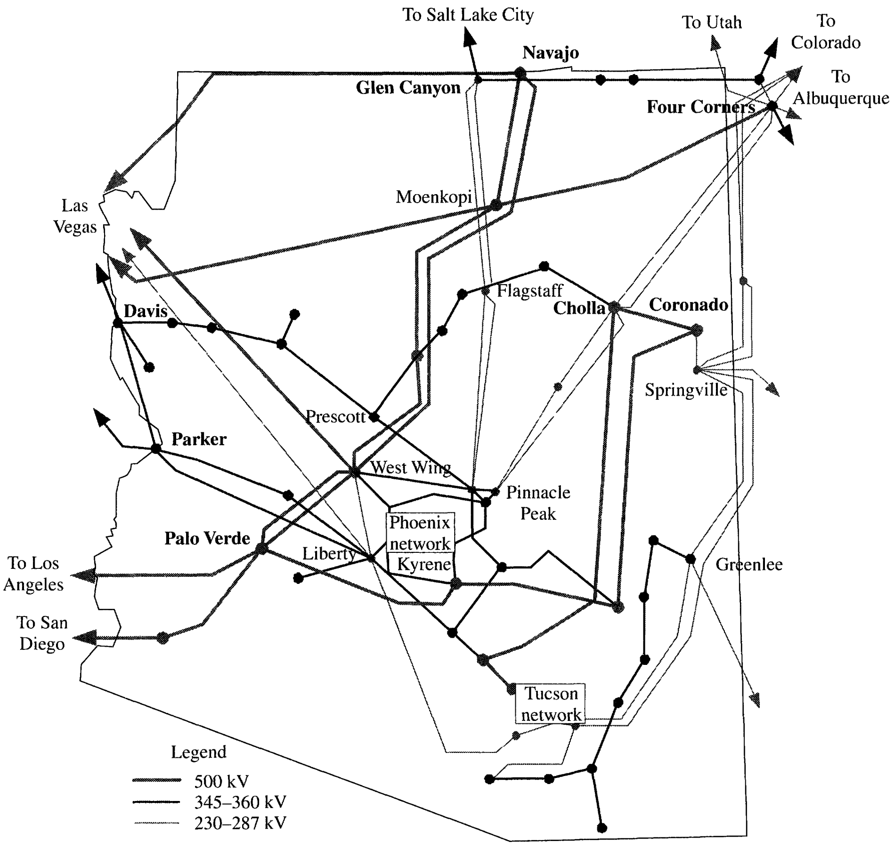


Figure 1.2 High- and extra-high-voltage transmission system in Arizona (power generation sites shown in bold). (Data from Western Systems Coordinating Council, 1999).

with a maximum length of 400–500 miles. The 115 kV to 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 5–10 miles with voltages at or below 46 kV.

1.1.1 Transmission System

The *transmission system* transfers three-phase power from the electric generating stations to the load centers. As an example, Figure 1.2 shows a typical electrical network that supplies the Phoenix metropolitan area in Arizona. In this system 500 kV, 345 kV, 230 kV and 115 kV lines connect the loads and power plants

TABLE 1.1 Standard System Voltages (ANSI C84.1-1995[1] and C92.2-1987[2])

Name or Category	Nominal Voltage in kV
Sub-transmission	34.5
	46
	69
High voltage	115
	138
	161
	230
Extra-high voltage	345
	400 (Europe)
	500
	765
Ultra-high voltage	1100 (not used)

together. In addition, the figure shows that 500 kV lines interconnect the Arizona (AZ) system with California, Utah and New Mexico. These interconnections provide instantaneous help 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. At present all networks in the eastern United States are interconnected and all networks in the western United States are interconnected, which increases the reliability of the electrical supply.

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. The 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 extra-high-voltage substation, transformers reduce the voltage to 230 kV 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 sub-transmission lines connect the high-voltage substation to local distribution stations, which are located in the town. The sub-transmission lines are built along larger streets.

1.1.2 Distribution System

The *distribution system* uses both three-phase and single-phase systems. The larger industrial loads require a three-phase supply. Large industrial plants and

[1] ANSI C84.1–1995, "Voltage ratings for electric power systems and equipment (60 Hz)".
[2] ANSI C92.2–1987, "Alternating-current electrical systems and equipment operating at voltages above 230 kV nominal—preferred voltage ratings".

factories are supplied directly by a sub-transmission line or a dedicated distribution line. Ordinary residences are supplied by a single-phase system.

The voltage is reduced at the distribution substation that 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. The actual voltage varies. Typical examples for the 15 kV class are 12.47 kV 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 figure also shows that 12 kV cables supply the downtown area in a large city.

The residential areas also can be supplied by a 12 kV cable 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 supply the homes, shopping centers and other local loads.

1.2 ELECTRIC GENERATION STATIONS

An electric generating station converts the chemical energy of gas, oil and coal, or nuclear fuel to electric energy. In the late 1800s, reciprocating steam engines were used to drive generators and produce electricity. The more efficient steam boiler–turbine system replaced the steam engine around the turn of the 19^{th} century. The steam boiler burns fuel in a furnace. The heat generates steam that drives the turbine-generator set. Typically, the steam turbine and generator are mounted on a common platform/foundation and the shafts are connected together. The turbine-driven generator converts the mechanical rotational energy to electrical energy. Figure 1.3 shows a steam turbine and electric generator with its exciter unit.

In the beginning, oil was the most frequently used fuel. Increased petroleum costs, owing to increased gasoline consumption by automobiles, elevated coal to the primary fuel for electricity generation. However, environmental concerns (*e.g.*, sulfur dioxide generation, acid rain, dust pollution, and ash-handling problems) of coal burning have curtailed the building of new coal-fired power plants.

Recently, natural gas has emerged as the power plant fuel of choice due to three factors. First, natural gas burns cleaner making plant siting and adherence to environmental regulations easier. Second, natural gas is available in large quantities at a reasonable price. Third, significant increases in plant thermal efficiency have been achieved using combined cycle plants that utilize gas turbine technology advances from the aerospace industry. The *thermal efficiency* is defined as

$$\eta_{th} = \frac{P_e}{Q_{th}} = \frac{plant\ net\ electric\ power\ (energy)\ output}{plant\ thermal\ power\ (energy)\ input}. \tag{1.1}$$

Historically, the hydroelectric power plants developed nearly simultaneously with the thermal power plants. The river water level is increased by a dam, which

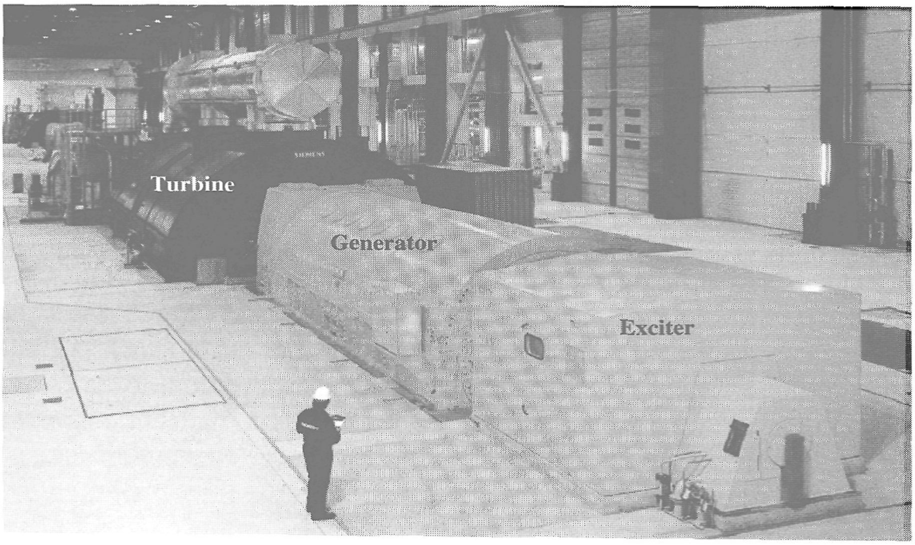


Figure 1.3 Steam turbine and electric generator with exciter. (Courtesy Siemens).

creates a head. The head-generated pressure difference produces fast-flowing water that drives a hydraulic turbine, which turns the generator. The generator converts the mechanical energy to electrical energy.

After World War II, electricity generation from nuclear power plants emerged. More than 500 nuclear plants operate worldwide. In these plants, atomic fission is produced using enriched uranium. The fission chain reaction heats water and produces steam. The steam drives the turbine and generator. In the last two decades, environmental considerations and nuclear power plant capital costs stopped the building of new plants in the United States and curtailed the operation of existing plants.

Coal, nuclear, natural gas and hydro power plants generate most of the electricity in the United States. A breakdown of electricity generation in the United States for 2000 is given in Figure 1.4. At the present time other energy generation approaches such as wind, solar, geothermal and biomass produce very little of the electricity consumed in the United States. Typical technical data of power plants are presented in Table 1.2.

Economics drives the selection of an appropriate power generation scheme for the given situation. A utility may need additional generation during high electricity demand hours (peak load) or the new power may be needed 24 hours a day (base load). *Base load* is that load below which the demand never falls, that is, the base load must be supplied 100% of the time. The *peaking load* occurs less than about 15% of the time; the intermediate load is between 15% to 85% of the time.

In calculating the cost of electricity production (¢/kW·hr), the energy cost is broken into three categories:

1. Capital: land, equipment, construction, interest;

2. Operational and maintenance (O&M): wages, maintenance, some taxes and insurance; and
3. Fuel costs.

Costs are often expressed in mills per kilowatt-hour (kW·hr) where 1,000 mills equal \$1. Since costs are expressed on a per kW·hr basis, a high capacity factor is desired so the capital cost is spread out. The *capacity factor* is the ratio of energy produced during some time interval to the energy that could have been

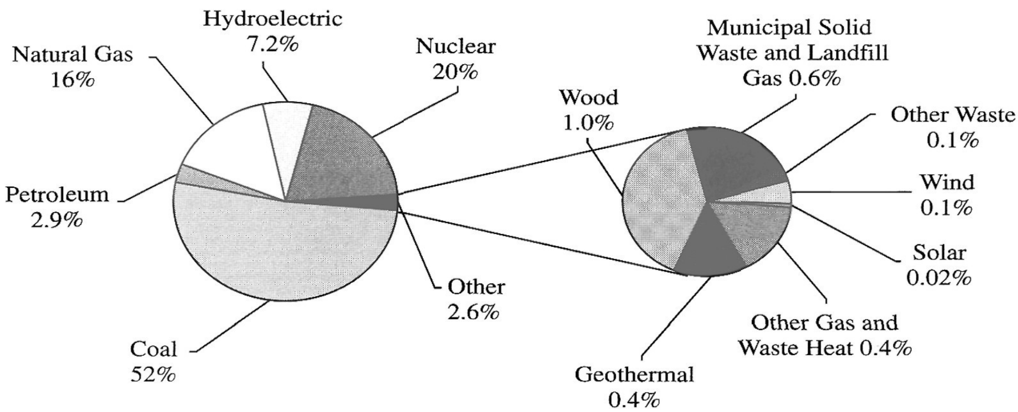


Figure 1.4 Net electricity generation in the United States for year 2000. (Data from *Annual Energy Review 2000*, Energy Information Administration).

TABLE 1.2 Power Plant Technical Data

Generation Type	Typical Size (MW)	Plant Capital Cost (\$/kWe)	Construction Lead Time (yrs)	Fuel Cost (\$/MBtu)	Fuel Type	Equivalent Forced Outage Rate (days/yr)	O&M Fixed (\$/kW/yr)	Cost Variable (\$/MWh)
Nuclear	1200	2400	10	1.25	Uranium	20	25	8
Pulverized coal steam	500	1400	6	2.25	Coal	12	20	5
Atmospheric fluidized bed	400	1400	6	2.25	Coal	14	17	6
Gas turbine	100	350	2	4.00	Nat. gas	7	1	5
Combined cycle	300	600	4	4.00	Nat. gas	8	9	3
Coal-gasification combined cycle	300	1500	6	2.25	Coal	12	25	4
Pumped storage hydro	300	1200	6	—	—	5	5	2
Conventional hydro	300	1700	6	—	—	3	5	2

Source: H.G. Stoll: *Least Cost Electric Utility Planning*, 1989, John Wiley & Sons, Reprinted by permission.

produced at net rated power (P_e) during the same period (T), that is,

$$CF = \frac{energy\ produced\ during\ time\ interval,\ T}{\int_0^T P_e(t)dt}. \quad (1.2)$$

Fuel costs are generally proportional to the plant output so the related energy cost is constant. The capital and O&M costs generally dictate how a plant is used on the grid (hydroelectric units are an exception to the following):

Loading	Capital Costs	O&M Costs	Example Plants
Base	High	Low	Coal, Nuclear
Peak	Low	High	Oil

Natural gas is used frequently for intermediate load plants.

1.3 FOSSIL POWER PLANTS

Fossil power plants include coal-fired, oil-fired, and natural gas fueled power plants. Figure 1.5 shows an aerial view of a small generating station in Arizona. The major components of a thermal power plant are

- Fuel storage and handling;
- Boiler;
- Turbine;
- Generator and electrical system.

1.3.1 Fuel Storage and Handling

Coal is transported by long coal trains with special railcars, or by barge if the power plant is at a river or seaside. The railcars are tipped and the coal dropped into a dumper. Conveyer belts carry the coal to an open-air coal yard. The coal yard stores several weeks of supply. Additional conveyer belts move the coal into the power plant where the coal is fed through hoppers to large mills. The mills pulverize the coal to a fine powder. The coal powder is mixed with air and injected to the boiler through burners. The mixture is ignited as it enters the furnace.

Oil and liquefied natural gas are also transported by rail, or pipelines. The power plant stores this fuel in large steel tanks, holding several days of supply. The oil is pumped to the burners. The burners atomize the oil and mix the small oil particles with air. The mixture is injected into the furnace and ignited.

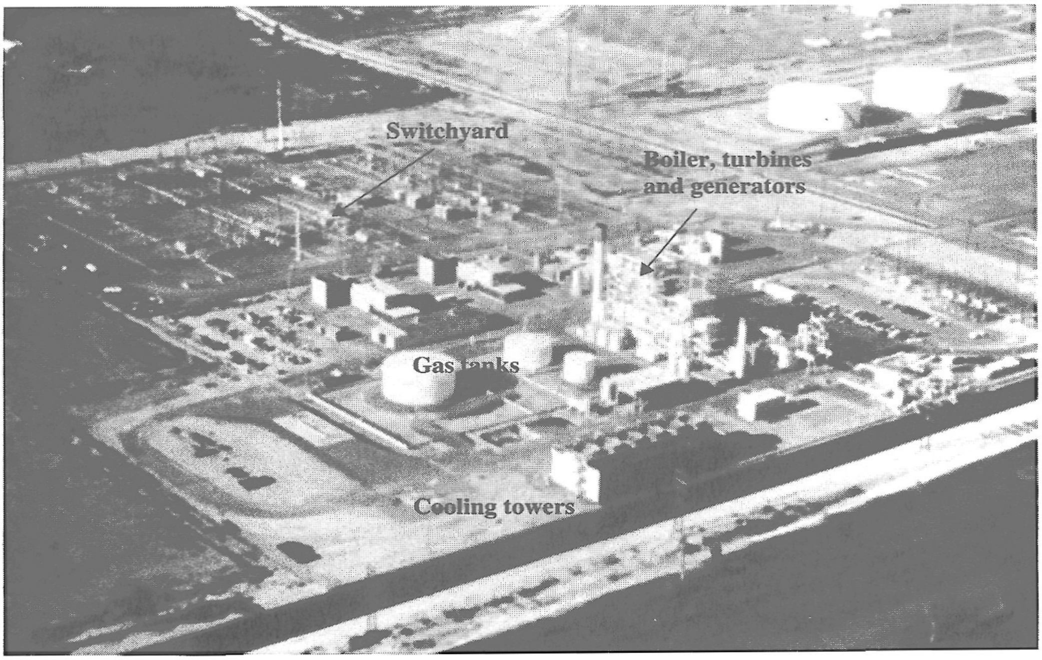


Figure 1.5 Aerial view of a small generating station (Kyrene Generation Station). (Courtesy Salt River Project).

The natural gas, also mixed with air, is fed to the boiler through the burners, which ignite the mixture as it enters the furnace. Natural gas is the easiest of the fossil fuels to burn as it mixes well with air and it burns cleanly with little ash.

1.3.2 Boiler

Figure 1.6 shows the flow diagram of a boiler. The boiler is an inverted U-shaped steel structure. The walls of the boiler are covered by water tubes. The major systems of a boiler are

- Fuel injection system;
- Air-flue gas system;
- Water-steam system; and
- Ash handling system;

which are discussed below.

