1

Introduction

1.1 History

In 1882 Edison inaugurated the first central generating station in the USA. This fed a load of 400 lamps, each consuming 83 W. At about the same time the Holborn Viaduct Generating Station in London was the first in Britain to cater for consumers generally, as opposed to specialized loads. This scheme used a 60 kW generator driven by a horizontal steam engine; the voltage of generation was 100 V direct current.

The first major alternating current station in Great Britain was at Deptford, where power was generated by machines of 10 000 h.p. and transmitted at 10 kV to consumers in London. During this period the battle between the advocates of alternating current and direct current was at its most intense with a similar controversy raging in the USA and elsewhere. Owing mainly to the invention of the transformer the supporters of alternating current prevailed and a steady development of local electricity generating stations commenced with each large town or load centre operating its own station.

In 1926, in Britain, an Act of Parliament set up the Central Electricity Board with the object of interconnecting the best of the 500 generating stations then in operation with a high-voltage network known as the Grid. In 1948 the British supply industry was nationalized and two organizations were set up: (1) the Area Boards, which were mainly concerned with distribution and consumer service; and (2) the Generating Boards, which were responsible for generation and the operation of the high-voltage transmission network or grid.

All of this changed radically in 1990 when the British Electricity Supply Industry was privatized. Separate companies were formed to provide competition in the supply of electrical energy (sometimes known as electricity retail businesses) and in power generation. The transmission and distribution networks are natural monopolies, owned and operated by a Transmission System Operator and Distribution Network Operators. The Office of Gas and Electricity Markets (OFGEM) was

Electric Power Systems, Fifth Edition. B.M. Weedy, B.J. Cory, N. Jenkins, J.B. Ekanayake and G. Strbac.

established as the Regulator to ensure the market in electricity generation and energy supply worked effectively and to fix the returns that the Transmission and Distribution Companies should earn on their monopoly businesses.

For the first 80 years of electricity supply, growth of the load was rapid at around 7% per year, implying a doubling of electricity use every 10 years and this type of increase continues today in rapidly industrializing countries. However in the USA and in other industrialized countries there has been a tendency, since the oil shock of 1973, for the rate of increase to slow with economic growth no longer coupled closely to the use of energy. In the UK, growth in electricity consumption has been under 1% per year for a number of years.

A traditional objective of energy policy has been to provide secure, reliable and affordable supplies of electrical energy to customers. This is now supplemented by the requirement to limit greenhouse gas emissions, particularly of CO_2, and so mitigate climate change. Hence there is increasing emphasis on the generation of electricity from low-carbon sources that include renewable, nuclear and fossil fuel plants fitted with carbon capture and storage equipment. The obvious way to control the environmental impact of electricity generation is to reduce the electrical demand and increase the efficiency with which electrical energy is used. Therefore conservation of energy and demand reduction measures are important aspects of any contemporary energy policy.

1.2 Characteristics Influencing Generation and Transmission

There are three main characteristics of electricity supply that, however obvious, have a profound effect on the manner in which the system is engineered. They are as follows:

Electricity, unlike gas and water, cannot be stored and the system operator traditionally has had limited control over the load. The control engineers endeavour to keep the output from the generators equal to the connected load at the specified voltage and frequency; the difficulty of this task will be apparent from a study of the load curves in Figure 1.1. It will be seen that the load consists of a steady component known as the base load, plus peaks that depend on the time of day and days of the week as well as factors such as popular television programmes.

The electricity sector creates major environmental impacts that increasingly determine how plant is installed and operated. Coal burnt in steam plant produces sulphur dioxide that causes acid rain. Thus, in Europe, it is now mandatory to fit flue gas desulphurisation plant to coal fired generation. All fossil fuel (coal, oil and gas) produce CO_2 (see Table 1.1) which leads to climate change and so its use will be discouraged increasingly with preference given to generation by low-carbon energy sources.

The generating stations are often located away from the load resulting in transmission over considerable distances. Large hydro stations are usually remote from urban centres and it has often been cost-effective to burn coal close to where it is mined and transport the electricity rather than move the coal. In many countries, good sites for wind energy are remote from centres of population and,

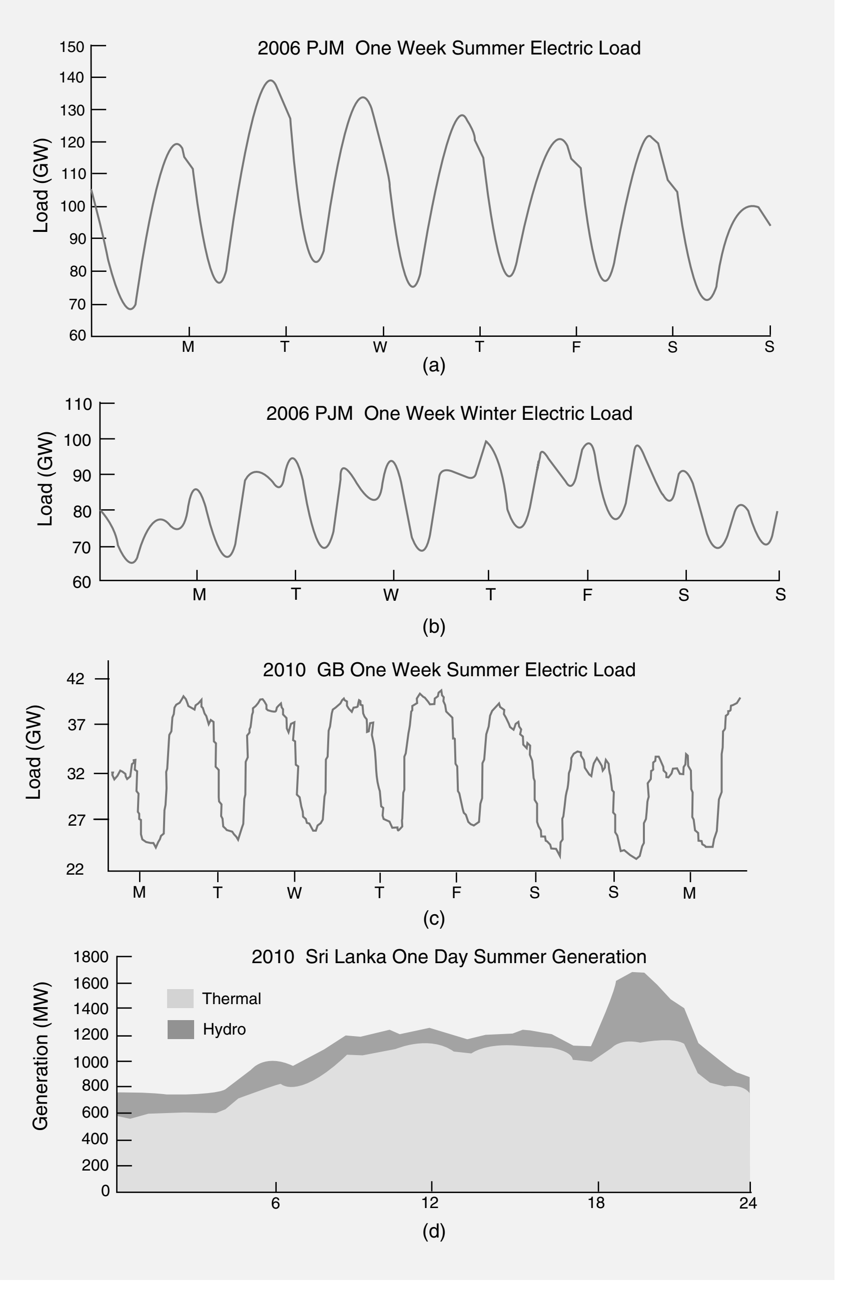

Figure 1.1 Load curves. (a) PJM (Pennsylvania, Jersey, Maryland) control area in the east of the USA over a summer week. The base load is 70 GW with a peak of 140 GW. This is a very large interconnected power system. (b) PJM control area over a winter week. Note the morning and evening peaks in the winter with the maximum demand in the summer. (c) Great Britain over a summer week. The base load is around 25 GW with a daily increase/decrease of 15 GW. GB is effectively an isolated power system. (d) Sri Lanka over 1 day. Note the base load thermal generation with hydro used to accommodate the rapid increase of 500 MW at dusk

although it is possible to transport gas in pipelines, it is often difficult to obtain permission to construct generating stations close to cities. Moreover, the construction of new electrical transmission is subject to delays in many developed countries caused by objections from the public and the difficulty in obtaining permission for the construction of new overhead line circuits.

1.3 Operation of Generators

The national electrical load consists of a base plus a variable element, depending on the time of day and other factors. In thermal power systems, the base load should be supplied by the most efficient (lowest operating cost) plant which then runs 24 hours per day, with the remaining load met by the less efficient (but lower capital cost) stations. In hydro systems water may have to be conserved and so some generators are only operated during times of peak load.

In addition to the generating units supplying the load, a certain proportion of available plant is held in reserve to meet sudden contingencies such as a generator unit tripping or a sudden unexpected increase in load. A proportion of this reserve must be capable of being brought into operation immediately and hence some machines must be run at, say, 75% of their full output to allow for this spare generating capacity, called spinning reserve.

Reserve margins are allowed in the total generation plant that is constructed to cope with unavailability of plant due to faults, outages for maintenance and errors in predicting load or the output of renewable energy generators. When traditional national electricity systems were centrally planned, it was common practice to allow a margin of generation of about 20% over the annual peak demand. A high proportion of intermittent renewable energy generation leads to a requirement for a higher reserve margin. In a power system there is a mix of plants, that is, hydro, coal, oil, renewable, nuclear, and gas turbine. The optimum mix gives the most economic operation, but this is highly dependent on fuel prices which can fluctuate with time and from region to region. Table 1.2 shows typical plant and

Table 1.1 Estimated carbon dioxide emissions from electricity generation in Great Britain

Fuel	Tonnes of CO_2/GWh of Electrical Output
Coal	915
Oil	633
Gas	405
Great Britain generation portfolio (including nuclear and renewables)	452

Data from the Digest of UK Energy Statistics, 2010, published by the Department of Energy and Climate Change.

Table 1.2 Example of costs of electricity generation

Generating Technology	Capital Cost of Plant £/MW	Cost of electricity £/MWh
Combined Cycle Gas Turbine	720	80
Coal	1800	105
Onshore wind	1520	94
Nuclear	2910	99

Data from UK Electricity Generating Costs Update, 2010, Mott MacDonald, reproduced with permission

generating costs for the UK. It is clear some technologies have a high capital cost (for example, nuclear and wind) but low fuel costs.