1.3.2.1 Fuel Injection System. Natural gas, atomized oil or pulverized coal is mixed with primary air by the nozzles in the burners and injected into the furnace. The mixture is ignited either by the high heat in the boiler or by an oil or gas torch.

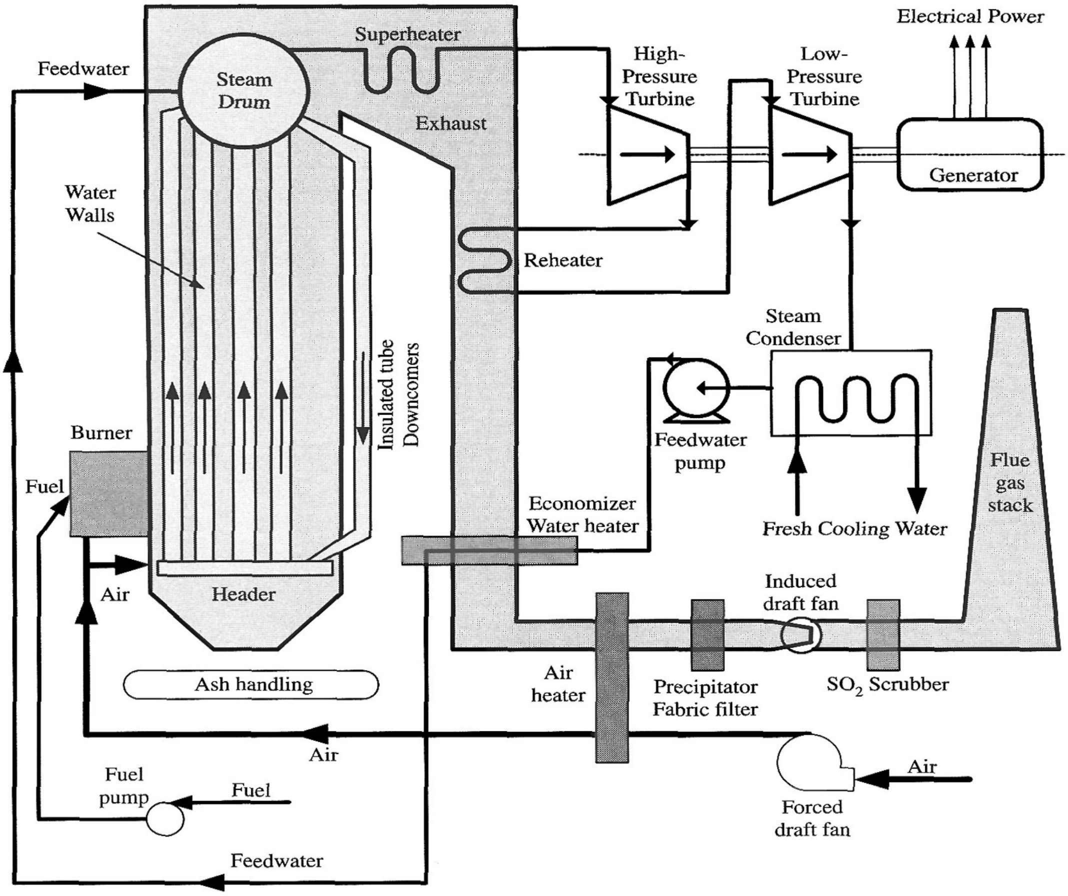


Figure 1.6 Flow diagram of a drum type steam boiler.

Secondary air is pumped into the boiler to assure complete burning of the fuel. The burning fuel produces a high-temperature (around 3000°F) combustion gas in the boiler, which heats the water in the tubes covering the walls by convection and radiative heat transfer. The high heat evaporates the water and produces steam, which is collected in the steam drum.

1.3.2.2 Water-steam System. A large water pump drives the feedwater through a high-pressure water heater (not shown in Figure 1.6) and the economizer. Steam removed from the turbine heats the high-pressure feedwater heater. The hot flue gas heats the economizer. The water is pre-heated to 400–500°F.

The high-pressure and high-temperature feedwater is pumped into the steam drum. Insulated tubes (called downcomers) located outside the boiler connect the steam drum to the header at the bottom of the boiler. The water flows through the downcomer tubes to the header. The header distributes the water among the riser tubes covering the furnace walls. The water circulation is assured by the density difference between the water in the downcomer and riser tubes.

The burning fuel evaporates the water and produces steam. The saturated steam is separated in the steam drum. The superheater dries the saturated steam and increases its temperature to around 1000°F. The superheated steam drives the high-pressure turbine. The steam exhausted from the high-pressure turbine is reheated by the flue gas heated reheater. The intermediate-pressure and/or low-pressure turbines are driven by the re-heated steam. The steam exhausted from the turbine is condensed into water in the condenser. The condensation generates vacuum, which extracts the steam from the turbine.

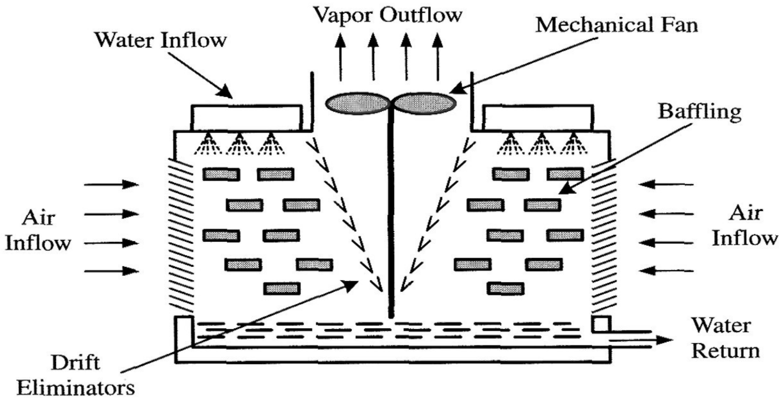
A deaerator is built in the condenser to remove the air from the condensed water. This is necessary because the air (oxygen) in the water produces corrosion of the pipes. The power plant loses a small fraction of water during operation. This necessitates that the gas-free condensed water is mixed with purified feedwater that replaces the water loss. The mixture is pumped back to the boiler through the high-pressure feedwater heater and economizer. It can be seen that the boiler has a closed water circuit. The replacement feedwater is highly purified and chemically treated. The use of highly purified water reduces corrosion in the system.

The condenser is a heat exchanger, where the steam condenses in tubes, which are cooled by water from a nearby source. Heat dissipation techniques include:

- Once-through cooling to a river, lake, or ocean;
- Cooling ponds including spray ponds; and
- Cooling towers.

The former method is the least expensive but can result in thermal pollution. *Thermal pollution* is the introduction of waste heat into bodies of water supporting aquatic life. The addition of heat reduces the water's ability to hold dissolved gases, including oxygen which aquatic life requires; although aquatic life growth is usually enhanced by warm water. To avoid thermal pollution the latter two methods have been employed. A cooling pond, and its smaller, specialized version—the spray pond, are man-made lakes. In a spray pond, the water is pumped through nozzles to generate fine spray. The evaporation cools the water as it falls back to the pond.

Most cooling towers are of the wet (vs. dry) variety that employs direct water-to-air contact that can cool more efficiently from the evaporation but which suffers water loss. Another classification of cooling towers is the air draft mechanism: natural versus mechanical draft. The natural draft towers are large, tall structures whereas mechanical draft towers are shorter and employ either forced or induced draft fans. Most cooling towers are filled with a latticework of horizontal bars (see Figure 1.7). The baffling within the tower increases the water surface area for more efficient cooling. The warm water is sprayed on the latticework at the top of the tower. The water slowly drifts from the top of the tower to the bottom through the bars. Simultaneously, fans and/or the natural-draft drive air from the bottom of the tower to the top. The evaporation cools the water efficiently.



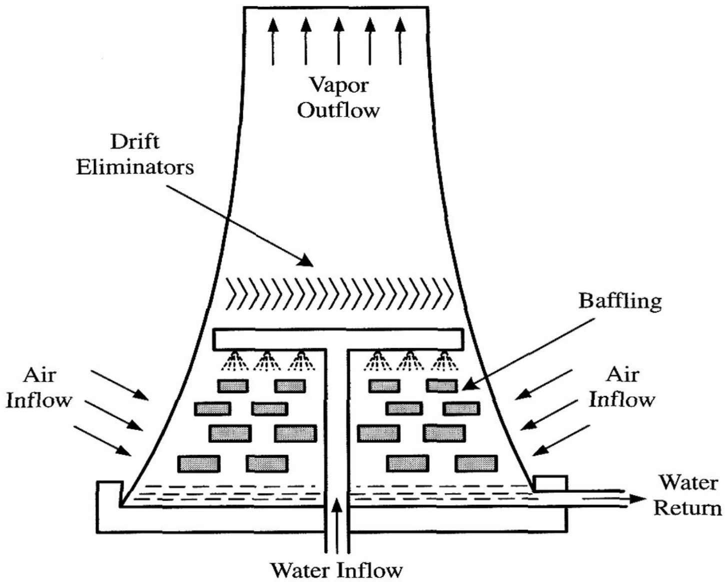


Figure 1.7 Wet cooling towers (**a**) Cross-flow induced draft tower; (**b**) Hyperbolic natural draft tower.

1.3.2.3 Air-flue Gas System. The forced draft fan drives the fresh ambient air through the air heater, which increases the air temperature to 500–600°F. The warm flue gas heats the air heater. The pre-heated primary air, mixed with the fuel, supports the burning in the boiler. The secondary air assures complete burning of all the injected fuel.

The hot combustion gas flows through the boiler, generates steam, heats the superheater, reheater, economizer and air heater. An induced draft fan drives the flue gas into the atmosphere through the stack. The exhaust gas temperature is around 300°F. The stack must disperse the flue gases into the atmosphere without disturbing the environment. This requires filters to remove harmful chemicals and particles, and sufficient stack height that assures that the residual pollution in the flue gas is distributed over a large area without causing dangerous concentrations of pollutants.

Particulate emissions (*e.g.*, flyash) from burning have historically received the greatest attention since they are easily seen leaving smokestacks. For a pulverized coal unit, 60%–80% of the ash leaves the furnace with the flue gas. Two emission control devices for flyash are the traditional fabric filters and the more recent electrostatic precipitators. The fabric filters are large baghouse filters having a high maintenance cost since the cloth bags have a life of only 18 to 36 months, although the bags can be temporarily cleaned by shaking or back flushing with air. These fabric filters are inherently large structures resulting in a large pressure drop, which reduces the plant efficiency.

Electrostatic precipitators have a collection efficiency of 99%, but do not work well for flyash with a high electrical resistivity (as commonly results from combustion of low-sulfur coal). In addition, the designer must avoid allowing unburned gas to enter the electrostatic precipitator since the gas could be ignited. A side view of an electrostatic precipitator is shown in Figure 1.8. The flue gas, laden with flyash, is sent through pipes having negatively charged plates that give the particles a negative charge. The particles are then routed past positively charged plates, or grounded plates, which attract the now negatively charged ash particles. The particles stick to the positive plates until they are collected. Rappers are activated to shake the particles loose so the ash exits through the hoppers at the base of the unit. The air that leaves the plates is then clean from harmful pollutants.

Ideally, the hydrocarbon combustion produces water and carbon dioxide gases; however, without sufficient oxygen (air), incomplete combustion may

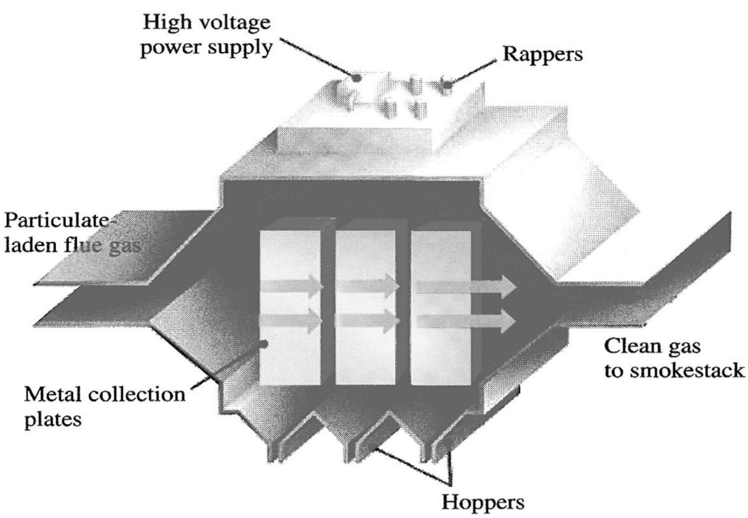


Figure 1.8 Electrostatic precipitator.

occur leaving the intermediate product of carbon monoxide (CO). Carbon monoxide production is generally reduced by providing excess air (oxygen) to the furnace.

$$2H_2 + O_2 \rightarrow 2\ H_2O$$

$$C + O_2 \rightarrow CO_2$$

The main gaseous pollutants from combustion include sulfur oxides (SO_X), nitrous oxides (NO_X), and carbon monoxide (CO). Both SO_X and NO_X can create *acid rain* composed of H_2SO_4 and HNO_3, respectively. The SO_X, mostly SO_2 and some SO_3, can cause respiratory irritation. The NO_X contributes to smog and ozone formation, and vegetation damage. The CO reduces the oxygen carrying capability of the blood, referred to as carbon monoxide poisoning. The Clean Air Act sets the federal standards for plant emissions, although individual states may establish limits that are more stringent.

To reduce SO_X emissions, many power plants have chosen to use low-sulfur fuel. Coal from the western United States typically is low in sulfur content whereas high-sulfur coal dominates from eastern states. Natural gas that is high in H_2S is known as sour gas, in contrast to sweet gas, which is low in sulfur. A flue-gas desulfurization system is often employed to remove the SO_2. Both wet and dry sulfur scrubbing processes are in use today. The dry process, in which a lime or limestone solution is sprayed into the flue gas, is the most economical. The wet scrubbing process is more efficient and may be implemented as either a throwaway or a recovery method. Although the recovery products of sulfur and sulfuric acid can be sold, the more popular is the wet, throwaway lime/limestone process which utilizes the chemical reaction:

$$SO_2 + CaCO_3 \rightarrow CaSO_3 + CO_2$$

Most NO_X originates from the nitrogen in the fuel rather than N_2 in the air. To reduce NO_X emissions tighter control of the combustion process is employed through combustion temperature (reduction) or lowering the air–fuel ratio. As in automobiles, exhaust gas recirculation can be used to reduce combustion temperature.

1.3.2.4 Ash Handling system. The coal-fired power plant produces large amounts of ash. Ash is mineral matter present in the fuel. The larger ash particles are collected at the bottom of the furnace and mixed with water. The flyash is extracted by the bag filters and mixed with water. The produced slurry is pumped into a clay-lined pond, from which the water evaporates, without polluting the groundwater of the nearby community. The evaporation of the water produces an environmentally undesirable deposit, which could form a cement-like hard surface. The utilities cover the ash fields with soil and restart the vegetation to minimize the adverse environmental effects. Some utilities utilize the ash as an aggregate in concrete.

1.3.3 Turbine

The high-pressure, high-temperature steam drives the turbine. The heat energy in the steam is converted to mechanical energy. The turbine has a stationary part and a rotating shaft. Both are equipped with blades. The length of the turbine blades decreases from the exhaust to the steam entrance. The shaft is supported by bearings. The steam is supplied through the stationary part of the turbine. Figure 1.9 shows the stationary part with the stationary blades and the rotor with the moving blades. The change in blade length is clearly visible. Figure 1.10 shows the turbine blades from a much larger steam turbine in common use today.

The turbine operating concept is that the high-pressure, high-temperature steam is injected into the turbine through nozzles. The nozzles increase the steam velocity. The high-speed steam flows through a set of blades placed on the turbine rotor. The direction of the flow changes in the moving blades and the pressure drops. The direction change-caused impact and pressure drop drive the moving blades and the rotor. The concept is illustrated in Figure 1.11. The efficiency of the process is improved by using several sets of moving and stationary blades, alternately. The steam flows through the moving blades and drives the rotor shaft. After that, the stationary blades change the direction of the flow and direct the steam into the next set of moving blades. The pressure drops, and the impact of the steam drives the rotor.

Modern power plants have one high-pressure and one low-pressure turbine, and in some cases an intermediate pressure turbine. Figure 1.9 shows a typical

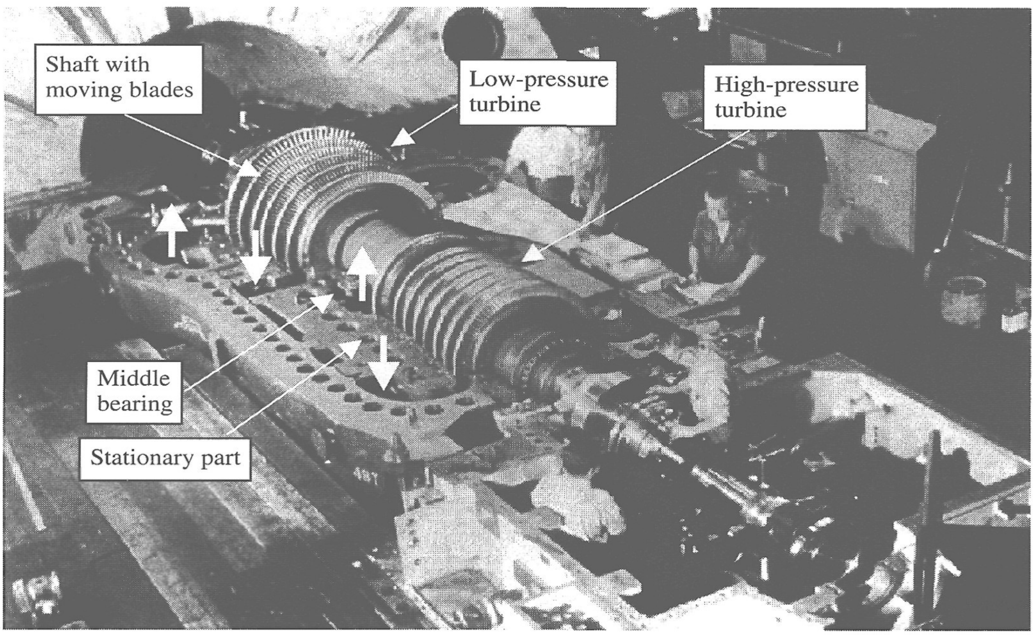


Figure 1.9 Steam turbine internals. (Courtesy Salt River Project).

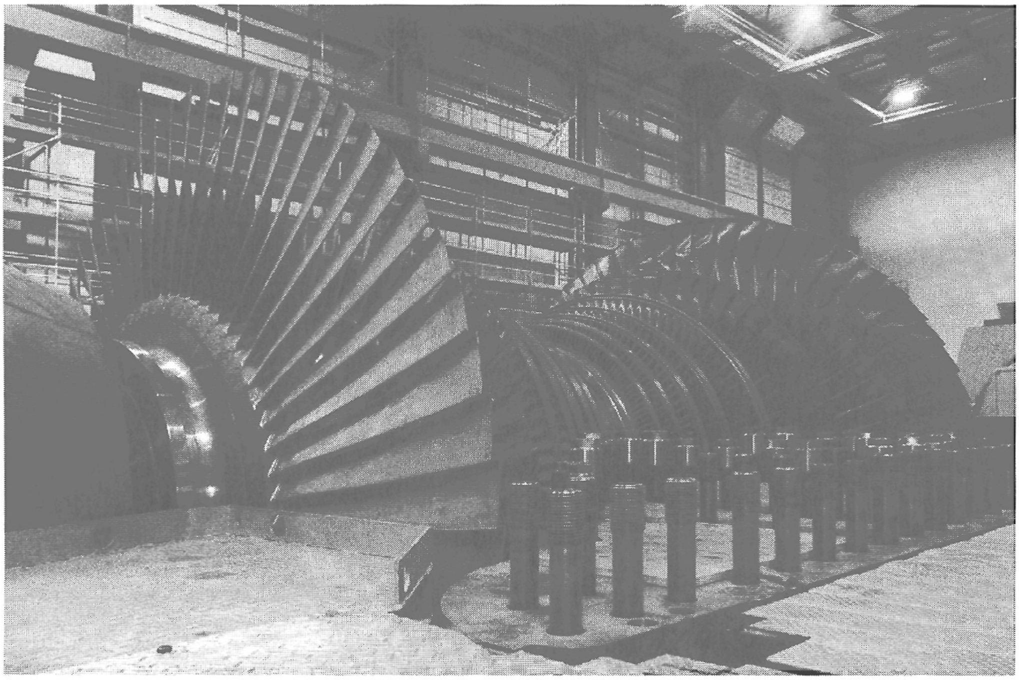


Figure 1.10 Turbine blades in a large unit. (Courtesy Siemens).

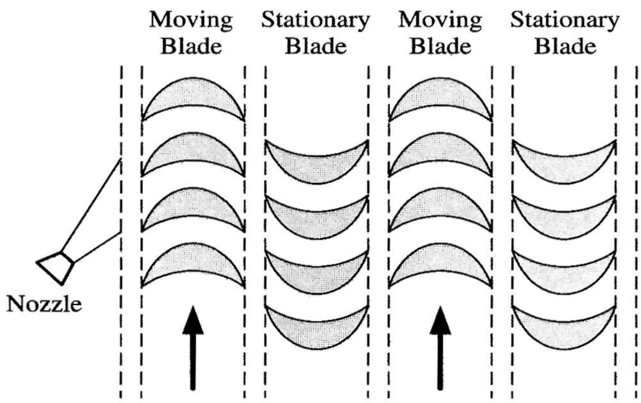


Figure 1.11 Operating concept of a steam turbine.

unit with two turbines. The right-hand side is the high-pressure turbine; the left-hand side is the low-pressure turbine. A bearing is placed between the two units. The steam enters at the right-hand side, drives the high-pressure turbine and exhausts before the middle bearing. The exhausted steam is reheated and fed to the low-pressure turbine. The reheated steam enters just behind the middle bearing and drives the low-pressure turbine. The steam exhausts at the end of the turbine. The arrows indicate the steam entrance and exhaust points.

1.3.4 Generator and Electrical System

The generator and turbine are mounted on the same pedestal and the shafts are directly connected. A condenser, turbine, generator and main transformer of the Kyrene Generation Station are shown in Figure 1.12.

The generator stator has a laminated iron core with slots. Three-phase windings are placed in the slots. The large generators are wye (Y) connected. The winding is made of mica insulated copper bars. Figure 1.13 shows the *stator* of a large generator under construction.

Typically, the high-speed generator used in steam power plants has a round *rotor*. The round rotor is a solid iron cylinder with slots. Insulated copper bars are placed in the slots to form a coil, which is supplied by dc excitation current. Figure 1.14 shows the massive iron core with the slots, but without the winding. It can be seen that the slots do not cover the entire surface of the rotor. The area without the slots forms the magnetic poles.

The generator operating principle is that the dc current in the rotor generates a magnetic field. The turbine spins the rotor and the magnetic field. The rotating field induces voltage in the stator three-phase windings.

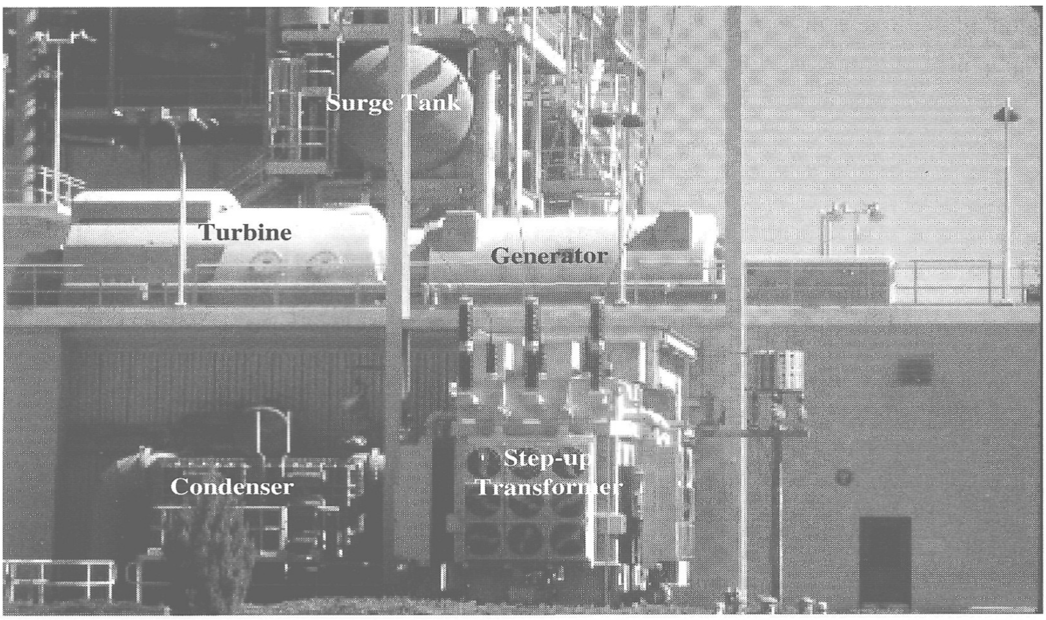


Figure 1.12 Turbine, generator and main transformer of Kyrene Generation Station. (Courtesy Salt River Project).

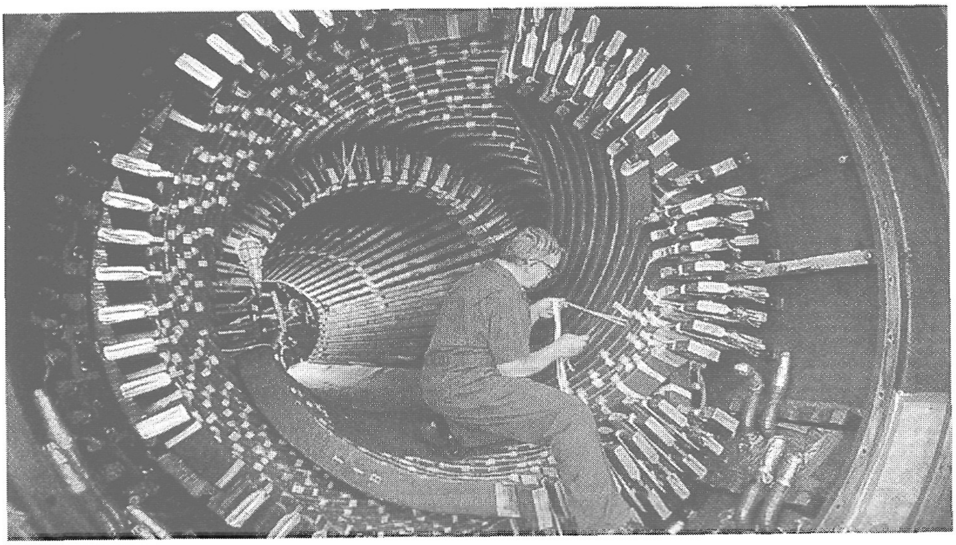


Figure 1.13 Synchronous generator stator. (Courtesy Westinghouse Corporation).

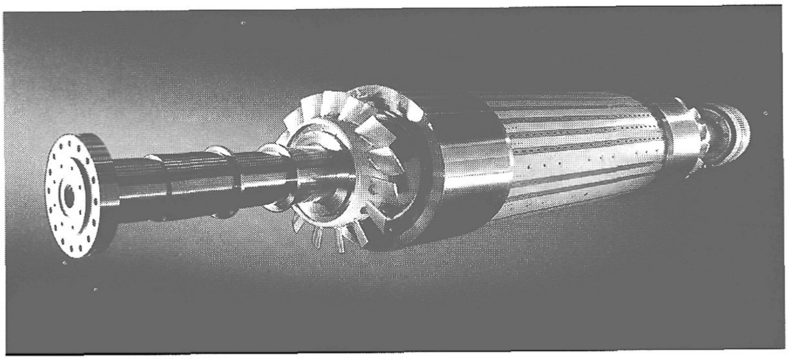


Figure 1.14 Synchronous generator rotor. (Courtesy Siemens).

The hydro generators use a salient pole rotor, as shown in Figure 1.15. This rotor has poles with dc windings. The poles are supplied by dc current through brushes connected to the slip rings.

High-pressure oil-lubricated bearings support the rotor at both ends. The bearings are insulated at the opposite side of the turbine connection to avoid shaft currents generated by stray magnetic fields.

The small generators are cooled by air, which is circulated by fans attached to the rotor. The large generators are hydrogen cooled. The hydrogen is circulated in a closed loop and cooled by a hydrogen-to-water heat exchanger. The very large generators are water-cooled. The cooling water is circulated through the special hollow conductors of the windings.

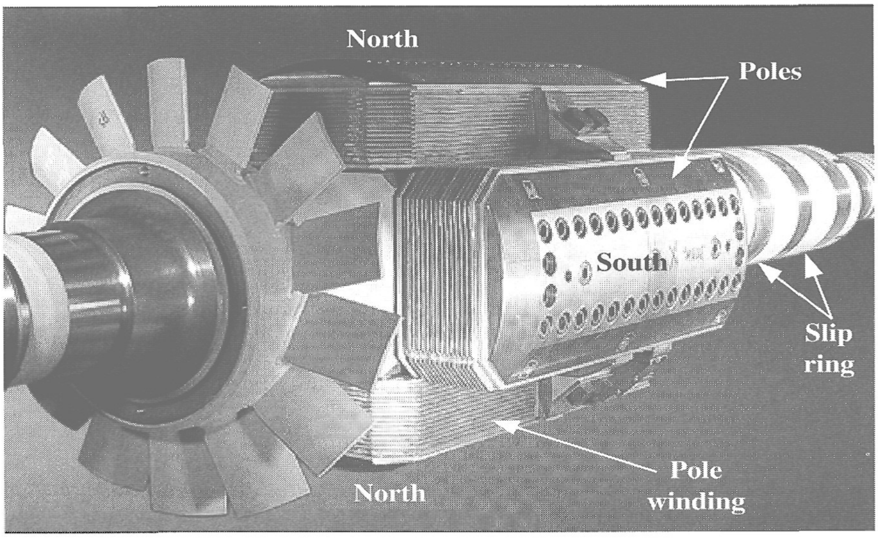


Figure 1.15 Salient pole rotor. (Courtesy Siemens).

The dc excitation current may be produced by rectifiers and connected to the rotor through slip rings and brushes. Some units are equipped with a shaft-mounted brushless excitation system.

The generator operation and construction will be discussed in greater detail in Chapter 6, which addresses synchronous machines.

The generator converts the turbine mechanical energy to electrical energy. The energy generated by the power plant supplies loads through transmission lines. The motors, mills, and pumps in a power plant require auxiliary electrical energy, which amounts to 10–15% of the power plant capacity.

Figure 1.16 shows a simplified connection diagram for a generating station. The generator is connected directly to the main transformer. The main transformer

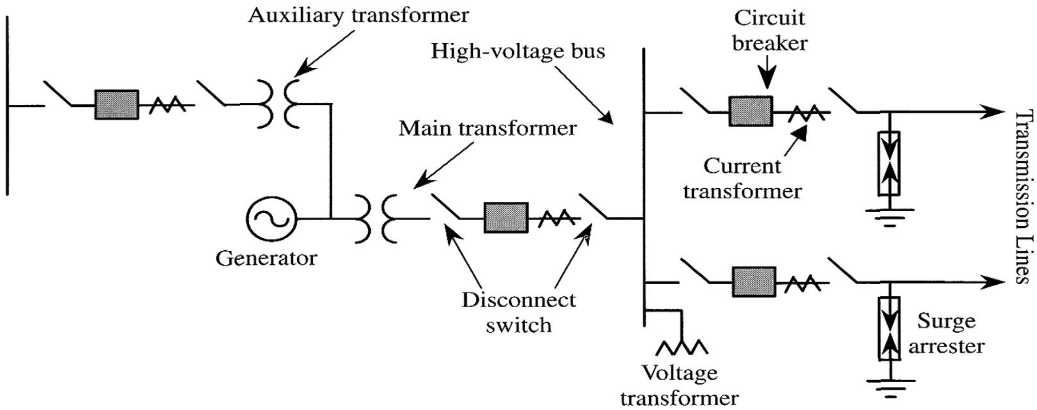


Figure 1.16 Simplified connection diagram of a generating station.

supplies the high-voltage bus through a circuit breaker, disconnect switches and current transformer. An auxiliary transformer is also connected directly to the generator. The generating station auxiliary power is supplied through this transformer. A circuit breaker, disconnect switches and current transformer protect the auxiliary transformer at the secondary side of the transformer. The use of a circuit breaker at the generator side is uneconomical in the case of large generators.

The high-voltage bus forms a node point and distributes the generator power among the transmission lines. The voltage of the bus is monitored using a voltage transformer.