1.4 Energy Conversion

1.4.1 Energy Conversion Using Steam

The combustion of coal, gas or oil in boilers produces steam, at high temperatures and pressures, which is passed through steam turbines. Nuclear fission can also provide energy to produce steam for turbines. Axial-flow turbines are generally used with several cylinders, containing steam of reducing pressure, on the same shaft.

A steam power-station operates on the Rankine cycle, modified to include superheating, feed-water heating, and steam reheating. High efficiency is achieved by the use of steam at the maximum possible pressure and temperature. Also, for turbines to be constructed economically, the larger the size the less the capital cost per unit of power output. As a result, turbo-generator sets of 500 MW and more have been used. With steam turbines above 100 MW, the efficiency is increased by reheating the steam, using an external heater, after it has been partially expanded. The reheated steam is then returned to the turbine where it is expanded through the final stages of blading.

A schematic diagram of a coal fired station is shown in Figure 1.2. In Figure 1.3 the flow of energy in a modern steam station is shown.

In coal-fired stations, coal is conveyed to a mill and crushed into fine powder, that is pulverized. The pulverized fuel is blown into the boiler where it mixes with a supply of air for combustion. The exhaust steam from the low pressure (L.P.) turbine is cooled to form condensate by the passage through the condenser of large quantities of sea- or river-water. Cooling towers are used where the station is located inland or if there is concern over the environmental effects of raising the temperature of the sea- or river-water.

Despite continual advances in the design of boilers and in the development of improved materials, the nature of the steam cycle is such that vast quantities of heat are lost in the condensate cooling system and to the atmosphere. Advances in design and materials in the last few years have increased the thermal

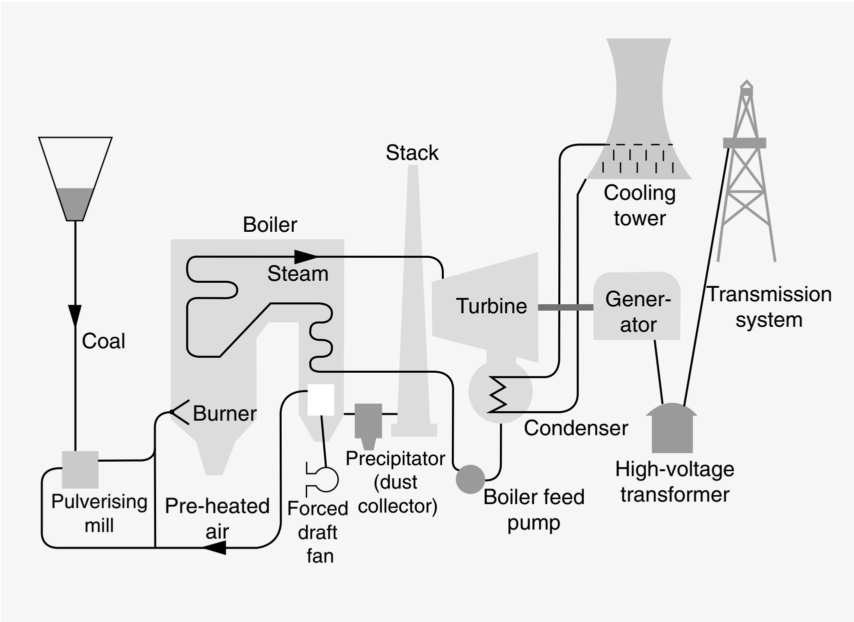

Figure 1.2 Schematic view of coal fired generating station

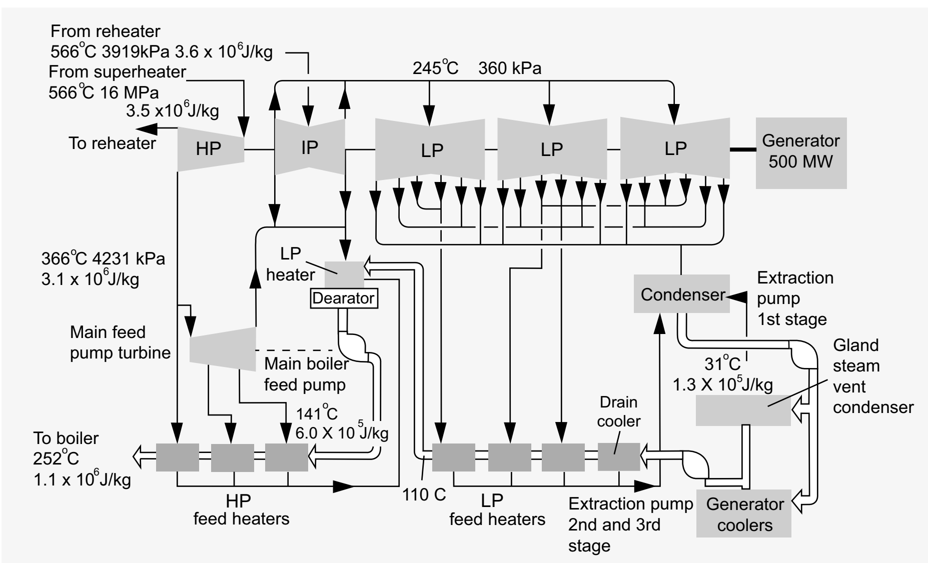

Figure 1.3 Energy flow diagram for a 500 MW turbine generator (Figure adapted from Electrical Review)

efficiencies of new coal stations to approaching 40%. If a use can be found for the remaining 60% of energy rejected as heat, fairly close to the power station, forming a Combined Heat and Power (or Co-generation) system then this is clearly desirable.

1.4.2 Energy Conversion Using Water

Perhaps the oldest form of energy conversion is by the use of water power. In a hydroelectric station the energy is obtained free of cost. This attractive feature has always been somewhat offset by the very high capital cost of construction, especially of the civil engineering works. Unfortunately, the geographical conditions necessary for hydro-generation are not commonly found, especially in Britain. In most developed countries, all the suitable hydroelectric sites are already fully utilized. There still exists great hydroelectric potential in many developing countries but large hydro schemes, particularly those with large reservoirs, have a significant impact on the environment and the local population.

The difference in height between the upper reservoir and the level of the turbines or outflow is known as the head. The water falling through this head gains energy which it then imparts to the turbine blades. Impulse turbines use a jet of water at atmospheric pressure while in reaction turbines the pressure drops across the runner imparts significant energy.

A schematic diagram of a hydro generation scheme is shown in Figure 1.4.

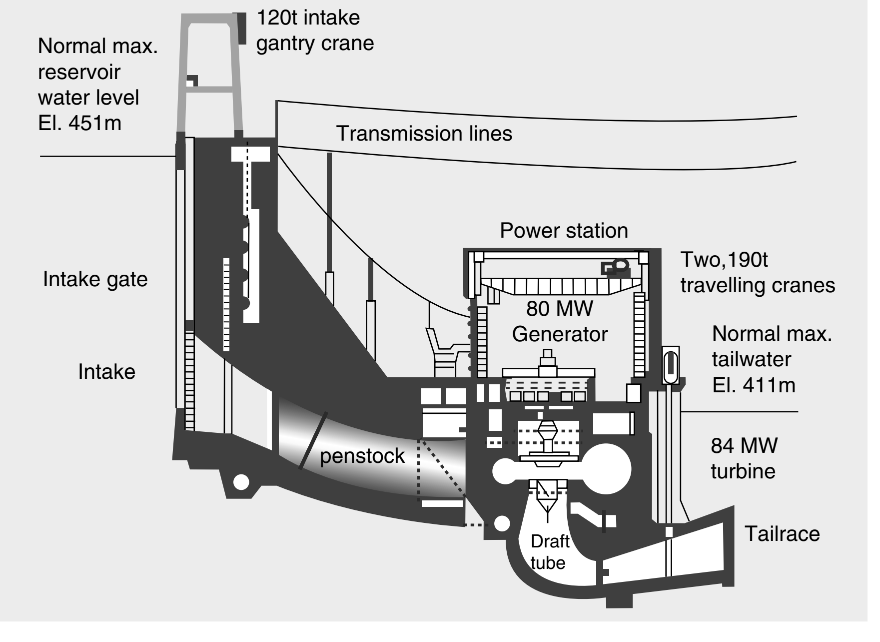

Figure 1.4 Schematic view of a hydro generator (Figure adapted from Engineering)

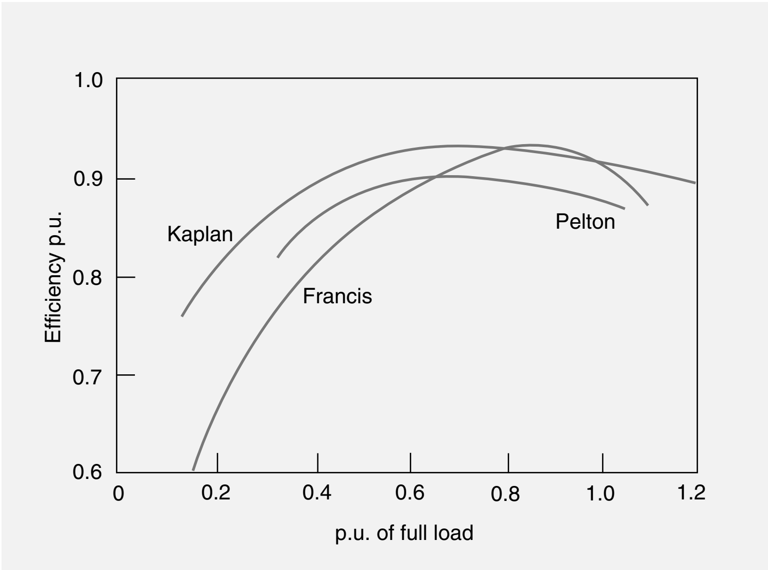

Figure 1.5 Typical efficiency curves of hydraulic turbines (1 per unit (p.u.). = 100%)

Particular types of turbine are associated with the various heights or heads of water level above the turbines. These are:

1. **Pelton:** This is used for heads of 150–1500 m and consists of a bucket wheel rotor with water jets from adjustable flow nozzles.
2. **Francis:** This is used for heads of 50–500 m with the water flow within the turbine following a spiral path.
3. **Kaplan:** This is used for run-of-river stations with heads of up to 60 m. This type has an axial-flow rotor with variable-pitch blades.

Typical efficiency curves for each type of turbine are shown in Figure 1.5. Hydroelectric plant has the ability to start up quickly and the advantage that no energy losses are incurred when at a standstill. It has great advantages, therefore, for power generation because of this ability to meet peak loads at minimum operating cost, working in conjunction with thermal stations – see Figure 1.1(d). By using remote control of the hydro sets, the time from the instruction to start up to the actual connection to the power network can be as short as 3 minutes.