The two outgoing transmission lines are connected to the bus. The lines are protected against lightning and switching surge by a surge arrester. Each line is also protected by a circuit breaker. Two disconnect switches permit the separation of the circuit breaker in case of circuit breaker fault. The current transformer measures the line current and activates the protection in the event of a line fault. The protection relay triggers the circuit breaker, which switches off (opens) the line. The high-voltage bus configuration in Figure 1.16 is not typical; the operation of a circuit breaker and other protection components will be discussed in more detail in Section 1.6.1.

1.3.5 Combined Cycle Plants

Combined cycle plants have become a popular generation scheme in recent years. A combined cycle unit uses a gas turbine (Brayton) top cycle with the excess heat going to a steam turbine (Rankine) bottom cycle, as shown in Figure 1.17. Air is compressed before injecting fuel for ignition in the gas turbine. The resulting combustion gases are first used to drive the gas turbine, then the hot exhaust gases

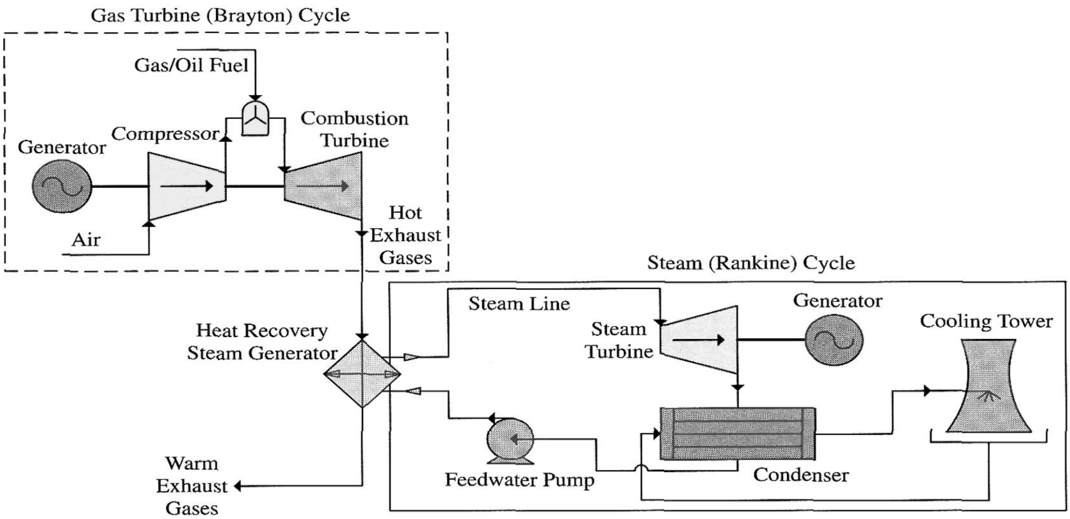


Figure 1.17 Combined cycle plant flow diagram.

are sent to a heat recovery steam generator (HRSG), before release through the stack. The heat transferred to the HRSG produces steam, which is used to drive a steam turbine-generator set. Some combined cycle plants use burners to increase (augment) the Rankine cycle steam quality. The bottom steam cycle employs condenser cooling, as is normally found in a thermal power plant.

The overall thermal efficiency of combined cycle plants built today is a remarkable 60%. Combined cycle plants are designed for intermediate load since they are relatively quick to start. Additional advantages of these plants are that they can be constructed in a relatively short period (about 2 years), and their use of natural gas, which is an environmentally good choice (except for greenhouse gas emission), and a reasonably priced fuel.

The *greenhouse effect* on global warming has received significant attention in recent years. Many scientists believe that the increased emission of greenhouse gases, such as water vapor, carbon dioxide, nitrous oxide and methane, is causing the temperature of the Earth to rise. Short-wavelength radiation from the sun passes through the atmosphere without interference from the greenhouse gases. The transmitted sunlight is then absorbed by the Earth's surface. Later, the absorbed energy is re-emitted by the Earth as long-wavelength radiation. This long-wavelength radiation (unlike the short-wavelength sunlight) is absorbed by the greenhouse gases (such as CO_2, which can originate from combustion); thus heating the Earth's atmosphere.

1.4 NUCLEAR POWER PLANTS

Nuclear power plants are a major part of the electrical energy generation industry. More than 500 plants are in operation worldwide. The most popular plants (close to 300) are the pressurized water reactors (PWRs). In addition, there are more than 100 boiling water reactors (BWRs) and 50 gas-cooled reactors. Further, close to 50 heavy-water reactors and a few breeder reactors operate around the world.

A nuclear power plant generates electricity in a manner very similar to a fossil power plant. Typically, nuclear plants provide base energy, running at practically constant load. Their electric output is around 1000 MW. Concern with thermal pollution increased with the construction of nuclear plants due to their large size and lower thermal efficiency ($\eta_{th} \approx 33\%$) as compared to coal-fired units ($\eta_{th} \approx 40\%$), and the fact that all the heat rejection from a nuclear plant is via the condenser cooling water, whereas a fossil unit also releases excess heat through the stack. For this reason nuclear plants sought alternative heat-dissipation techniques such as the tall natural draft cooling towers, with which nuclear units are so commonly associated.

The advantages of nuclear power are the abundant and relatively cheap fuel, and the pollution free operation in normal conditions. However, leaks or equipment failure could allow radioactive gas or liquid (water) discharge that might pose a health hazard to the surrounding communities. An additional unanswered question is the final storage of the spent fuel, which is radioactive and hazardous. A similar concern is the decommissioning of old and obsolete plants.

Decreased energy consumption in the United States after the energy crises of the 1970s, along with the listed environmental and health concerns, stopped or slowed the building of new nuclear plants and curtailed the operation of several existing plants in the United States. These actions resulted in severe financial losses for several utilities. Nevertheless, several hundred nuclear plants are in operation and generating large amounts of energy worldwide.

1.4.1 Nuclear Reactor

Most power reactors use enriched uranium as a fuel. The UO_2 is pressed into pellets and the pellets are stacked in a Zircaloy-clad rod. These rods are the fuel elements used in a reactor. Many fuel rods are placed in a square lattice to construct a fuel assembly, as shown in Figure 1.18. A couple hundred fuel assemblies are generally needed to fuel the entire reactor core. This reactor core is housed in a reactor pressure vessel that is composed of steel 8 to 10 inches thick. The reactor core is filled with fuel and control rods. The atomic reaction is controlled by the position of the control rods. Figure 1.19 shows the nuclear reactor vessel where the core is located. The control and fuel rods are arranged in a pattern carefully calculated during the reactor design.

Most reactors use neutrons in thermal equilibrium (<0.1 eV) with a moderator to sustain the chain reaction, and hence, are called thermal reactors. The fission reaction emits neutrons at fast energy levels (>1 MeV). Thermal reactors employ a moderator such as light water, heavy water, or graphite to slow down the

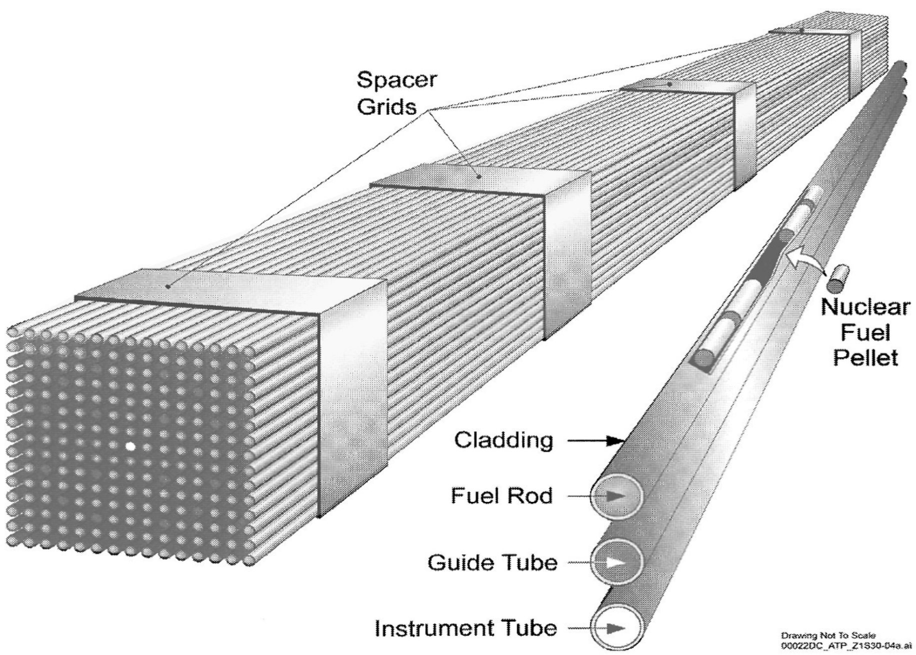


Figure 1.18 Nuclear reactor fuel pellet, rod and assembly. (*Source*: DOE OCRWM).

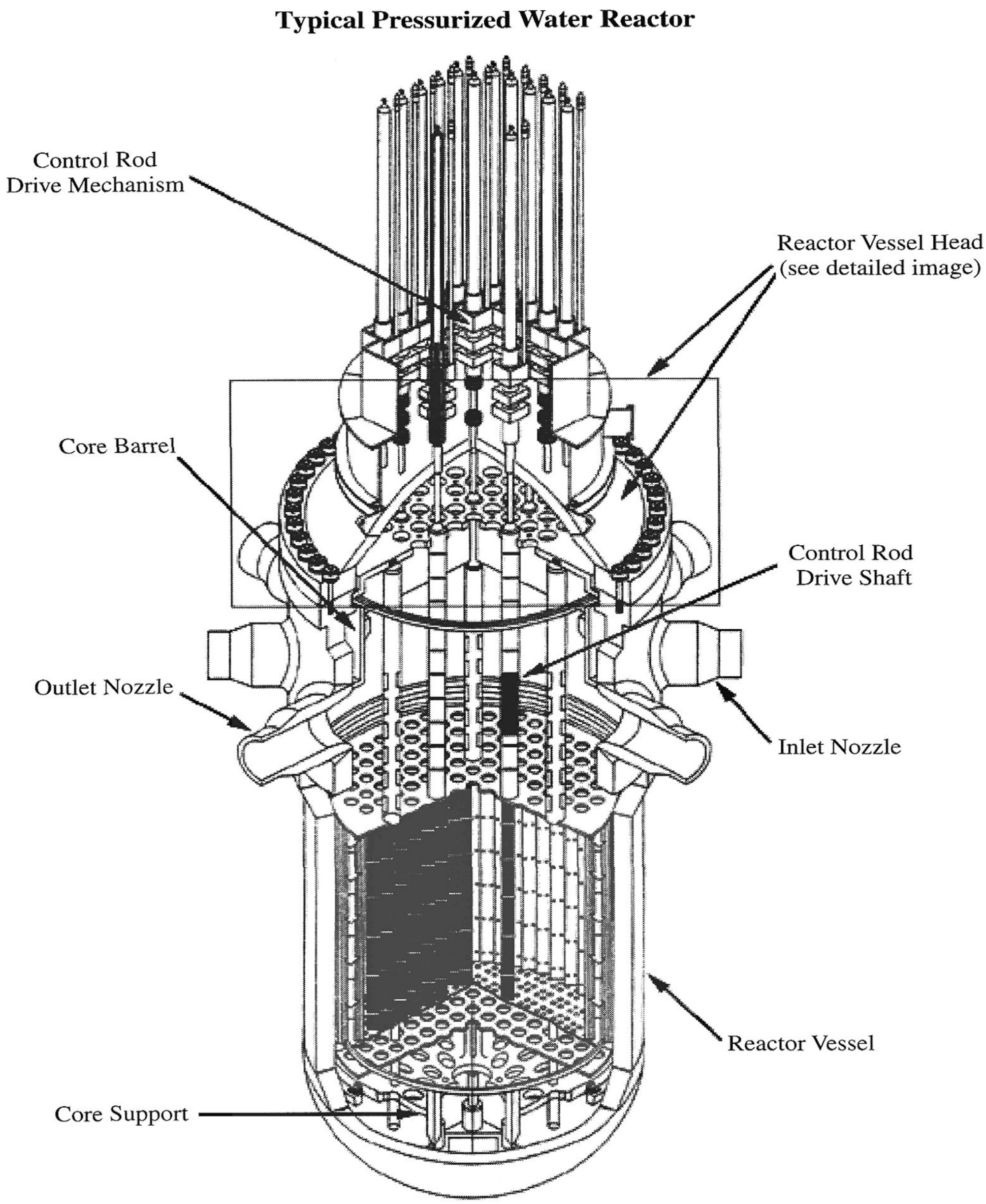


Figure 1.19 Nuclear reactor vessel. (*Source*: DOE EIA).

neutrons. Such thermal reactors are easier to control than fast (breeder) reactors and some designs can use natural uranium. In the United States, most nuclear plants utilize light water reactors (LWRs), which include the PWRs and BWRs.

The nuclear reaction starts if sufficient numbers (a critical mass) of rods are placed in a confined space. Natural uranium consists of about 0.7% of the isotope uranium-235 (U-235) and the remainder (99.3%) is U-238. Uranium-235 readily undergoes fission by thermal neutrons, whereas U-238 does not. In most cases, the fuel is enriched to about 3% U-235 to achieve a sustained reaction.

The neutron absorption by the uranium initiates atomic fission. The fission of the uranium expels ν neutrons and releases heat energy (Q).

$$^{235}_{92}\mathrm{U} + ^{1}_{0}n \rightarrow (^{236}_{92}\mathrm{U})^{*} \rightarrow ^{A_1}_{Z_1}\mathrm{X} + ^{A_2}_{Z_2}\mathrm{X} + \nu\ ^{1}_{0}n + Q$$

The freed neutrons ($\nu \approx 2$–3 emitted neutrons per fission) sustain the chain reaction; the generated heat is utilized to produce steam. In addition to neutrons and heat, the nuclear fission produces 2–3 fission fragments (X). These fission products are radioactive and have half-lives on the order of a thousand years.

The cooling water enters the reactor, flows through the core and removes the heat generated by the nuclear fission. Safe reactor operation basically involves making sure that heat is adequately removed from the core in order to avoid release of radioactivity from the plant. This can be ensured by maintaining the UO_2 fuel temperature below its melting temperature of about 5000°F, and by keeping the cladding temperature below the point (≈2200°F) at which the exothermic zirconium–water reaction occurs.

The nuclear reaction is controlled to maintain proper heat generation. The reaction is regulated using control rods, which can be constructed of neutron-absorbing material such as boron, silver, cadmium, and indium. The withdrawal of the control rods increases the reaction rate and heat generation. The insertion of the control rods reduces the power generation. The reactor is shut down by inserting all the control rods into the core.

In addition to causing fission, some neutrons undergo parasitic capture by the uranium-238. The added neutron increases the atomic mass of the U-238, which can be transformed to plutonium-239 via the following reactions and radioactive decays:

$$^{238}_{92}\mathrm{U} + ^{1}_{0}n \longrightarrow ^{239}_{92}\mathrm{U} \xrightarrow{23.5\ \mathrm{min}} ^{239}_{93}\mathrm{Np} + ^{0}_{-1}\mathrm{e}$$

$$^{239}_{93}\mathrm{Np} \xrightarrow{2.355\ \mathrm{day}} ^{239}_{94}\mathrm{Pu} + ^{0}_{-1}\mathrm{e}$$

Pu-239 and other nuclides of higher atomic number than uranium are termed the *transuranics*. The transuranics are radioactive and long-lived, having half-lives of thousands of years.

Nuclear waste is classified as either low-level or high-level waste. Low-level waste includes clothing, rags, and tools, which are sealed in a drum for ultimate placement in a dedicated landfill. The high-level waste includes fission products and transuranic isotopes, and is highly radioactive and must be stored for long periods. Approximately once every 18 months the reactor is shutdown for refueling, at which point about one-third of the (spent) fuel assemblies are removed. At present, United States government policy prohibits chemical reprocessing of spent fuel rods from commercial nuclear power plants. Instead, the spent fuel assemblies will likely be placed in corrosion-resistant metal canisters, which will be housed in an underground repository. For the past 20 years, studies have been conducted to determine whether Yucca Mountain (located 100 miles northwest of Las Vegas, Nevada) can serve as a suitable geologic repository.

1.4.2 Pressurized Water Reactor

Pressurized water reactors (PWRs) are the dominant reactor type for electric power plants and are also the basis of naval reactors. The flow diagram of a pressurized water reactor (PWR) is presented in Figure 1.20. The reactor has two water loops: a primary (radioactive) water loop and a secondary water (steam) loop. This two-loop system separates the reactor cooling fluid from the steam loop. The entire reactor coolant system is housed in a concrete containment building designed to prevent the release of radioactivity to the environment.

A coolant pump circulates the water in the primary loop through the reactor and steam generator (heat exchanger). The reactor heats the primary coolant system water to about 550°–600°F. The pressurizer maintains a water pressure around 2200 psia. This high pressure prevents water boiling and steam generation in the reactor core.