The power available from a hydro scheme is given by

$$P = \rho g Q H \qquad [\mathrm{W}]$$

where

Q = flow rate (m^3/s) through the turbine;
ρ = density of water (1000 kg/m^3);

g = acceleration due to gravity (9.81 m/s^2);
H = head, that is height of upper water level above the lower (m).

Substituting,

$$P = 9.81QH \qquad [\text{kW}]$$

1.4.3 Gas Turbines

With the increasing availability of natural gas (methane) and its low emissions and competitive price, prime movers based on the gas turbine cycle are being used increasingly. This thermodynamic cycle involves burning the fuel in the compressed working fluid (air) and is used in aircraft with kerosene as the fuel and for electricity generation with natural gas (methane). Because of the high temperatures obtained, the efficiency of a gas turbine is comparable to that of a steam turbine, with the additional advantage that there is still sufficient heat in the gas-turbine exhaust to raise steam in a conventional boiler to drive a steam turbine coupled to another electricity generator. This is known as a combined-cycle gas-turbine (CCGT) plant, a schematic layout of which is shown in Figure 1.6. Combined efficiencies of new CCGT generators now approach 60%.

The advantages of CCGT plant are the high efficiency possible with large units and, for smaller units, the fast start up and shut down (2–3 min for the gas turbine, 20 min for the steam turbine), the flexibility possible for load following, the comparative speed of installation because of its modular nature and factory-supplied units,

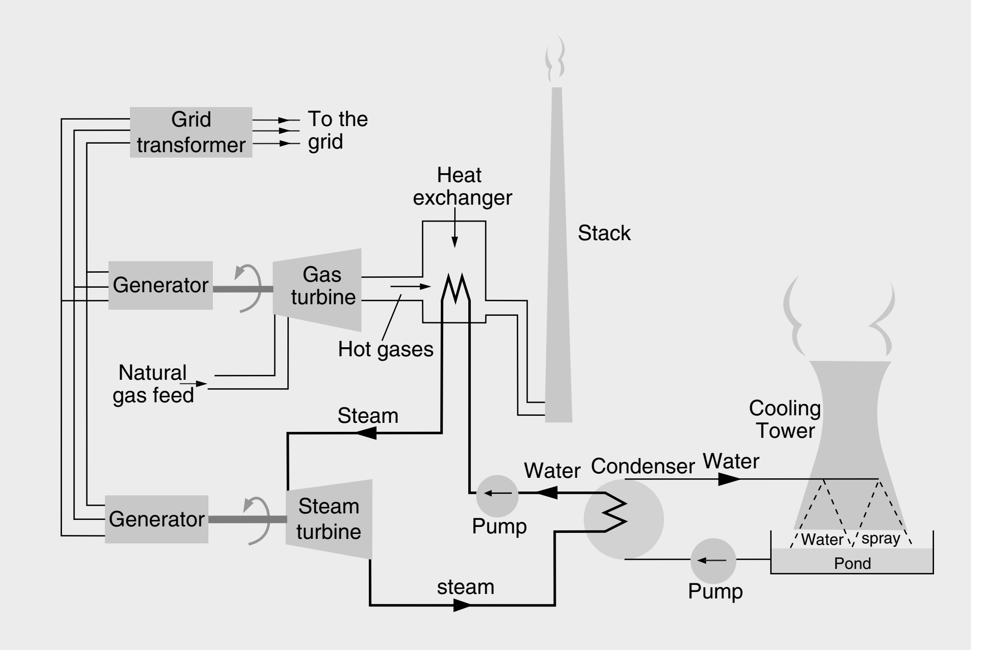

Figure 1.6 Schematic diagram of a combined-cycle gas-turbine power station

and its ability to run on light oil (from local storage tanks) if the gas supply is interrupted. Modern installations are fully automated and require only a few operators to maintain 24 hour running or to supply peak load, if needed.

1.4.4 Nuclear Power

Energy is obtained from the fission reaction which involves the splitting of the nuclei of uranium atoms. Compared with chemical reactions, very large amounts of energy are released per atomic event. Uranium metal extracted from the base ore consists mainly of two isotopes, ^{238}U (99.3% by weight) and ^{235}U (0.7%). Only ^{235}U is fissile, that is when struck by slow-moving neutrons its nucleus splits into two substantial fragments plus several neutrons and 3×10^{-11} J of kinetic energy. The fast moving fragments hit surrounding atoms producing heat before coming to rest. The neutrons travel further, hitting atoms and producing further fissions. Hence the number of neutrons increases, causing, under the correct conditions, a chain reaction. In conventional reactors the core or moderator slows down the moving neutrons to achieve more effective splitting of the nuclei.

Fuels used in reactors have some component of ^{235}U. Natural uranium is sometimes used although the energy density is considerably less than for enriched uranium. The basic reactor consists of the fuel in the form of rods or pellets situated in an environment (moderator) which will slow down the neutrons and fission products and in which the heat is evolved. The moderator can be light or heavy water or graphite. Also situated in the moderator are movable rods which absorb neutrons and hence exert control over the fission process. In some reactors the cooling fluid is pumped through channels to absorb the heat, which is then transferred to a secondary loop in which steam is produced for the turbine. In water reactors the moderator itself forms the heat-exchange fluid.

A number of versions of the reactor have been used with different coolants and types of fissile fuel. In Britain the first generation of nuclear power stations used Magnox reactors in which natural uranium in the form of metal rods was enclosed in magnesium-alloy cans. The fuel cans were placed in a structure or core of pure graphite made up of bricks (called the moderator). This graphite core slowed down the neutrons to the correct range of velocities in order to provide the maximum number of collisions. The fission process was controlled by the insertion of control rods made of neutron-absorbing material; the number and position of these rods controlled the heat output of the reactor. Heat was removed from the graphite via carbon dioxide gas pumped through vertical ducts in the core. This heat was then transferred to water to form steam via a heat exchanger. Once the steam had passed through the high-pressure turbine it was returned to the heat exchanger for reheating, as in a coal- or oil-fired boiler.

A reactor similar to the Magnox is the advanced gas-cooled reactor (AGR) which is still in use in Britain but now coming towards the end of its service life. A reinforced-concrete, steel-lined pressure vessel contains the reactor and heat exchanger. Enriched uranium dioxide fuel in pellet form, encased in stainless steel cans, is used; a number of cans are fitted into steel fitments within a graphite tube to

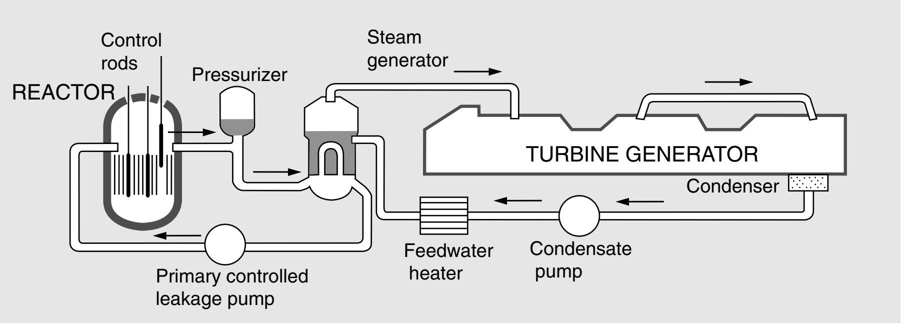

Figure 1.7 Schematic diagram of a pressurized-water reactor (PWR)

form a cylindrical fuel element which is placed in a vertical channel in the core. Depending on reactor station up to eight fuel elements are held in place one above the other by a tie bar. Carbon dioxide gas, at a higher pressure than in the Magnox type, removes the heat. The control rods are made of boron steel. Spent fuel elements when removed from the core are stored in a special chamber and lowered into a pond of water where they remain until the level of radioactivity has decreased sufficiently for them to be removed from the station and disassembled.

In the USA and many other countries pressurized-water and boiling-water reactors are used. In the pressurized-water type the water is pumped through the reactor and acts as a coolant and moderator, the water being heated to 315 °C at around 150 bar pressure. At this temperature and pressure the water leaves the reactor at below boiling point to a heat exchanger where a second hydraulic circuit feeds steam to the turbine. The fuel is in the form of pellets of uranium dioxide in bundles of zirconium alloy.

The boiling-water reactor was developed later than the pressurized-water type. Inside the reactor, heat is transferred to boiling water at a pressure of 75 bar (1100 p.s.i.). Schematic diagrams of these reactors are shown in Figures 1.7 and 1.8. The ratio of pressurized-water reactors to boiling-water reactors throughout the world is around 60/40%.

Both pressurized- and boiling-water reactors use light water.[1] The practical pressure limit for the pressurized-water reactor is about 160 bar (2300 p.s.i.), which limits its efficiency to about 30%. However, the design is relatively straightforward and experience has shown this type of reactor to be stable and dependable. In the boiling-water reactor the efficiency of heat removal is improved by use of the latent heat of evaporation. The steam produced flows directly to the turbine, causing possible problems of radioactivity in the turbine. The fuel for both light-water reactors is uranium enriched to 3–4% ^{235}U. Boiling-water reactors are probably the cheapest to construct; however, they have a more complicated fuel make up with different enrichment levels within each pin. The steam produced is saturated and requires wet-steam turbines. A further type of water reactor is the heavy-water

[1] Light water refers to conventional H_2O while heavy water describes deuterium oxide (D_2O).

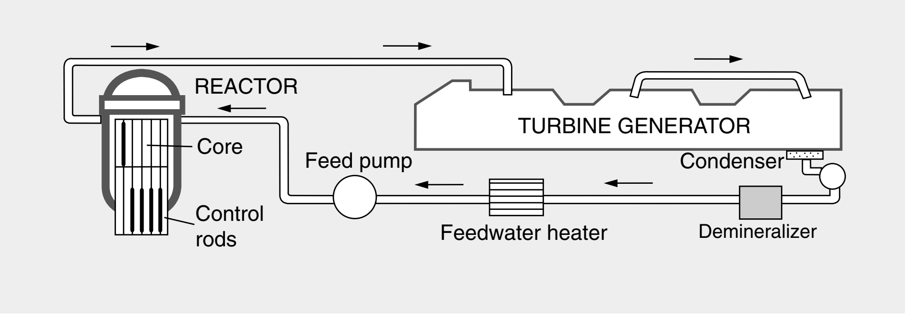

Figure 1.8 Schematic diagram of a boiling-water reactor (BWR)

CANDU type developed by Canada. Its operation and construction are similar to the light-water variety but this design uses naturally occurring, un-enriched or slightly enriched uranium.