In the clean water-steam loop, pumps drive the feedwater into the steam generator. Because of the relatively low secondary-side pressure ($\approx$1000 psia), the heat exchanger evaporates the water and produces steam. The produced steam drives the turbine. This system is similar to that of the conventional thermal plants previously described. The condenser produces vacuum and extracts the steam from the turbine when the water is condensed. The condensed water is reheated by the high-pressure feedwater heater and fed back to the steam generator. The feedwater is heated by steam extracted from the turbine.

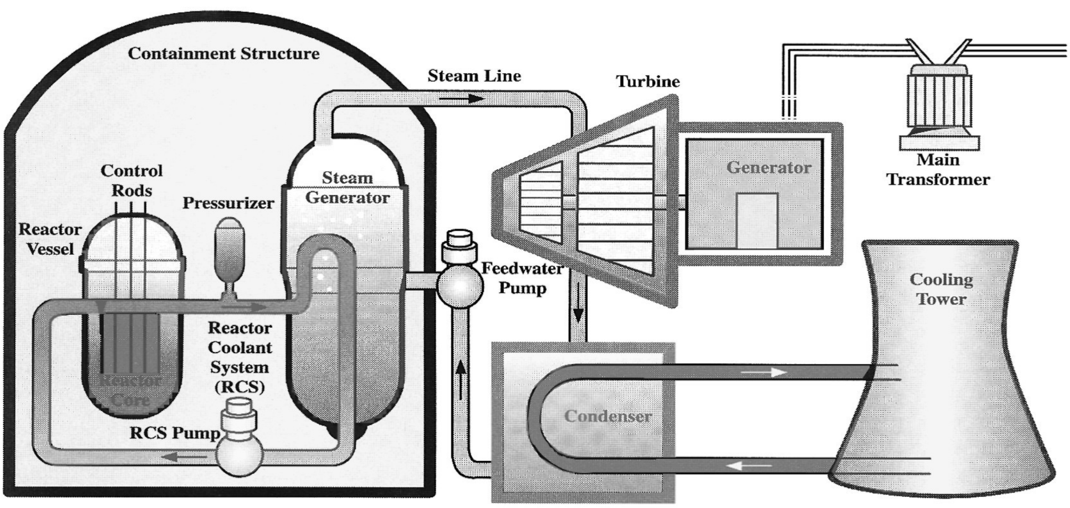


Figure 1.20 Pressurized water reactor (PWR) nuclear power plant.

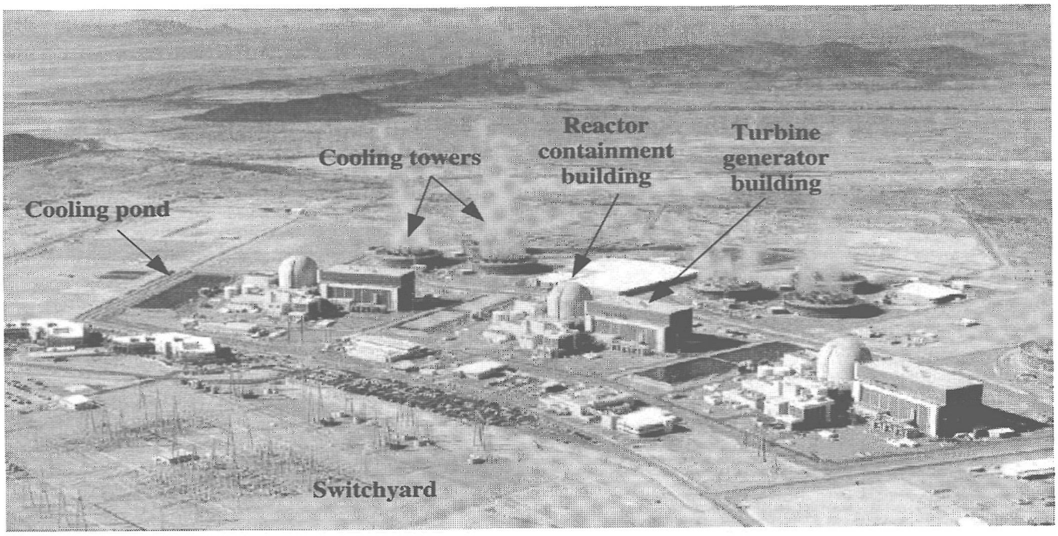


Figure 1.21 Aerial view of the Palo Verde Nuclear Generating Station. (Courtesy Salt River Project).

Figure 1.21 shows an aerial view of the Palo Verde Nuclear Generating Station in Arizona. The plant has three reactors that are housed in dome-shaped concrete structures. The turbines and generators are placed in separate buildings. The nuclear fuel is stored in bunkers just in front of the reactors. The condensers are cooled by mechanical draft cooling towers. Each reactor has three cooling towers and a cooling pond. A large 500 kV switchyard is in the front of the PWR power plant.

1.4.3 Boiling Water Reactor

Boiling water reactors (BWRs) are another reactor type commonly used for electric power plants. The boiling water reactor (BWR) has a single water-steam loop. The reactor heats the water and generates steam. Unlike a PWR, the water heated by the BWR nuclear core is sent directly to the turbine. The steam temperature is around 545°F and the pressure is 1000 psia. Steam separators located within the reactor vessel partition the water liquid and vapor. The liquid water flows downward, mixes with the feedwater and returns to the reactor. The steam drives the turbine, which typically rotates with a speed of 1800 rpm. Figure 1.22 shows that the feedpumps drive the condensed water back to the reactor. The remainder of the plant is similar to a conventional thermal power plant system.

Jet pumps maintain water circulation through the reactor core. The control rods (blades) of the BWR enter the reactor from the bottom since steam separators are located above the reactor core and because the boiling of water near the top of the reactor core decreases the nuclear fission rate.

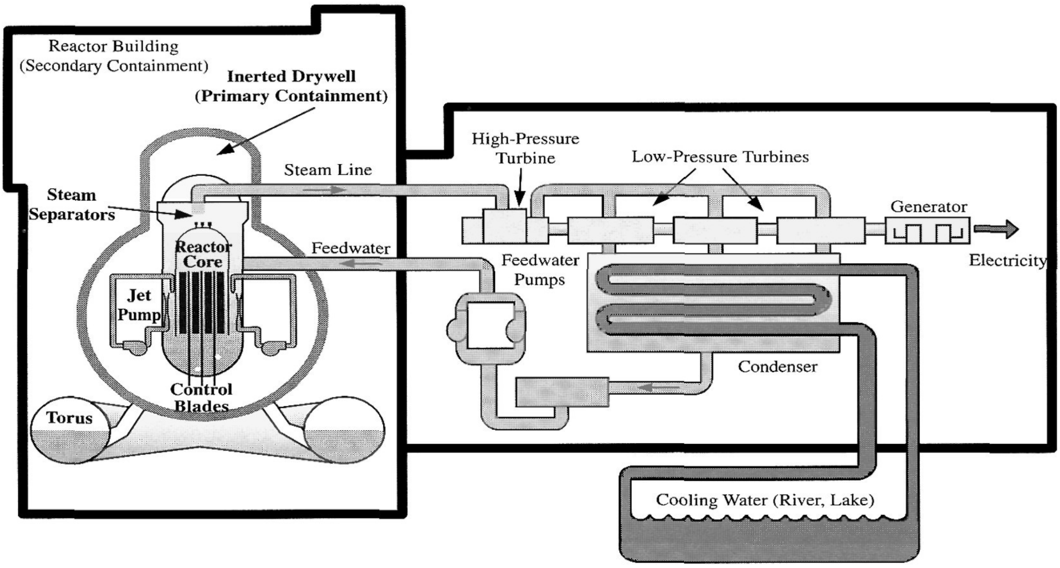


Figure 1.22 Boiling water reactor (BWR) nuclear power plant.

1.5 HYDROELECTRIC POWER PLANTS

Hydroelectric power plants convert the potential energy of the water head to mechanical energy by a hydraulic turbine, and the generator converts the mechanical energy to electric energy. There are two kinds of hydroelectric plants (dams):

1. "Run-of-the-river" (diversion) plants, in which water is continuously passed with limited reservoir storage (*e.g.*, the Bonneville Dam on the lower Columbia River); and
2. "Storage" dams, in which water is released as needed and available (*e.g.*, the Glen Canyon Dam on the Colorado River).

Although storage dams are used for peak power production, the large capital costs incurred from dam construction are nevertheless justifiable since a dam may have several purposes including electricity generation, flood control, navigation, irrigation, public water supply, and recreation.

Figure 1.23 shows the general concept of a hydro plant using the medium or low head plant as an example. A dam built across a river produces an upper-level reservoir and tail water. The difference between the water level at the reservoir side and tail waterside of the dam is the *head*. A powerhouse is built into the dam. The powerhouse has a hydro turbine, generator, and control gates. The generator and turbine have vertical shafts, which are directly connected. The head generates fast-flowing water through the turbine. The water drives the turbine-generator set. The rotating generator produces the electricity. The power

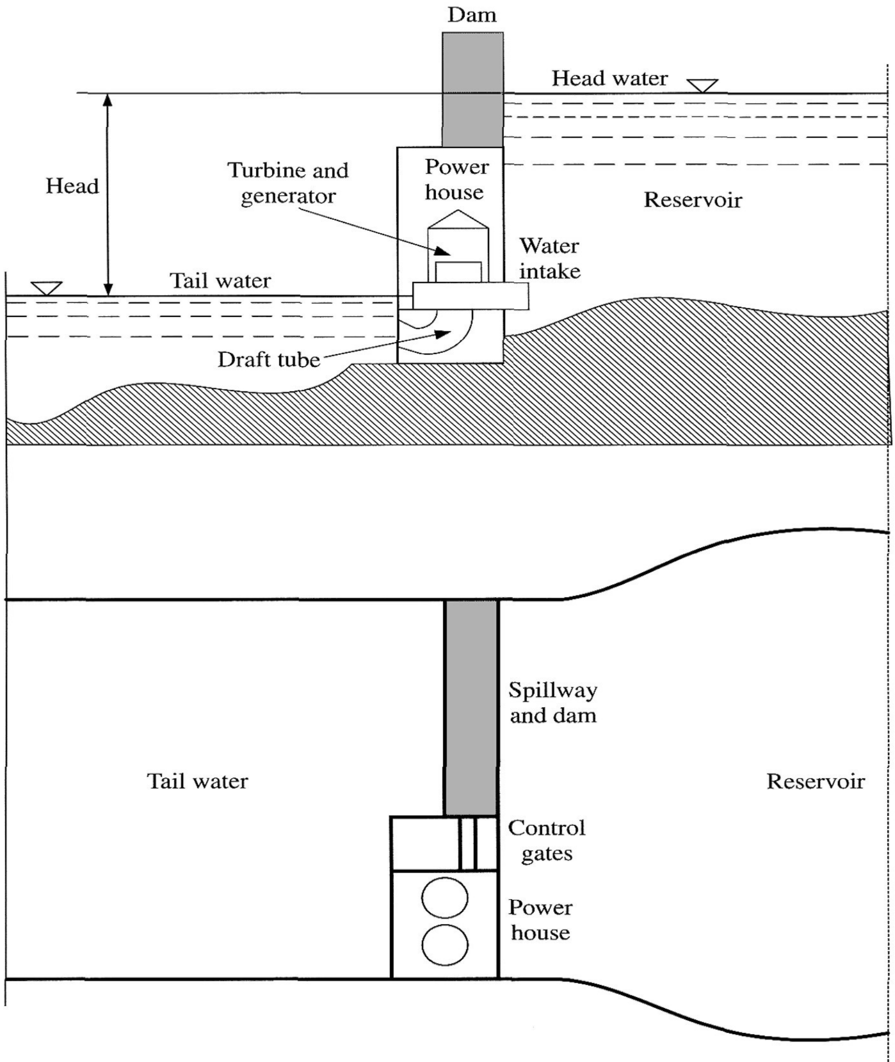


Figure 1.23 Hydroelectric power plant (medium or low head).

obtained from a hydro plant is the product of the head (H), water density (ρ), and volumetric flow rate ($\dot{V}$):

$$P = H \rho g \dot{V}, \qquad (1.3)$$

where g is gravitational acceleration. The water discharged from the turbine flows to the tail water reservoir, which frequently is the continuation of the original river. Control gates regulate the flow through the turbine. In the event of a flood, the spillway gates open sending overflow across the dam, or diversion gates at the bottom of the dam may be opened. Both actions allow the direct flow of the excess water to the tail water reservoir, which eliminates the overloading of the dam. Additional gates at the water intake and draft tube permit the isolation and removal of water from the turbine during maintenance.

1.5.1 Low Head Hydro Plants

Figure 1.24 shows the cross-section of a low head powerhouse, with a Kaplan turbine. A large oil-immersed truss bearing supports both the generator and turbine. The upper, watertight chamber houses the vertical shaft generator. The vertical shaft Kaplan turbine is like a large propeller with 4–10 blades. The pitch of the blades is adjustable between 5° to 35° by a hydraulic servomechanism.

The water enters the turbine through gates and is evenly distributed by a spiral casing surrounding the turbine. The flow is regulated by "wicket gates" and by the adjustment of the pitch. The water speed in the turbine is around 10–30 ft/s. The water is discharged from the turbine through an elbow-shaped draft tube that reduces the water velocity to 1–2 ft/s.

The hydro generator is a salient pole machine. Typically, the machine has 20–72 poles. These poles are supplied by dc current and they produce the magnetic field that induces the voltage in the generator. The shaft speed is 100–300 rpm. Figure 1.25 shows a large hydro generator in the construction phase.

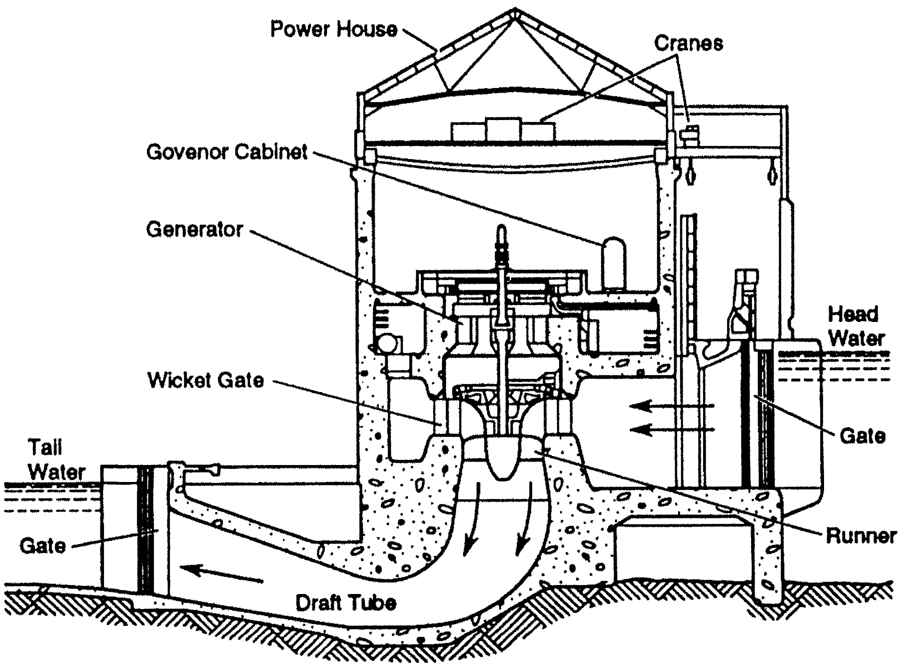


Figure 1.24 Cross-section of a hydropower house. (*Source*: D.G. Fink, *Standard Handbook for Electrical Engineers*, New York: McGraw-Hill, 1978, with permission).