Concerns over the availability of future supplies of uranium led to the construction of a number of prototype breeder reactors. In addition to heat, these reactors produce significant new fissile material. However, their cost, together with the technical and environmental challenges of breeder reactors, led to most of these programmes being abandoned and it is now generally considered that supplies of uranium are adequate for the foreseeable future.

Over the past years there has been considerable controversy regarding the safety of reactors and the management of nuclear waste. Experience is still relatively small and human error is always a possibility, such as happened at Three Mile Island in 1979 and Chernobyl in 1986 or a natural event such as the earthquake and tsunami in Fukishima in 2011. However, neglecting these incidents, the safety record of power reactors has been good and now a number of countries (including Britain) are starting to construct new nuclear generating stations using Light Water Reactors. The decommissioning of nuclear power stations and the long term disposal of spent fuel remains controversial.

1.5 Renewable Energy Sources

There is considerable international effort put into the development of renewable energy sources. Many of these energy sources come from the sun, for example wind, waves, tides and, of course, solar energy itself. The average peak solar energy received on the earth's surface is about 600 W/m^2, but the actual value, of course, varies considerably with time of day and cloud conditions.

1.5.1 Solar Energy–Thermal Conversion

There is increasing interest in the use of solar energy for generating electricity through thermal energy conversion. In large-scale (central station) installations the sun's rays are concentrated by lenses or mirrors. Both require accurately curved surfaces and steering mechanisms to follow the motion of the sun. Concentrators may

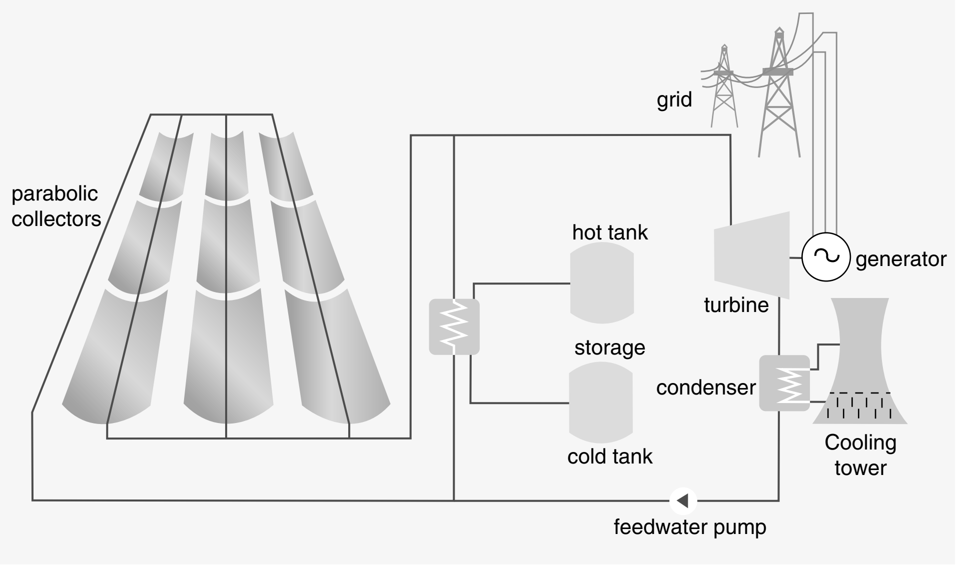

Figure 1.9 Solar thermal generator

be designed to follow the sun's seasonal movement, or additionally to track the sun throughout the day. The former is less expensive and concentration of the sun up to 30 times has been obtained. However, in the French solar furnace in the Pyrenees, two-axis mirrors were used and a concentration of 16 000 was achieved. The reflectors concentrated the rays on to a single receiver (boiler), hence raising steam.

An alternative to this scheme (with lower temperatures) is the use of many individual parabolic trough absorbers tracking the sun in one direction only (Figure 1.9), the thermal energy being transferred by a fluid to a central boiler. In the arid regions of the world where direct solar radiation is strong and hence solar thermal generation effective the limited supply of water for the steam cycle and for cooling can be an important consideration. In solar thermal schemes, heat energy storage can be used to mitigate the fluctuating nature of the sun's energy.

1.5.2 Solar Energy-Photovoltaic Conversion

Photovoltaic conversion occurs in a thin layer of suitable material, typically silicon, when hole-electron pairs are created by incident solar photons and the separation of these holes and electrons at a discontinuity in electrochemical potential creates a potential difference. Whereas theoretical efficiencies are about 25%, practical values are lower. Single-crystal silicon solar cells have been constructed with efficiencies of the complete module approaching 20%. The cost of fabricating and interconnecting cells is high. Polycrystalline silicon films having large-area grains with efficiencies of over 16% have been made. Although photovoltaic devices do not pollute they occupy large areas if MWs of output are required. It has been estimated that to produce 10^{12} kWh per year (about 65% of the 1970 US generation output) the necessary cells would occupy about 0.1% of the US land area (highways occupied 1.5% in

1975), assuming an efficiency of 10% and a daily insolation of 4 kWh/m^2. Automated cell production can now produce cells at less than US $3 per peak watt.

1.5.3 Wind Generators

Horizontal axis wind turbine generators each rated at up to 5 MW mounted on 90–100 m high towers are now commercially available.

The power in the wind is given by

$$P_w = \frac{1}{2}\rho A U^3 \qquad [W]$$

While the power developed by the aerodynamic rotor is

$$P = C_p P_w = C_p \frac{1}{2}\rho A U^3 \qquad [W]$$

where

ρ = density of air (1.25 kg/m^3);
U = wind velocity (m/s);
A = swept area of rotor (m^2).
C_p = power coefficient of the rotor

The operation of a wind turbine depends upon the wind speed and is shown in Figure 1.10.

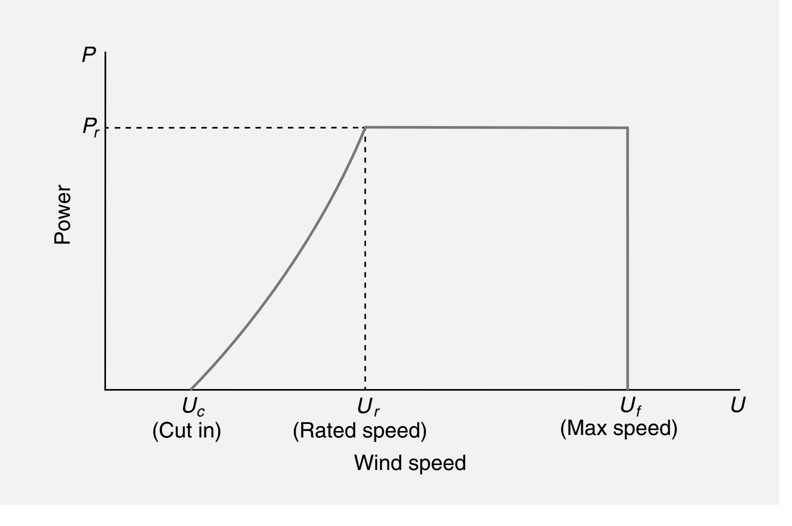

Figure 1.10 Wind turbine power curve

At low wind speeds, there is insufficient energy to operate the turbine and no power is produced. At the cut-in U_c speed, between 3 and 5 m/s, power starts to be generated until rated power P_r is produced at rated wind speed U_r. At higher wind speeds, the turbine is controlled, usually by altering the blade pitch angle, to give rated output up to a maximum wind speed U_f. After this the blades are 'furled' and the unit is shut down to avoid excessive wind loading. Typically, wind turbines with rotors of 80 m diameter, rotate at 15–20 rpm, and are geared up to a generator speed of around 1000 r.p.m. All modern large wind turbines operate at variable speed using power electronic converters to connect the generator to the 50/60 Hz electrical network. This is in order to reduce mechanical loads and to allow the aerodynamic rotor to run at its most effective speed.

Example 1.1

Calculate the number of wind generators required to produce the equivalent energy of a 600 MW CCGT operating at 80% load factor. Assume the average wind speed is 8 m/s, rotor diameter is 80 m, and conversion efficiency (coefficient of performance, C_p) is 0.45.

Calculation
Power in the wind:

$$P_{wind} = \frac{1}{2}\rho A U^3$$
$$= \frac{1}{2} \times 1.25 \times \pi \times 40^2 \times 8^3 = 1.6\,\mathrm{MW}$$

Power in generator:

$$P_{generator} = 1.6 \times 0.45 = 724\,\mathrm{kW}$$

Number of turbines required = 600 × 0.8/0.724 = 663.

A regular spacing of turbines at 5 times rotor diameter (400 m), gives 6.25 turbines/km^2. Thus a total area of 106 km^2 is required.

From this calculation, it is apparent that wind generators spread over a wide area (e.g. 11 km × 10 km) would be required although the ground beneath them could be used for grazing. The saving in CO_2 emissions would be approximately:

Daily electrical energy generated = 600 × 0.8 × 24 = 11.5 GWh.
CO_2 emissions saved (see Table 1.1) = 11.5 × 405 = 4657 tonnes/day

1.5.4 Biofuels

Biofuels are derived from vegetable matter produced by agriculture or forestry operations or from waste materials collected from industry, commerce and residential households. As an energy resource, biomass used as a source of heat by burning wood, dung, and so on, in developing countries is very important and contributes about 14% of the world's energy requirements. Biomass can be used to produce electricity in two ways:

1. by burning in a furnace to produce steam to drive turbines; or
2. by fermentation in landfill sites or in special anaerobic tanks, both of which produce a methane-rich gas which can fuel a spark ignition engine or gas turbine.

It can also be co-fired with coal in large steam power stations.

If crops are cultivated for combustion, either as a primary source of heat or as a by-product of some other operation; they can be considered as CO_2 neutral, in that their growing cycle absorbs as much CO_2 as is produced by their combustion. In industrialized countries, biomass has the potential to produce up to 5% of electricity requirements if all possible forms are exploited, including household and industrial waste, sewage sludge (for digestion), agricultural waste (chicken litter, straw, sugar cane, and so on). The use of good farmland to grow energy crops is controversial as it obviously reduces the area of land available to grow food.

1.5.5 Geothermal Energy

In most parts of the world the vast amount of heat in the earth's interior is too deep to be tapped. In some areas, however, hot springs or geysers and molten lava streams are close enough to the surface to be used. Thermal energy from hot springs has been used for many years for producing electricity, starting in 1904 in Italy. In the USA the major geothermal power plants are located in northern California on a natural steam field called the Geysers. Steam from a number of wells is passed through turbines. The present utilization is about 900 MW and the total estimated capacity is about 2000 MW. Because of the lower pressure and temperatures the efficiency is less than with fossil-fuelled plants, but the capital costs are less and, of course, the fuel is free. New Zealand and Iceland also exploit their geothermal energy resources.

1.5.6 Other Renewable Resources

1.5.6.1 Tides

An effective method of utilizing the tides is to allow the incoming tide to flow into a basin, thus operating a set of turbines, and then at low tide to release the stored water, again operating the turbines. If the tidal range from high to low water is h (m) and the area of water enclosed in the basin is A (m^2), then the energy in the full basin with the tide outside at its lowest level is:

$$E = \rho g A \int_0^h x\,dx$$

$$= \frac{1}{2}\rho g h^2 A \qquad [J]$$

Table 1.3 Sites that have been studied for tidal range generation

Site	Tidal Range(m)	Area (km^2)	Generators (MW)
Passamaquoddy Bay (N. America)	5.5	262	1800
Minas-Cohequid (N. America)	10.7	777	19 900
San Jose (S. America)	5.9	750	5870
Severn (U.K.)	9.8	700	8000

The maximum total energy for both flows is therefore twice this value, and the maximum average power is $pgAh^2/T$, where T is the period of tidal cycle, normally 12 h 44 min. In practice not all this energy can be utilized. The number of sites with good potential for tidal range generation is small. Typical examples of those which have been studied are listed in Table 1.3 together with the size of generating plant considered.

A 200 MW installation using tidal flow has been constructed on the La Rance Estuary in northern France, where the tidal height range is 9.2 m (30 ft) and the tidal flow is estimated at 18 000 m^3/s. Proposals for a 8000 MW tidal barrage in the Severn Estuary (UK) were first discussed in the nineteenth century and are still awaiting funding.

The utilization of the energy in tidal flows has long been the subject of attention and now a number of prototype devices are undergoing trials. In some aspects, these resemble underwater wind turbines, Figure 1.11. The technical and economic difficulties are considerable and there are only a limited number of locations where such schemes are feasible.

1.5.6.2 Wave Power

The energy content of sea waves is very high. The Atlantic waves along the northwest coast of Britain have an average energy value of 80 kW/m of wave crest length. The energy is obviously very variable, ranging from greater than 1 MW/m for 1% of the year to near zero for a further 1%. Over several hundreds of kilometres a vast source of energy is available.

The sea motion can be converted into mechanical energy in several ways with a number of innovative solutions being trialled, Figure 1.12. An essential attribute of any wave power device is its survivability against the extreme loads encountered during storms.

1.6 Energy Storage

The tremendous difficulty in storing electricity in any large quantity has shaped the architecture of power systems as they stand today. Various options exist for the large-scale storage of energy to ease operation and affect overall economies. However, energy storage of any kind is expensive and incurs significant power losses. Care must be taken in its economic evaluation.

The options available are as follows: pumped storage, compressed air, heat, hydrogen gas, secondary batteries, flywheels and superconducting coils.

1.6.1 Pumped Storage

Very rapid changes in load may occur (for example 1300 MW/min at the end of some programmes on British TV) or the outage of lines or generators. An instantaneous loss of 1320 MW of generation (two 660 MW generating units) is considered when planning the operation of the Great Britain system. Hence a considerable amount of conventional steam plant must operate partially loaded to respond to these events. This is very expensive because there is a fixed heat loss for a steam turbogenerator regardless of output, and the efficiency of a thermal generating unit is reduced at part load. Therefore a significant amount of energy storage capable of instantaneous use would be an effective method of meeting such loadings, and by far the most important method to date is that of pumped storage.

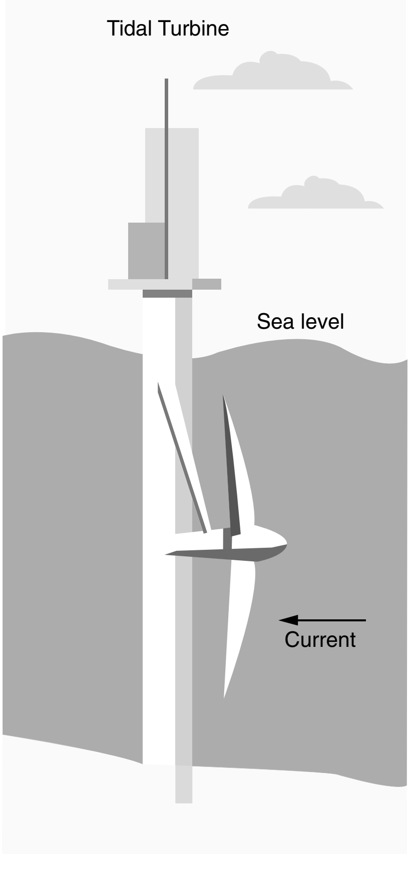

Figure 1.11 Tidal stream energy (Figure adapted from Marine Current Turbines)

A pumped storage scheme consists of an upper and a lower reservoir and turbine-generators which can be used as both turbines and pumps. The upper reservoir typically has sufficient storage for 4–6 hours of full-load generation.

The sequence of operation is as follows. During times of peak load on the power system the turbines are driven by water from the upper reservoir and the electrical machines generate in the normal manner. During the night, when only base load stations are in operation and electricity is being produced at its cheapest, the water in the lower reservoir is pumped back into the higher one ready for the next day's peak load. At these times of low network load, each generator changes to synchronous motor action and, being supplied from the general power network, drives its turbine which now acts as a pump.

Typical operating efficiencies attained are:

- Motor and generator 96%
- Pump and turbine 77%
- Pipeline and tunnel 97%
- Transmission 95%

giving an overall efficiency of 68%. A further advantage is that the synchronous machines can be easily used as synchronous compensators to control reactive power if required.

A large pumped hydro scheme in Britain uses six 330 MVA pump-turbine (Francis-type reversible) generator-motor units generating at 18 kV. The flow of water and hence power output is controlled by guide vanes associated with the turbine. The maximum pumping power is 1830 MW. The machines are 92.5% efficient as turbines and 91.7% efficient as pumps giving an exceptionally high round trip efficient of 85%. The operating speed of the 12-pole electrical machines is 500 r.p.m. Such a plant can be used to provide fine frequency control for the whole British system. The machines will be expected to start and stop about 40 times a day as well as

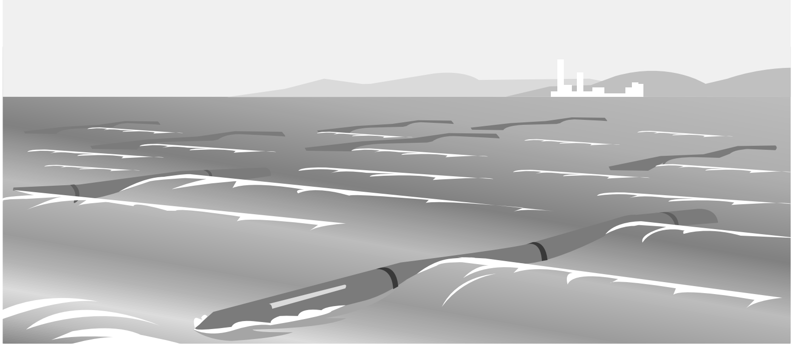

Figure 1.12 Wave power generation (Figure adapted from Pelamis)

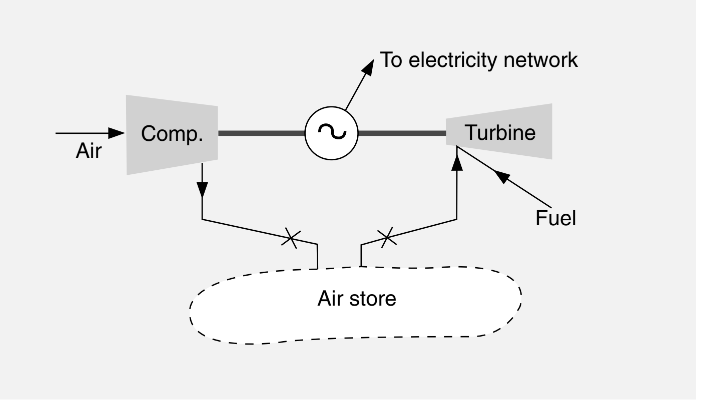

Figure 1.13 Storage using compressed air in conjunction with a gas turbine generator

provide frequency response in the event of a sudden load pick up or tripping of other generators.

1.6.2 Compressed-Air Storage

Air is pumped into large receptacles (e.g. underground caverns or old mines) at night and used to drive gas turbines for peak, day loads. The energy stored is equal to the product of the air pressure and volume. The compressed air allows fuel to be burnt in the gas turbines at twice the normal efficiency. The general scheme is illustrated in Figure 1.13. A German utility has installed a 290 MW scheme. In one discharge/charge cycle it generated 580 MWh of on-peak electricity and consumed 930 MWh of fuel plus 480 MWh of off-peak electricity. A similar plant has been installed in the USA. One disadvantage of these schemes is that much of the input energy to the compressed air manifests itself as heat and is wasted. Heat could be retained after compression, but there would be possible complications with the store walls rising to a temperature of 450 °C at 20 bar pressure. A solution would be to have a separate heat store that could comprise stacks of stones or pebbles which store heat cheaply and effectively. This would enable more air to be stored because it would now be cool. At 100 bar pressure, approximately 30 m^3 of air is stored per MWh output.

1.6.3 Secondary Batteries

Although demonstrated in a number of pilot projects (for example, a 3 MW battery storage plant was installed in Berlin for frequency control in emergencies and a 35 MW battery system is used to smooth the output of a wind farm in Japan) the large-scale use of battery storage remains expensive and the key area where the use of secondary batteries is likely to have impact is in electric vehicles. The popular lead-acid cell, although reasonable in price, has a low energy density (15 Wh/kg). Nickel-cadmium cells are better (40 Wh/kg) but more

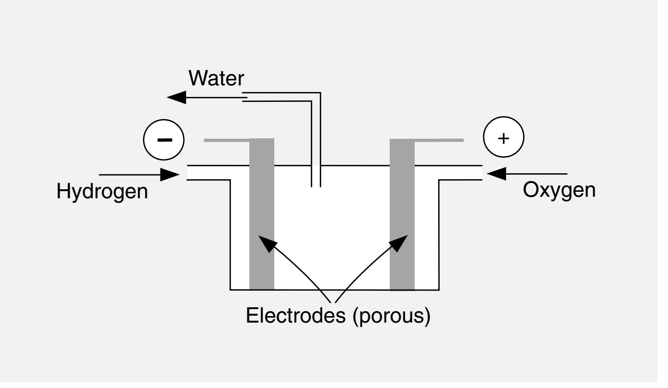

Figure 1.14 Hydrogen-oxygen fuel cell

expensive. Still under intensive development and demonstration is the sodium-sulphur battery (200 Wh/kg), which has a solid electrolyte and liquid electrodes and operates at a temperature of 300 °C. Modern electric vehicles use Lithium ion batteries (100–200 Wh/kg) but these remain expensive. Other combinations of materials are under active development in attempts to increase output and storage per unit weight and cost.