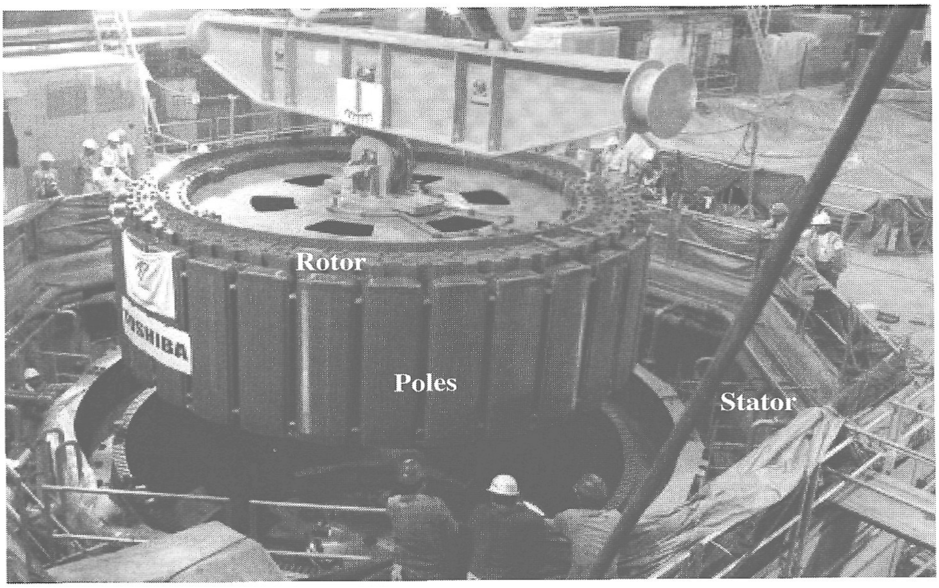


Figure 1.25 Large salient pole hydro generator under construction. (Courtesy Toshiba).

A welded spoke wheel supports the pole spider. The poles have a laminated iron core with dc windings, using stranded copper conductors. Short-circuited damper bars are built in each pole face.

The stator is laminated iron with slots. A welded steel frame holds the iron core. A three-phase winding is placed in the stator slots. The turn-to-turn insulation is fiberglass or Dacron glass. The turn-to-ground insulation is epoxy or polyester resin impregnated mica tape. The larger machines have a braking system that rapidly stops the machine when removed from service.

1.5.2 Medium- and High-head Hydro Plants

In addition to the described low-head hydro, medium- and high-head hydro plants are in operation. The medium-head hydro has similar construction, but uses the Francis turbine, which has a different blade arrangement, as shown in Figure 1.26.

Figure 1.27 shows the arrangement of a high-head hydro plant. The high-head hydro uses an impulse turbine. The large head-produced, high water pressure is converted to a high-velocity water jet, which drives the turbine. The rating of a high-head hydro plant is generally less than 100 MW.

1.5.3 Pumped Storage Facility

Also related to hydroelectric power is the practice of using pumped storage facilities as an energy storage device. Pumped storage facilities consist of both high-elevation and low-elevation reservoirs, as shown in Figure 1.28. The power-plant chamber of the pumped storage facility houses a reversible hydraulic turbine

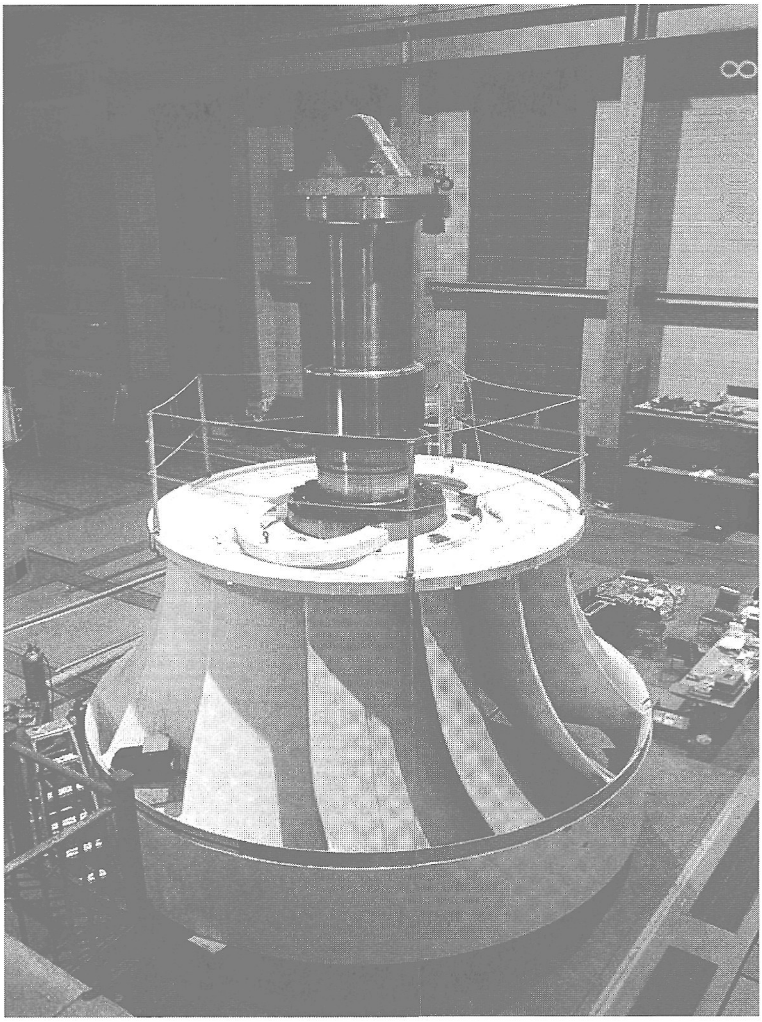


Figure 1.26 Wheel of a medium head Francis turbine. (Courtesy Hydro-Québec).

similar to that used in a dam. The direction of this turbine can be reversed by supplying the special motor-generator with electricity, such that it becomes a pump to transfer water to the upper reservoir. Such pumped storage units, like hydro plants, can provide power on very short notice.

The pumped storage plant consumes electricity during low-demand (night-time) to pump water from the low-elevation body of water to a high-elevation reservoir. Then during peak power demands (daytime), the water is allowed to flow back down and generate electricity before returning to the low-elevation lake. Of course, more electricity is used to pump the water uphill than is subsequently generated in the return downhill. However, overall the pumped storage is economical because it generates high-cost, on-peak electricity while consuming

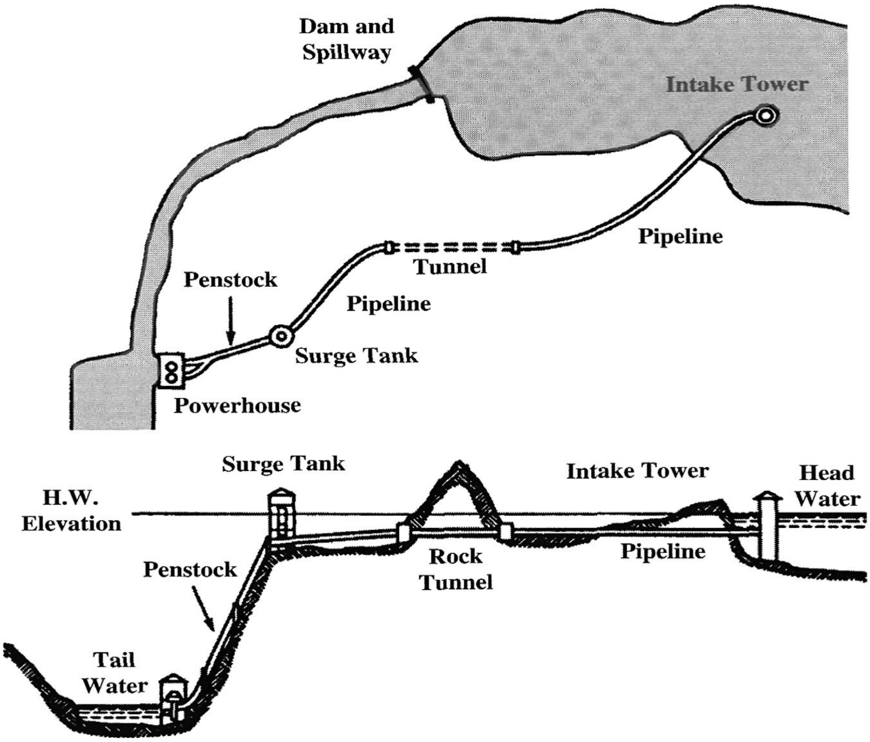


Figure 1.27 High-head hydro power plant (*Source*: D.G. Fink, *Standard Handbook for Electrical Engineers*, New York: McGraw-Hill, 1978, with permission).

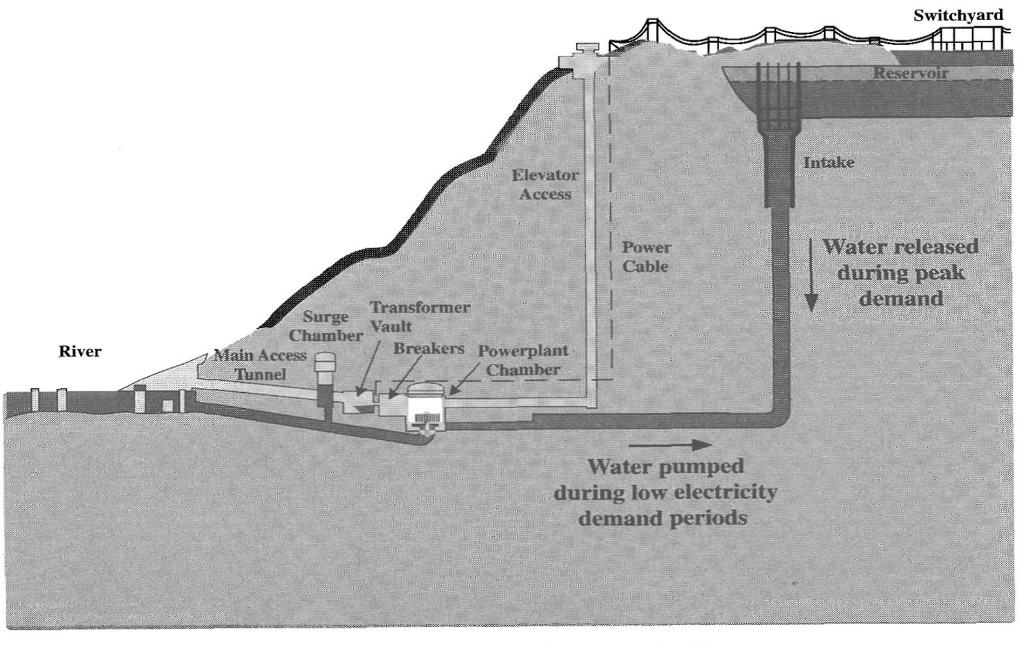


Figure 1.28 Pumped storage facility.

low-cost, off-peak energy. Additionally, the upper reservoir experiences some evaporative water loss.

1.6 DISTRIBUTION SYSTEM

The electrical network that connects the power plants and load centers together brings the electricity near to towns and other loads. Figure 1.2 shows that the high-voltage system has several loops, and in most cases, at least two transmission lines are connected to each substation or power plant. The sub-transmission lines supply the distribution stations around the town, as shown in Figure 1.1. The distribution system supplies the residential and industrial customers.

1.6.1 Substations and Equipment

Substations form the node points of the electric system. Figure 1.29 shows a typical substation. Their major role is to distribute the electrical energy and provide protection against faults on the lines and other equipment. Figure 1.1 shows three types of substations that are used:

1. Extra-high voltage substations (500 kV/230 kV);
2. High voltage substations (230 kV/69 kV); and
3. Distribution substations (69 kV/12 kV).

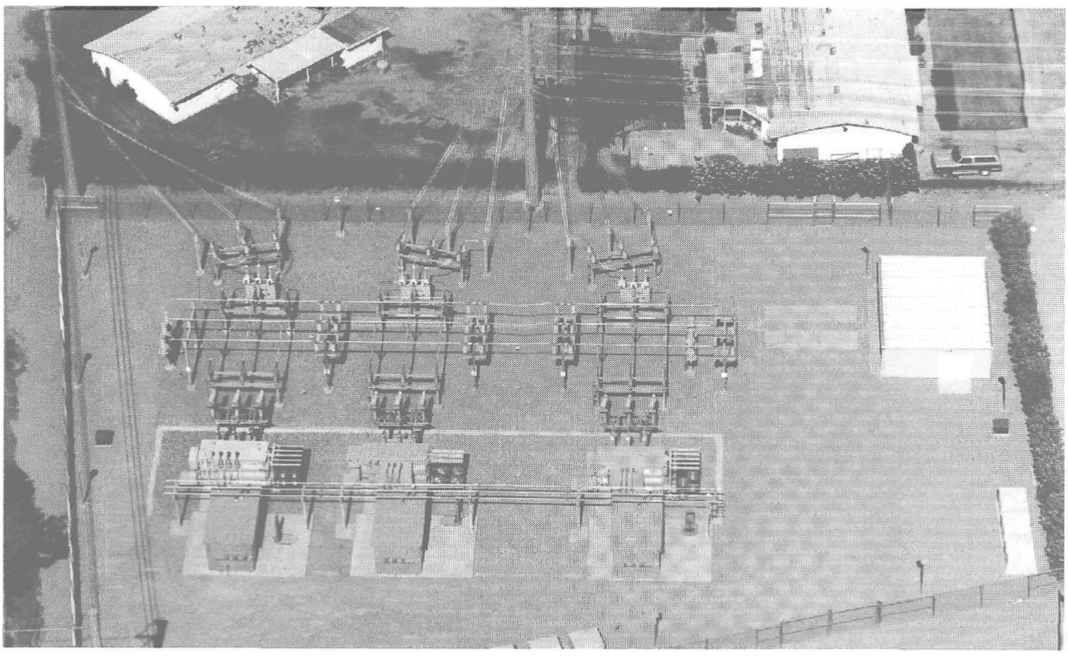


Figure 1.29 Aerial view of a three-bay distribution substation. (Courtesy Salt River Project).

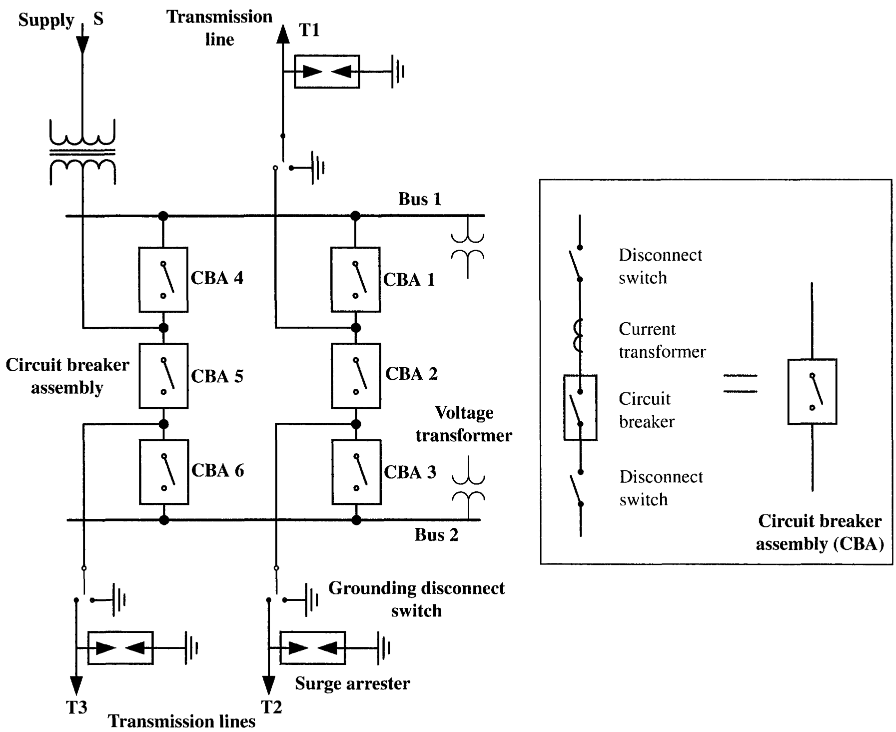


Figure 1.30 Concept of high-voltage substation electric circuit with a breaker-and-a-half configuration.

Although the circuit diagrams of these substations are different, the general circuit concept and major components are the same. Figure 1.30 presents a conceptual diagram for a high-voltage substation. That circuit is frequently called the "breaker-and-a-half bus scheme". The rationale behind the name is that two lines have three circuit breakers.

The primary equipment is as follows:

Circuit breaker (CB), which is a large switch that interrupts load and fault current. The fault current automatically triggers the CB, but the CB can be operated manually. A circuit breaker has a fixed contact and a moving contact placed in a housing that is filled with SF_6 (sulfur hexafluoride) gas. Figure 1.31 shows a simplified contact arrangement. 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 SF_6 blows out the arc. The operating principle for an actual circuit breaker is demonstrated in Figure 1.32. The

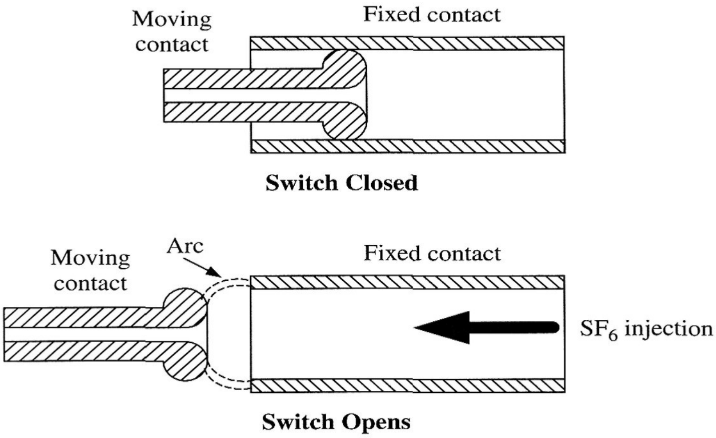


Figure 1.31 Simplified circuit breaker operation.

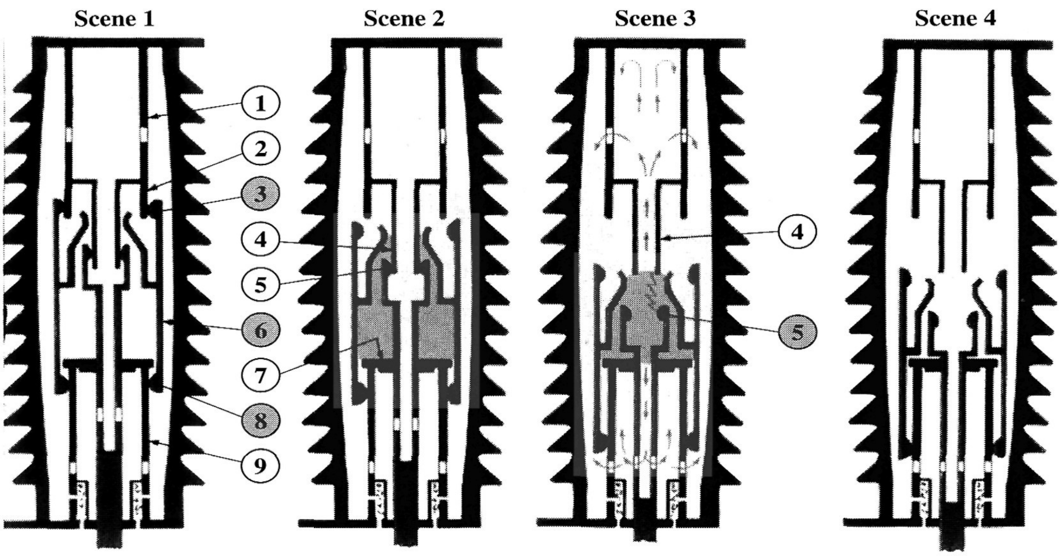


Figure 1.32 SF_6 circuit breaker operation sequence.

circuit breaker 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 SF_6, as

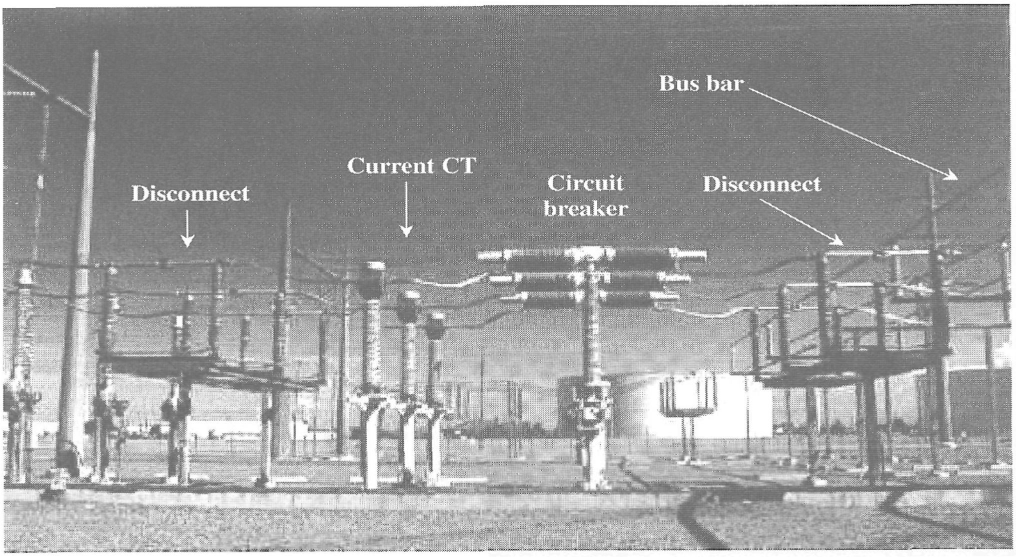


Figure 1.33 Circuit breaker assembly on a 69 kV substation.

shown by the small arrows in Scene 3. The SF_6 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 live-tank breaker, the switch is supported by insulators, and the switch is placed in a porcelain housing and insulated from the ground. Figure 1.33 shows a live-tank breaker. The switch is in the cross-arm. The vertical porcelain column insulates the 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 SF_6. Large bushings connect the electricity to the switch. Figure 1.34 shows a 500 kV SF_6 dead-tank circuit breaker.

Disconnect switch, which provides circuit separation and facilitates circuit breaker maintenance. The circuit breaker position cannot be determined by observation. But the lineman must know that the breaker is open for safety reasons. Also, in the event that CB maintenance is required, a disconnect switch is needed on each side of the CB to completely isolate the circuit breaker. A disconnect switch is a large device that provides visible evidence that the circuit is open, and it can be operated only when the circuit breaker is open. Figure 1.35 shows a typical disconnect switch, with a vertically rotating bar, that opens the switch. Figure 1.33 shows disconnect switches with horizontally moving bars.

Current and voltage transformers, which reduce the current to 5 A, or less, and the voltage to about 120 V, respectively. The current and potential transformers (PTs) insulate the instrumentation circuits from the high voltage and current. These signals trigger the protection relays, which operate

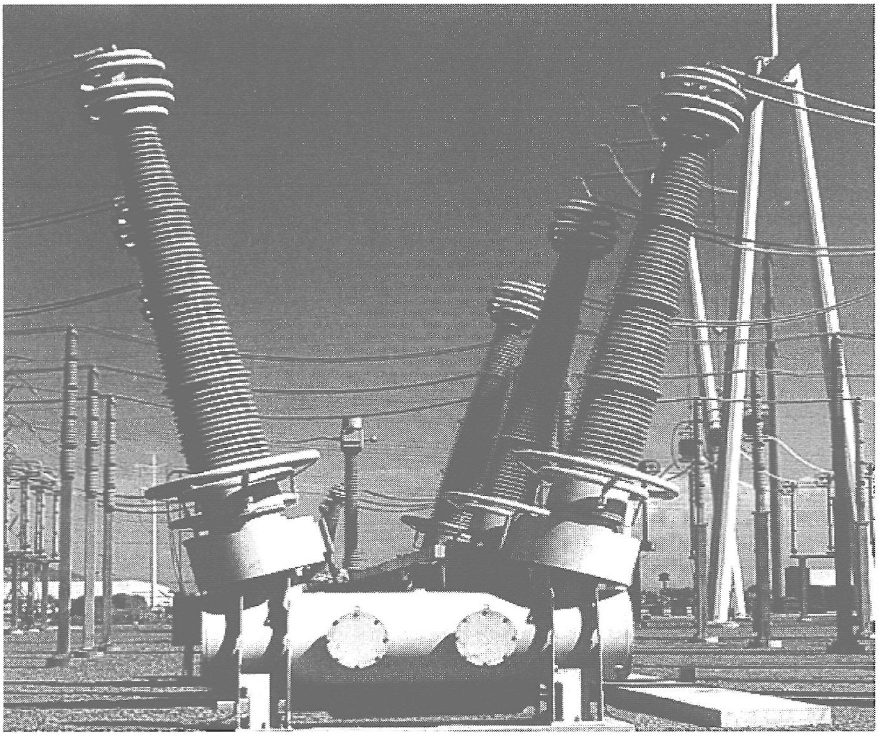


Figure 1.34 Dead tank 500 kV SF_6 circuit breaker.

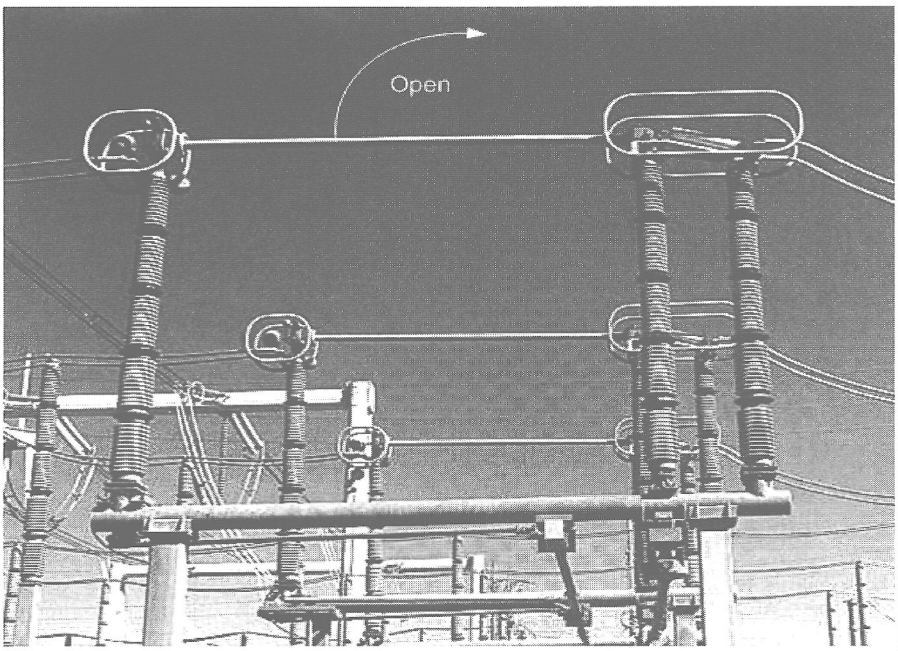


Figure 1.35 Disconnect switch, 500 kV.

the circuit breaker in case of fault. In addition, the low power quantities are used for metering and system control.

Surge arresters, which are used for protection against lightning and switching overvoltages. Figure 1.36 shows a surge arrester. The surge arrester contains a nonlinear resistor housed in a porcelain tube. A nonlinear resistor has very high resistance at normal voltage, but the resistance is greatly reduced when the voltage exceeds a specified level. This diverts lightning 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 current transformers (CTs) for proper operation. A circuit breaker assembly is shown on the right side of Figure 1.30 with a single CT. In the main diagram, the simplified box is used. The two disconnect switches in the circuit breaker assembly permit maintenance of any circuit breaker. In case of a circuit breaker failure, other breakers will provide backup to clear the fault. The opening of the two disconnect switches, after de-energization, permits breaker maintenance to be performed. The current transformer measures the line current and activates protection in case of a line fault. The protection triggers the circuit breaker, which opens the line to stop current flow. Figure 1.33 shows the circuit breaker assembly 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 1.30 shows that power entering through the supply transformer may flow directly through circuit breaker assembly 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: Circuit Breaker Failure Analysis. 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 1.30, there are two independent current paths between the supply (S) and each of the transmission lines (T1, T2 and T3). As an example, 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 1.30 is analyzed here for three cases: (*a*) short circuit on transmission line T1, (*b*) short circuit on Bus 1, and (*c*) circuit breaker 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 circuit breakers. For instance, a short circuit on line T1 triggers the protection that opens the two circuit breakers, CBA 1 and CBA 2. 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 1.37 shows the resultant current paths.

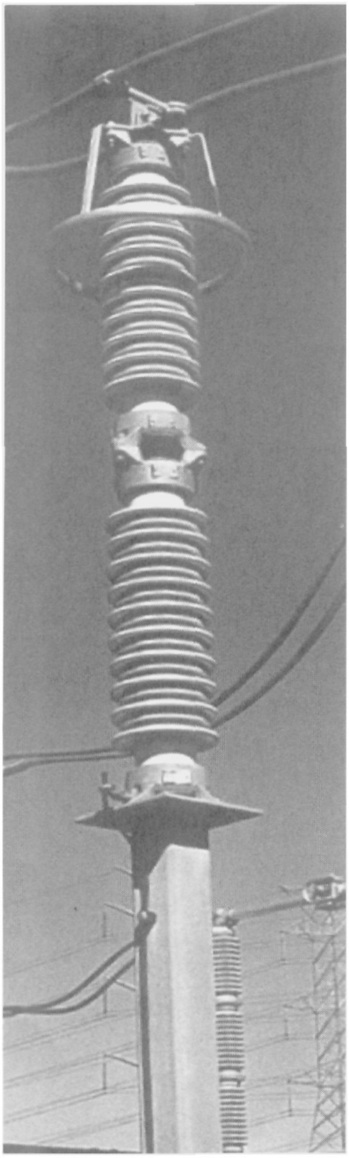


Figure 1.36 Surge arrester, 69 kV.

(*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, CBA 3 and 2; T2 is supplied through CBA 5, 6, Bus 2 and CBA 3; and T3 is supplied directly through CBA 5. Figure 1.38 shows the current pathways.

(c) Circuit breaker failure: The two circuit breaker failure modes are *fail open* and *fail close*. If a circuit breaker cannot be closed, it fails in the open

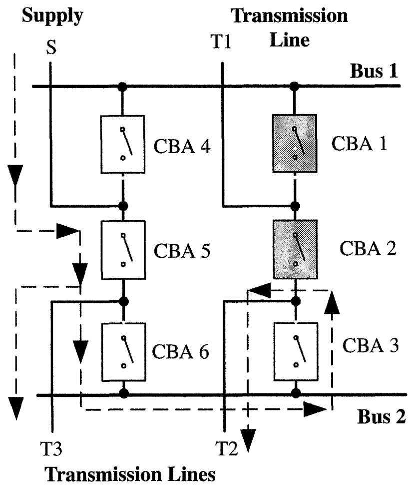


Figure 1.37 Current paths in the case of a short circuit on transmission line T1.

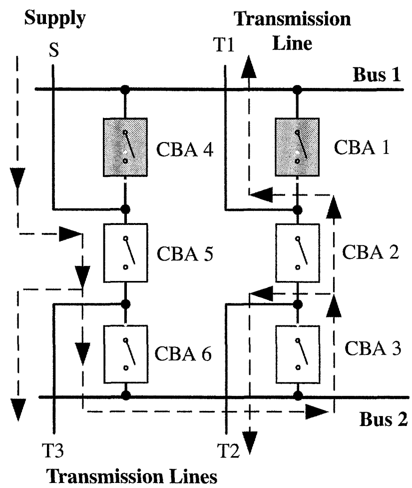


Figure 1.38 Current paths in the case of Bus 1 fault.

position. Similarly, if the circuit breaker cannot be opened (*i.e.*, current switched off), then it has failed closed. Below, 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 will be supplied through CBA 4, Bus 1 and CBA 1. T2 is powered through CBA 4, Bus 1, CBA 1 and 2; and T3 is supplied through CBA 4, Bus 1, CBA 1, 2, 3, Bus 2 and CBA 6. Figure 1.39 shows the current paths. It is observed from this scenario that the circuit breakers and busses must

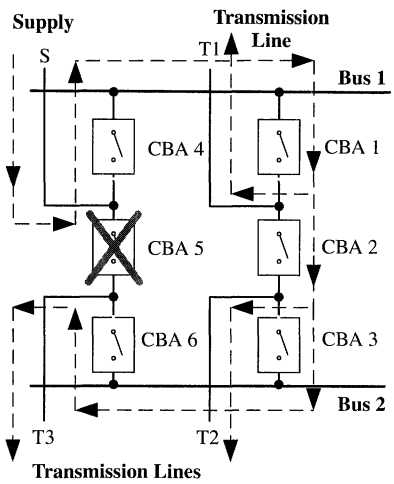


Figure 1.39 Circuit breaker CBA 5 fails in open position.