1.6.4 Fuel Cells

A fuel cell converts chemical energy to electrical energy by electrochemical reactions. Fuel is continuously supplied to one electrode and an oxidant (usually oxygen) to the other electrode. Figure 1.14 shows a simple hydrogen-oxygen fuel cell, in which hydrogen gas diffuses through a porous metal electrode (nickel). A catalyst in the electrode allows the absorption of H_2 on the electrode surface as hydrogen ions which react with the hydroxyl ions in the electrolyte to form water ($2H_2 + O_2 \rightarrow 2H_2O$). A theoretical e.m.f. of 1.2 V at 25 °C is obtained. Other fuels for use with oxygen are carbon monoxide (1.33 V at 25 °C), methanol (1.21 V at 25 °C), and methane (1.05 V at 25 °C). In practical cells, conversion efficiencies of 80% have been attained. A major use of the fuel cell could be in conjunction with a future hydrogen energy system.

Intensive research and development is still proceeding on various types of fuel cell – the most successful to date for power generation being the phosphoric fuel cell. A demonstration unit used methane as the input fuel and operated at about 200–300 °C to produce 200 kW of electrical power plus 200 kW of heat energy, with overall efficiency of around 80%. Compared with other forms of energy conversion, fuel cells have the potential of being up to 20% more efficient. Much attention is now being given to the high-temperature molten carbonate cell which has a high efficiency.

1.6.5 Hydrogen Energy Systems

The transmission capacity of a pipe carrying natural gas (methane) is high compared with electrical links, the installed cost being about one tenth of an equivalent capacity H.V. overhead line. For long transmission distances the pressure drop is compensated by booster compressor stations. A typical gas system uses a pipe of internal diameter 0.9 m and, with natural gas, a power transfer of 12 GW is possible at a pressure of 68 bar and a velocity of 7 m/s. A 1 m diameter pipe carrying hydrogen gas can transmit 8 GW of power, equivalent to four 400 kV, three phase transmission lines.

The major advantage of hydrogen is, of course, that it can be stored; the major disadvantage is that it must be produced for example, from water by electrolysis. Very large electrolysers can attain efficiencies of about 60%. This, coupled with the efficiency of electricity production from a nuclear plant, gives an overall efficiency of hydrogen production of about 21%. Alternative methods of production are under laboratory development, for example, use of heat from nuclear stations to 'crack' water and so release hydrogen; however, temperatures of 3000 °C are required.

1.6.6 Superconducting Magnetic Energy Stores (SMES)

Continuing development of high-temperature superconductors, where the transition temperature can be around 60–80 K (K is degrees Kelvin where 0 K is absolute zero and 273 K is 0 °C) has led to the possibility of storing energy in the magnetic field produced by circulating a large current (over 100 kA) in an inductance. For a coil of inductance L in air, the stored energy is given by

$$E = \frac{1}{2} L I^2 \qquad [J]$$

A big advantage of the high-temperature superconductor is that cooling by liquid nitrogen can be used, which is far cheaper than using helium to reach temperatures closer to absolute zero. Initially, it is expected that commercial units will be used to provide an uninterruptible supply for sensitive loads to guard against voltage sags or to provide continuity whilst emergency generators are started. Another use in transmission networks would be to provide fast response for enhanced transient stability and improved power quality.

1.6.7 Flywheels

The most compact energy store known is that of utilizing high-speed flywheels. Such devices coupled to an electrical generator/motor have been employed in buses on an experimental basis and also in special industrial applications. For power systems, very large flywheels constructed of composite high-tensile resisting materials have been proposed, but their cost and maintenance problems have so far ruled them out of economic contention compared with alternative forms of energy supply.

1.6.8 Supercapacitors

The interface between an anode and cathode immersed in an electrolyte has a very high permittivity. This property can be exploited in a capacitor to produce a 25 V capsule with a capacitance of 0.1 F. Many units in series and parallel would have the capability of storing many MWh of energy, which can be quickly released for transient control purposes. To date, higher voltage forms of a commercially useful device have not got beyond their employment for pulse or actuator applications.

1.7 Environmental Aspects of Electrical Energy

Increasingly, environmental considerations influence the development of energy resources, especially those involving electricity production, transmission, and distribution. Conversion of one form of energy to another produces unwanted side effects and, often, pollutants which need to be controlled and disposed of. In addition, safety and health are subject to increasing legislation by national and international bodies, thereby requiring all engineers to be aware of the laws and regulations governing the practice of their profession.

It must be appreciated that the extraction of fossil fuels from the earth is not only a hazardous business but also, nowadays, one controlled through licensing by governments and state authorities. Hydro plants require careful study and investigation through modelling, widespread surveys, and environmental impact statements to gain acceptance. Large installations of all kinds require, often lengthy, planning enquiries which are both time consuming and expensive, thereby delaying the start up of energy extraction and production. As a consequence, methods of producing electrical energy which avoid or reduce the enquiry process are to be favoured over those needing considerable consultation before receiving the go ahead. This is likely to favour small-scale projects or the redevelopment of existing sites where industry or production facilities are already operating.

In recent years, considerable emphasis has been placed on 'sustainable development', by which is meant the use of technologies that do not harm the environment, particularly in the long term. It also implies that anything we do now to affect the environment should be recoverable by future generations. Irreversible damage, for example, damage to the ozone layer or increase in CO_2 in the atmosphere, should be avoided.

1.7.1 Global Emissions from Fossil Fuelled Power Stations

It is generally accepted that the burning of fossil fuels and the subsequent emission of greenhouse gases, particularly CO_2, is leading to climate change and potentially catastrophic increase in the earth's temperature. Hence concern over the emission of greenhouse gases is a key element of energy policy and, in Europe, is recognized through the EU Emissions Trading Scheme which requires major emitters of CO_2, such as power stations, to purchase permits to emit CO_2. This has the effect of making high carbon generation (particularly from coal) increasingly expensive.

1.7.2 Regional and Local Emissions from Fossil Fuelled Power Stations

Fossil fuelled power plants produce sulphur oxides, particulate matter, and nitrogen oxides. Of the former, sulphur dioxide accounts for about 95% and is a by-product of the combustion of coal or oil. The sulphur content of coal varies from 0.3 to 5%. Coal can only be used for generation in some US states if it is below a certain percentage sulphur.

In the eastern USA this has led to the widespread use of coal from western states because of its lower sulphur content or the use of gas as an alternative fuel. Sulphur dioxide forms sulphuric acid (H_2SO_4) in the air which causes damage to buildings and vegetation. Sulphate concentrations of 9–10 $\mu g/m^3$ of air aggravate asthma and lung and heart disease. This level has been frequently exceeded in the past, a notorious episode being the London fog of 1952 (caused by domestic coal burning). It should be noted that although sulphur does not accumulate in the air it does so in the soil.

Sulphur oxide emission can be controlled by:

- the use of fuel with less than, say, 1% sulphur;
- the use of chemical reactions to remove the sulphur, in the form of sulphuric acid, from the combustion products, for example limestone scrubbers, or fluidized bed combustion;
- removing the sulphur from the coal by gasification or flotation processes.

European legislation limits the amount of SO_2, NO_x, and particulate emission, as in the USA. This has led to the retrofitting of flue gas desulphurization (FGD) scrubbers to coal burning plants. Without such equipment coal fired power stations must be retired. Emissions of NO_x can be controlled by fitting advanced technology burners which can ensure a more complete combustion process, thereby reducing the oxides going up the stack (chimney).

Particulate matter, particles in the air, is injurious to the respiratory system, in sufficient concentration, and by weakening resistance to infection may well affect the whole body. Apart from settling on the ground or buildings to produce dirt, a further effect is the reduction of the solar radiation entering the polluted area. Reported densities (particulate mass in 1 m^3 of air) are 10 $\mu g/m^3$ in rural areas rising to 2000 $\mu g/m^3$ in polluted areas. The average value in US cities is about 100 $\mu g/m^3$.

About one-half of the oxides of nitrogen in the air in populated areas are due to power plants and originate in high-temperature combustion processes. At levels of 25–100 parts per million they can cause acute bronchitis and pneumonia. Increasingly, city pollutants are due to cars and lorries and not power plants.

A 1000 MW(e) coal plant burns approximately 9000t of coal per day. If this has a sulphur content of 3% the amount of SO_2 emitted per year is 2×10^5t. Such a plant produces the following pollutants per hour (in kg): CO_2 8.5×10^5, CO 0.12×10^5, sulphur oxides 0.15×10^5, nitrogen oxides 3.4×10^3, and ash.

Both SO_2 and NO_x are reduced considerably by the use of FGD, but at considerable cost and reduction in the efficiency of the generating unit caused by the power used by the scrubber. Gas-fired CCGT plants produce very little NO_x or SO_2 and their CO_2 output is about 55% of an equivalent size coal-fired generator.

The concentration of pollutants can be reduced by dispersal over a wider area by the use of high stacks. If, in the stack, a vertical wire is held at a high negative potential relative to the wall, the expelled electrons from the wire are captured by the gas molecules moving up the stack. Negative ions are formed which accelerate to the wall, collecting particles on the way. When a particle hits the wall the charge is neutralized and the particle drops down the stack and is collected. Precipitators have particle-removing (by weight) efficiencies of up to 99%, but this is misleading as performance is poor for small particles; of, say, less than 0.1 μm in diameter. The efficiency based on number of particles removed is therefore less. Disposal of the resulting fly-ash is expensive, but the ash can be used for industrial purposes, for example, building blocks. Unfortunately, the efficiency of precipitators is enhanced by reasonable sulphur content in the gases. For a given collecting area the efficiency decreases from 99% with 3% sulphur to 83% with 0.5% sulphur at 150 °C. This results in much larger and more expensive precipitator units with low-sulphur coal or the use of fabric filters in 'bag houses' situated before the flue gas enters the stack.

1.7.3 Thermal Pollution from Power Stations

Steam from the low-pressure turbine is liquefied in the condenser at the lowest possible temperatures to maximize the steam-cycle efficiency. Where copious supplies of water exist the condenser is cooled by 'once-through' circulation of sea- or river-water. Where water is more restricted in availability, for example, away from the coasts, the condensate is circulated in cooling towers in which it is sprayed in nozzles into a rising volume of air. Some of the water is evaporated, providing cooling. The latent heat of water is 2×10^6 J/kg compared with a sensible heat of 4200 J/kg per degree C. A disadvantage of such towers is the increase in humidity produced in the local atmosphere.