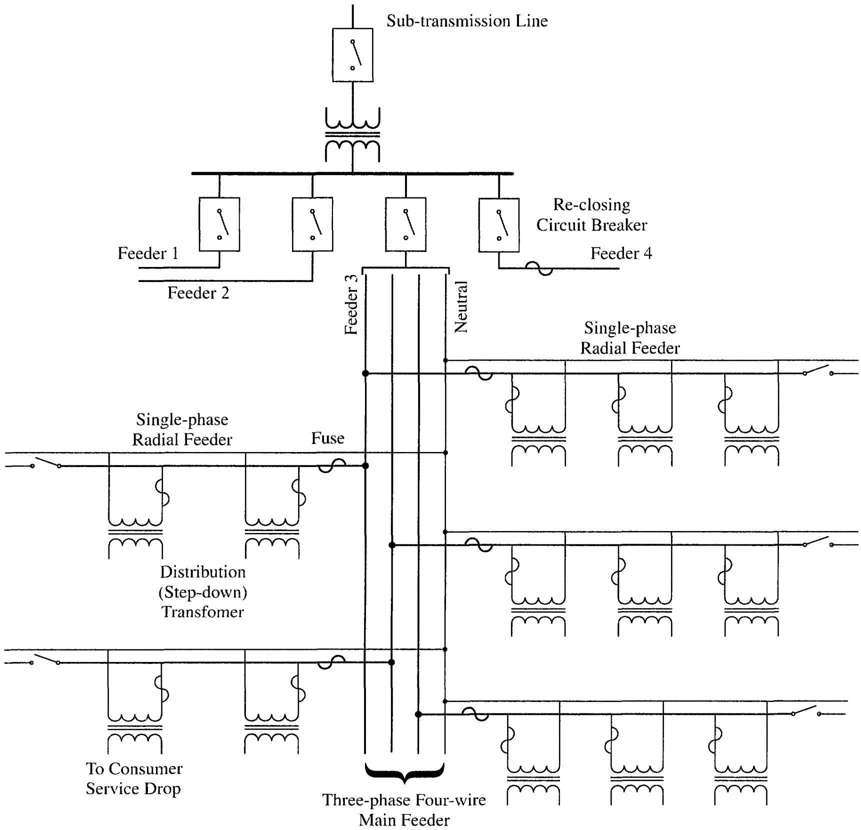


Figure 1.40 Concept of radial distribution system.

be specified to simultaneously carry all three load currents. Specifically in this case the full supply current passes through both CBA 4 and 1, and Bus 1.

Case 2: CBA 5 fails closed. If CBA 5 fails in closed position (that is, the circuit breaker cannot be opened), then a short circuit in T3 cannot be isolated locally because the faulty CBA 5 directly connects the source to the shorted line. Backup protection at the source (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.

1.6.2 Distribution Feeder

The distribution system is a radial system, without loops. Figure 1.40 shows 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 kV or 13.8 kV.

The main feeder is protected by a re-closing circuit breaker that switches off the feeder in case of a fault, and after a few seconds, the breaker re-closes

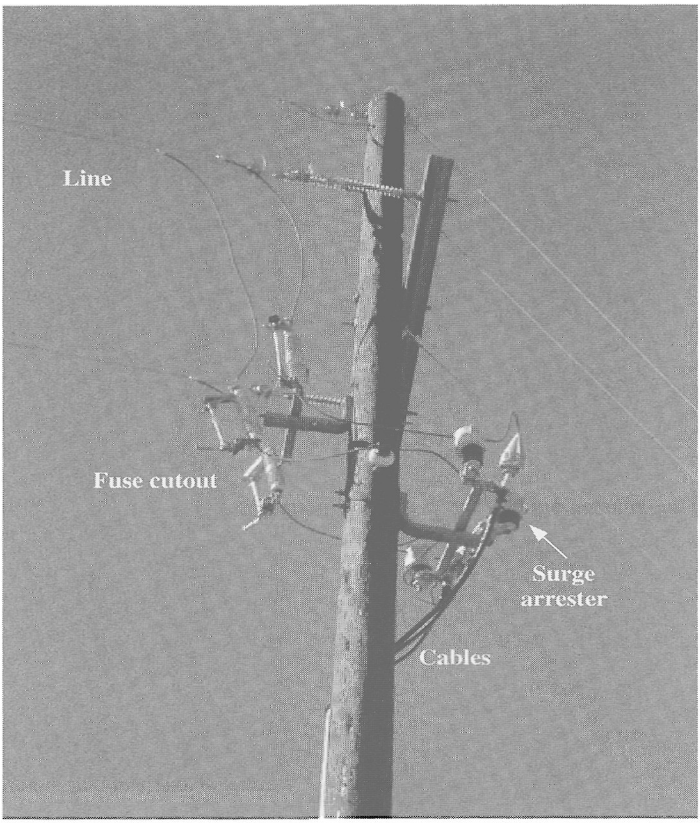


Figure 1.41 Overhead line and cable connections.

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 re-closing is unsuccessful, the breaker opens the line permanently.

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

Figure 1.41 shows the interconnection of a distribution line with a distribution cable. This connection is used to cross busy roads and to supply high-end residential areas. The figure shows the cable termination, the surge arrester that is

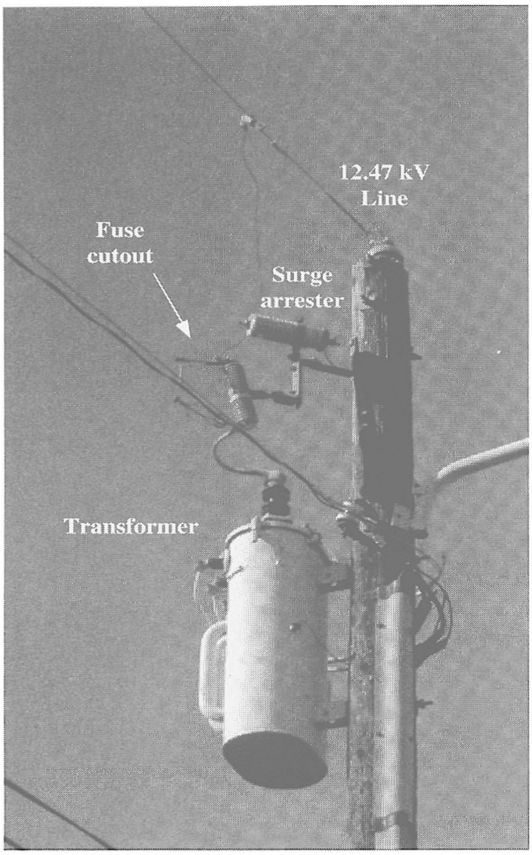


Figure 1.42 Consumer service drop.

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 isolated rod–commonly known as a *hot stick*. A metal conduit attached to the wooden pole protects the cable.

Figure 1.42 shows 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, the overhead distribution lines have been replaced by underground cables in some residential areas. In such cases, the transformer is placed in a ground-level metal casing, which is placed on a concrete slab, as shown in Figure 1.43. Figure 1.42 shows a typical single-phase pole mounted

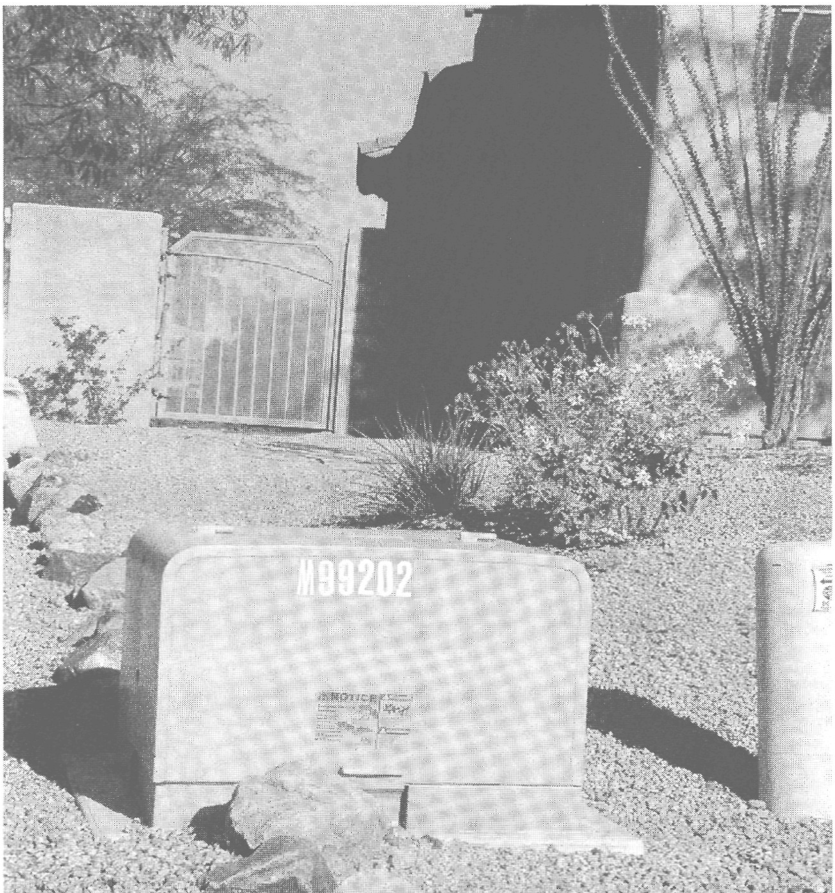


Figure 1.43 Ground level transformer in a residential area.

transformer that supplies a few (1–5) houses. The pole-mounted oil-insulated transformer is protected by a surge arrester and a fuse-cutout. The secondary of the transformer supplies a 240 V/120 V insulated conductor that is attached to carrier steel wire leading the electricity to the houses. Such transformers may supply a 240/120 V low voltage line.

1.6.3 Residential Electrical Connection

A low-voltage secondary feeder supplies individual houses. A distribution transformer has a three-wire electrical system, which accommodates both 120 V and 240 V loads. Figure 1.44 shows the electrical connection of a typical household supply.

The step-down transformer has a neutral and two phase wires. The neutral is grounded at the transformer secondary side. The three wires are connected to the kW and kWh meter at the house. The house 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 kW and kWh meters measure and record the kWh energy consumption, and in some cases the maximum 15-minute kW demand. Figure 1.45 shows a typical kWh meter and service panel with the main circuit breaker.

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 circuit breaker, 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 circuit

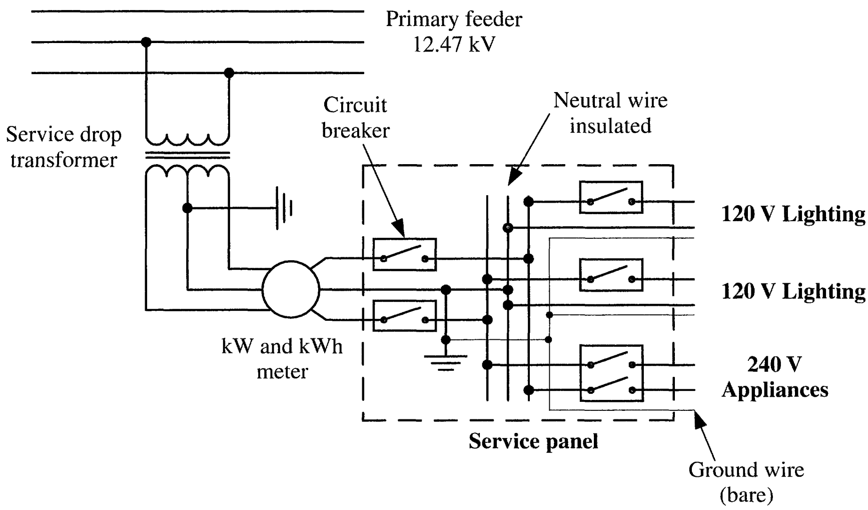


Figure 1.44 Residential electrical connection.

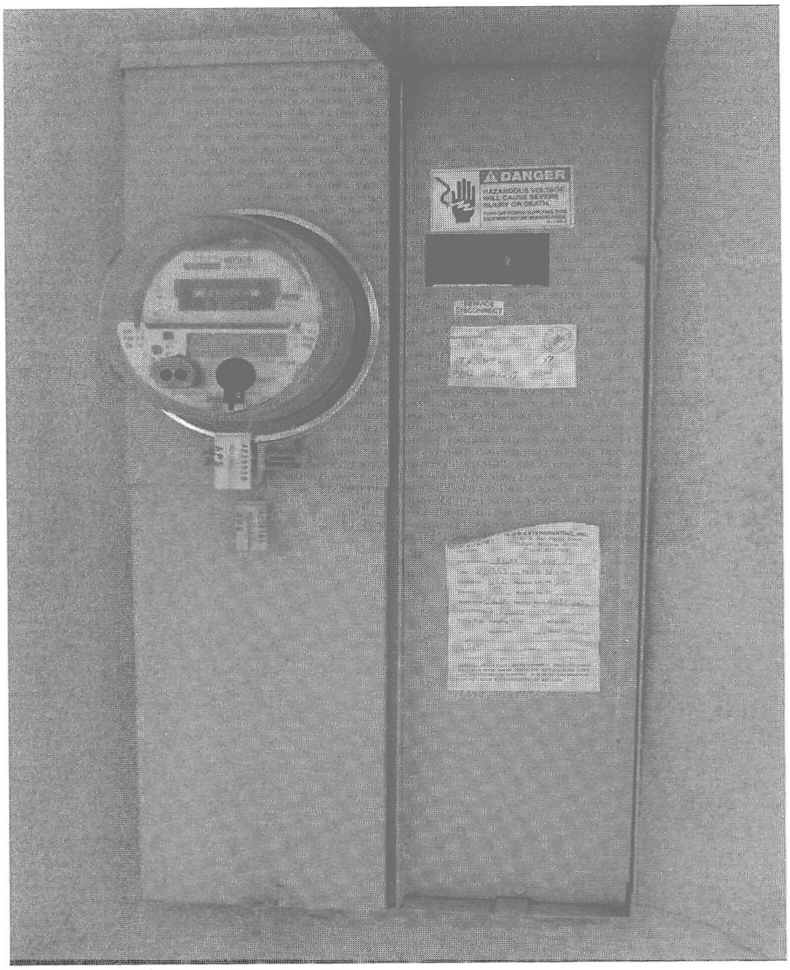


Figure 1.45 Typical residential kWh meter and service panel.

breakers. In older installations, fuses have been used instead of circuit breakers. The load is connected between the phase and neutral conductors. The housing of appliances and lamps is grounded by the ground wire. Larger appliances, such as the cooking stove and clothes dryer, are supplied by 240 V circuits.

1.7 EXERCISES

1. Draw a sketch and explain the concept of energy transmission. What are the advantages of the multi-level voltages?
2. What are the typical voltages for sub-transmission, high-voltage, extra-high-voltage and ultra-high-voltage systems?
3. What are the typical voltages for the distribution system?

4. What is the role of electric-generating stations?
5. List the types of electric-generating stations.
6. What are the base load and peak load? Illustrate them with a sketch.
7. List the components of a fossil power plant.
8. Describe typical fuel storage, handling and injection systems used in fossil power plants.
9. Describe the boiler used in a fossil power plant. Draw a sketch showing the major subsystems.
10. Describe typical water-steam and ash-handling systems used in fossil power plants.
11. What is the condenser? Draw a sketch.
12. What is an electrostatic precipitator?
13. Describe a typical wet cooling tower. Draw a sketch. What is the function of the cooling tower?
14. Describe the operating concept of a steam turbine.
15. Draw a simplified connection diagram of a power plant, and identify the components and their roles.
16. Describe the combined cycle power plant. Draw a sketch.
17. What is the operating principle of nuclear power generation?
18. Describe the concept of a boiling water reactor. Draw a sketch.
19. Describe the concept of a pressurized water reactor. Draw a sketch.
20. Describe the types of hydroelectric power plants and their operating principles.
21. What is a low-head hydro plant? Draw a sketch.
22. Describe a high-head hydro power plant. Draw a sketch.
23. What is a pumped storage facility?
24. Draw the connection diagram of a high-voltage substation using the breaker-and-a-half configuration. Identify the components.
25. What is a circuit breaker? Discuss its role and operating principle.
26. What are current and voltage transformers?
27. What is the disconnect switch and its purpose?
28. What is a surge arrester? Why is it important?
29. Draw a diagram of a typical radial distribution system. Describe briefly its operation.
30. Describe the residential electric connection. Draw the connection diagram.

1.8 PROBLEMS

Problem 1.1

Substations frequently use the connections shown in the one-line diagram of Figure 1.30. Analyze the circuit operation for the cases of CBA 4 (*a*) fails open, and (*b*) fails close.

Problem 1.2

An electric power plant is built with a rated output of 800 MWe. In the first year of operation, the plant operates at an average of 85% of its full power for 10 months, and then is shutdown for the remaining 2 months. In the second year, the plant generates an average of 700 MWe over the entire year. (*a*) Determine the plant capacity factor for each year. (*b*) If the total operating and maintenance (O&M) cost to the utility was equal in the first and second years, and the electricity-averaged O&M cost in the first year was 15 mills/kW·hr, then what was the O&M cost in mills/kW·hr for the second year?

Problem 1.3

Determine the condenser heat dissipation requirements in MWth (megawatts thermal) for two different 1000 MWe power plants. The first plant is a coal-fired unit that has a thermal efficiency of 40% and releases 15% of the heat produced in the furnace up the stack. The second plant is a nuclear unit with a thermal efficiency of 33%.