Dry cooling towers in which the water flows through enclosed channels (similar to a car radiator), past which air is blown, avoid local humidity problems, but at a much higher cost than 'wet towers'. Cooling towers emit evaporated water to the atmosphere in the order of 75 000 litres/min for a 1000 MW(e) plant.

A crucial aspect of once-through cooling in which the water flows directly into the sea or river is the increased temperature of the natural environment due to the large volume per minute (typically $360\,m^3/s$ for a coolant rise of 2.4 °C for a 2.4 GW nuclear station) of heated coolant. Because of their lower thermal efficiency, nuclear power stations require more cooling water than fossil-fuelled plants. Extreme care must be taken to safeguard marine life, although the higher temperatures can be used effectively for marine farming if conditions can be controlled.

1.7.4 Electromagnetic Radiation from Overhead Lines, Cables and Equipment

The biological effects of electromagnetic radiation have been a cause of considerable concern amongst the general public as to the possible hazards in the home and the

Table 1.4 Typical electric and magnetic field strengths directly under overhead lines[a]. Note that the magnetic field depends upon the current carried

Line Voltage (kV)	Electric Field Strength (V/m)	Magnetic Flux Density (μT)
400 and 275 tower lines	3000–5000	5–10
132 tower line	1000–2000	0.5–2
33 and 11 wood pole	200	0.2–0.5
UK recommendations on exposure limits (to the public)	9000	360
Earth's magnetic field	—	40–50

Data from http://www.emfs.info/. This site is maintained by the National Grid Company, reproduced with permission.

workplace. Proximity of dwellings to overhead lines and even buried cables has also led to concerns of possible cancer-inducing effects, with the consequence that research effort has been undertaken to allay such fears. In general it is considered that the power frequencies used (50 or 60 Hz) are not harmful. The electric field and magnetic field strengths below typical HV transmission lines are given in Table 1.4.

Considerable international research and cooperative investigation has now been proceeding for over 40 years into low-frequency electric and magnetic field exposure produced by household appliances, video display terminals, and local power lines. To date there is no firm evidence that they pose any demonstrable health hazards. Epidemiologic findings of an association between electric and magnetic fields and childhood leukaemia or other childhood or adult cancers are inconsistent and inconclusive; the same is likely to be true of birth defects or other reproductive problems.

1.7.5 Visual and Audible Noise Impacts

The presence of overhead lines constitutes an environmental problem (perhaps the most obvious one within a power system) on several counts.

1. Space is used which could be used for other purposes. The land allocated for the line is known as the right of way (or wayleave in Britain). The area used for this purpose is already very appreciable.
2. Lines are considered by many to mar the landscape. This is, of course, a subjective matter, but it cannot be denied that several tower lines converging on a substation or power plant, especially from different directions, is offensive to the eye.
3. Radio interference, audible noise, and safety considerations must also be considered.

Although most of the above objections could be overcome by the use of underground cables, these are not free of drawbacks. The limitation to cable transmitting current because of temperature-rise considerations coupled with high manufacture and installation costs results in the ratio of the cost of transmission underground to that for overhead transmission being between 10 and 20 at very high operating voltages. With novel cables, such as superconducting, still under development it is hoped to reduce this disadvantage. However, it may be expected that in future a larger proportion of circuits will be placed underground, especially in suburban areas. In large urban areas circuits are invariably underground, thereby posing increasing problems as load densities increase.

Reduction of radio interference can be achieved in the same way that electromagnetic effects are reduced, but audible noise is a function of the line design. Careful attention to the tightness of joints, the avoidance of sharp or rough edges, and the use of earth screen shielding can reduce audible noise to acceptable levels at a distance dependent upon voltage.

Safety clearances dependent upon International Standards are, of course, extremely important and must be maintained in adverse weather conditions. The most important of these is the increased sag due to ice and snow build up in winter and heavy loading of the circuits in summer.

1.8 Transmission and Distribution Systems

1.8.1 Representation

Modern electricity supply systems are invariably three-phase. The design of transmission and distribution networks is such that normal operation is reasonably close to balanced three-phase working, and often a study of the electrical conditions in one phase is sufficient to give a complete analysis. Equal loading on all three phases of a network is ensured by allotting, as far as possible, equal domestic loads to each phase of the low-voltage distribution feeders; industrial loads usually take three-phase supplies.

A very useful and simple way of graphically representing a network is the schematic or line diagram in which three-phase circuits are represented by single lines. Certain conventions for representing items of plant are used and these are shown in Figure 1.15.

A typical line or schematic diagram of a part of a power system is shown in Figure 1.16. In this, the generator is star connected, with the star point connected to earth through a resistance. The nature of the connection of the star point of rotating machines and transformers to earth is of vital importance when considering faults which produce electrical imbalance in the three phases. The generator feeds two three-phase circuits (overhead or underground). The line voltage is increased from that at the generator terminals by transformers connected as shown. At the end of the lines the voltage is reduced for the secondary distribution of power. Two lines are provided to improve the security of the supply that is, if one line develops a fault and has to be switched out the remaining one still delivers power to the receiving end. It is not necessary in straightforward current and voltage calculations to indicate the presence of switches on the diagrams, but in some cases, such as stability calculations, marking the location of switches, current transformers, and protection is very useful.

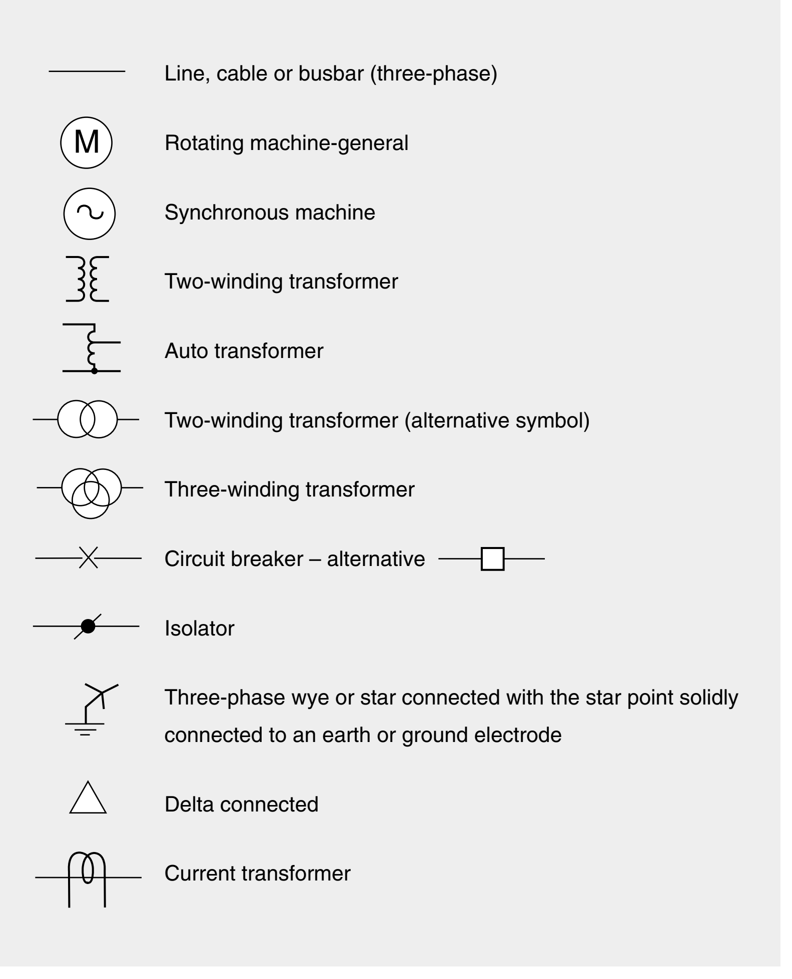

Figure 1.15 Symbols for representing the components of a three-phase power system

A short list of terms used to describe power systems follows, with explanations.

System: This is used to describe the complete electrical network: generators, circuits, loads, and prime movers.

Load: This may be used in a number of ways: to indicate a device or collection of devices which consume electricity; to indicate the power required from a given supply circuit; to indicate the power or current being passed through a line or machine.

Busbar: This is an electrical connection of zero impedance (or node) joining several items, such as lines, generators or loads. Often this takes the form of actual busbars of copper or aluminium.

Earthing (Grounding): This is connection of a conductor or frame of a device to the main body of the earth. This must be done in such a manner that the resistance

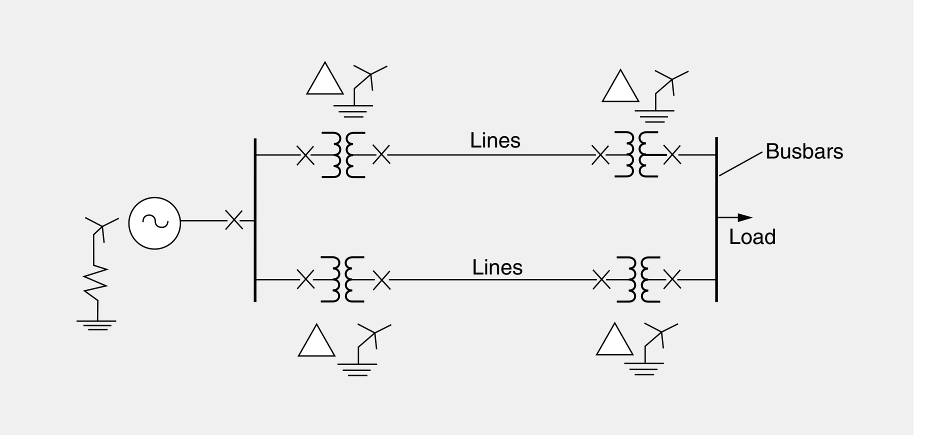

Figure 1.16 Line diagram of a simple system

between the item and the earth is below prescribed limits. This often entails the burying of the large assemblies of conducting rods in the earth and the use of connectors of a large cross sectional area. It is usual to earth the neutral point of 3-phase circuits at least once at each voltage level.

Fault: This is a malfunctioning of the network, usually due to the short-circuiting of conductors phase-phase or phase-earth.

Outage: Removal of a circuit either deliberately or inadvertently.

Security of Supply: Provision must be made to ensure continuity of supply to consumers, even with certain items of plant out of action. Usually, two circuits in parallel are used and a system is said to be secure when continuity is assured. This is obviously the item of first priority in design and operation.

1.8.2 Transmission

Transmission refers to the bulk transfer of power by high-voltage links between central generation and load centres. Distribution, on the other hand, describes the conveyance of this power to consumers by means of lower voltage networks.

Generators usually produce voltages in the range 11–25 kV, which is increased by transformers to the main transmission voltage. At substations the connections between the various components of the system, such as lines and transformers, are made and the switching of these components is carried out. Large amounts of power are transmitted from the generating stations to the load-centre substations at 400 kV and 275 kV in Britain, and at 765, 500 and 345 kV in the USA. The network formed by these very high-voltage lines is sometimes referred to as the Supergrid. Most of the large and efficient generating stations feed through transformers directly into this network. This grid, in turn, feeds a sub-transmission network operating at 132 kV in Britain and 115 kV in the USA. In Britain the lower voltage networks operate at 33, 11, or 6.6 kV and supply the final consumer feeders at 400 V three-phase, giving 230 V between phase and neutral. Other voltages exist

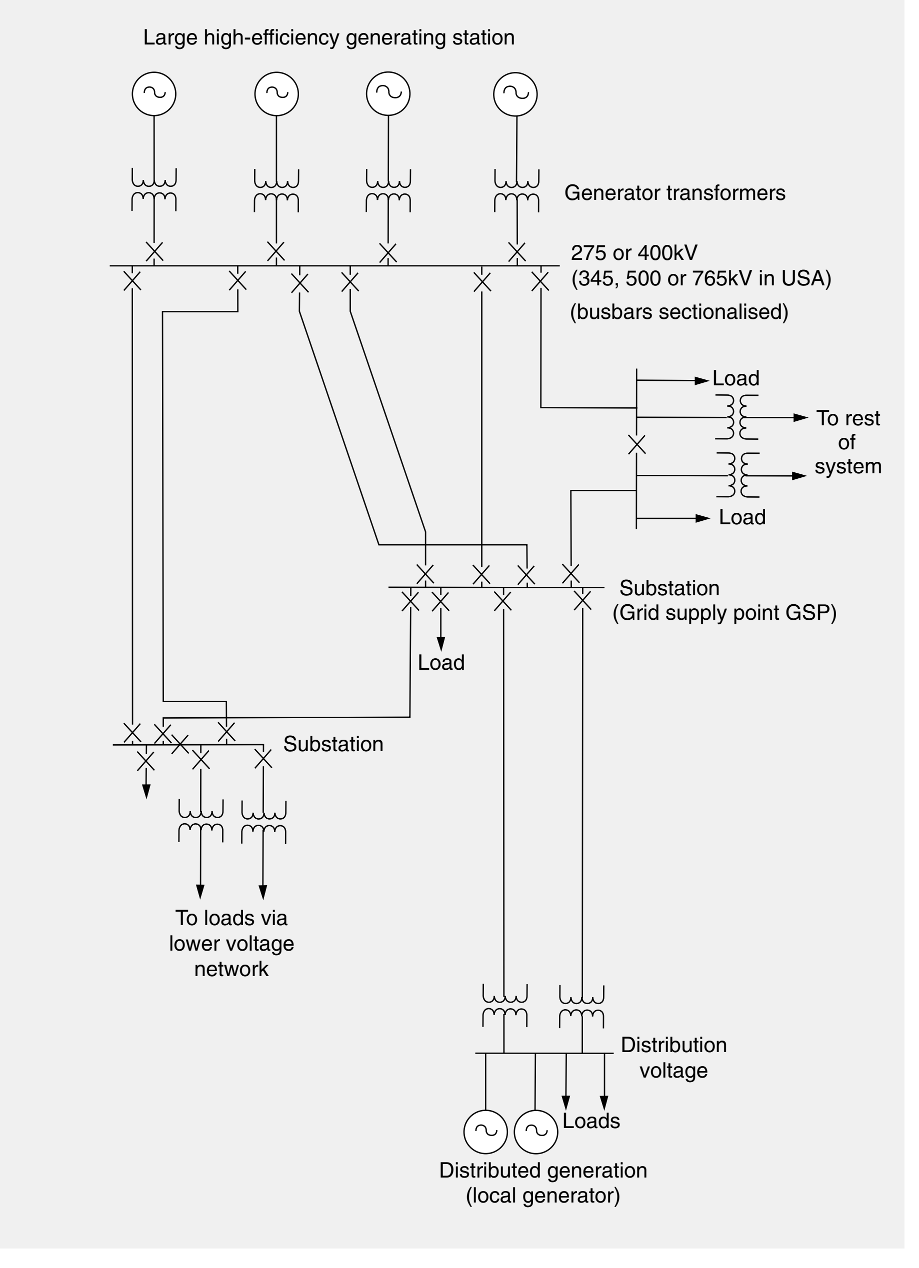

Figure 1.17 Part of a typical power system

in isolation in various places, for example the 66 and 22 kV London cable systems. A typical part of a supply network is shown schematically in Figure 1.17. The power system is thus made up of networks at various voltages. There exist, in effect, voltage tiers as represented in Figure 1.18.

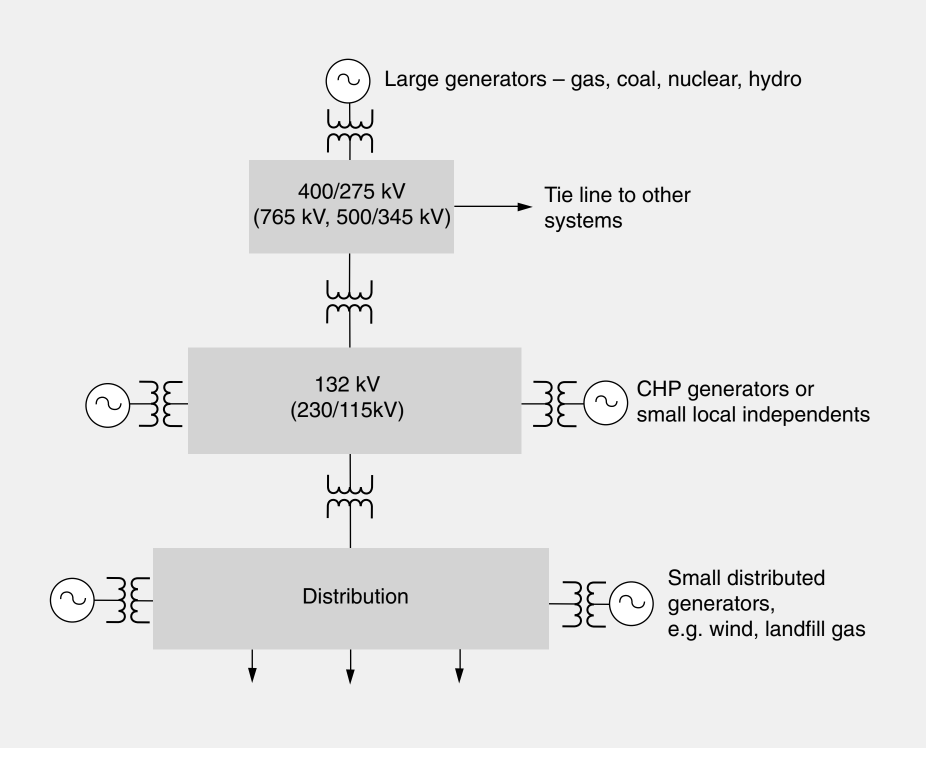

Figure 1.18 Schematic diagram of the constituent networks of a supply system. USA voltages in parentheses

Summarizing, transmission networks deliver to wholesale outlets at 132 kV and above; sub-transmission networks deliver to retail outlets at voltages from 115 or 132 kV, and distribution networks deliver to final step-down transformers at voltages below 132 kV, usually operated as radial systems.

1.8.2.1 Reasons for Interconnection

Many generating sets are large and power stations of more than 2000 MW are used to provide base load power. With CCGT units, their high efficiency and cheap long-term gas contracts mean that it is often more economic to use these efficient stations to full capacity 24 h a day and transmit energy considerable distances than to use less efficient more local stations. The main base load therefore is met by these high-efficiency stations which must be interconnected so that they feed into the general system and not into a particular load.

To meet sudden increases in load a certain amount of generating capacity, known as the spinning reserve, is required. This consists of part-loaded generators synchronized with the system and ready to supply power instantaneously. If the machines are stationary a reasonable time is required (especially for steam turbo-alternators) to run up to speed; this can approach 6 h, although small gas turbines can be started and loaded in 3 minutes or less. Hydro generators can be even quicker. It is more economic to have certain stations serving only this function than to have each station carrying its own spinning reserve.

The electricity supplies over the entire country are synchronized and a common frequency exists: 50 Hz in Europe, 60 Hz in N. America.

Interconnection also allows for alternative paths to exist between generators and bulk supply points supplying the distribution systems. This provides security of supply should any one path fail.

1.8.3 Distribution Systems

Distribution networks differ from transmission networks in several ways, quite apart from their voltage levels. The number of branches and sources is much higher in distribution networks and the general structure or topology is different. A typical system consists of a step-down (e.g. 132/11 kV) on-load tap-changing transformer at a bulk supply point feeding a number of circuits which can vary in length from a few hundred metres to several kilometres. A series of step-down three-phase transformers, for example, 11 kV/433 V in Britain or 4.16 kV/220 V in the USA, are spaced along the route and from these are supplied the consumer three-phase, four-wire networks which give 240 V, or, in the USA, 110 V, single-phase supplies to houses and similar loads.

1.8.3.1 Rural Systems

In rural systems, loads are relatively small and widely dispersed (5–50 kVA per consumer group is usual). In Great Britain a predominantly overhead line system at 11 kV, three-phase, with no neutral or single phase for spurs from the main system is used. Pole-mounted transformers (5–200 kVA) are installed, protected by fuses which require manual replacement after operation; hence rapid access is desirable by being situated as close to roads as possible. Essentially, a radial system is supplied from one step-down point; distances up to 10–15 miles (16–24 km) are feasible with total loads of 500 kVA or so (see Figure 1.19), although in sparsely populated areas, distances of 50 miles may be fed by 11 kV. Single-phase earth-return systems operating at 20 kV are used in some developing countries.

Over 80% of faults on overhead distribution systems are transitory due to flashover following some natural or man-made cause. This produces unnecessary fuse-blowing unless auto-reclosers are employed on the main supply; these have been used with great success in either single- or three-phase form. The principle, as shown in Figure 1.20, is to open on fault before the fuse has time to operate and to reclose after 1–2 s. If the fault still persists, a second attempt is made to clear, followed by another reclose. Should the fault still not be cleared, the recloser remains closed for a longer period to blow the appropriate protective fuse (for example, on a spur line or a transformer). If the fault is still not cleared, then the recloser opens and locks out to await manual isolation of the faulty section. This process requires the careful coordination of recloser operation and

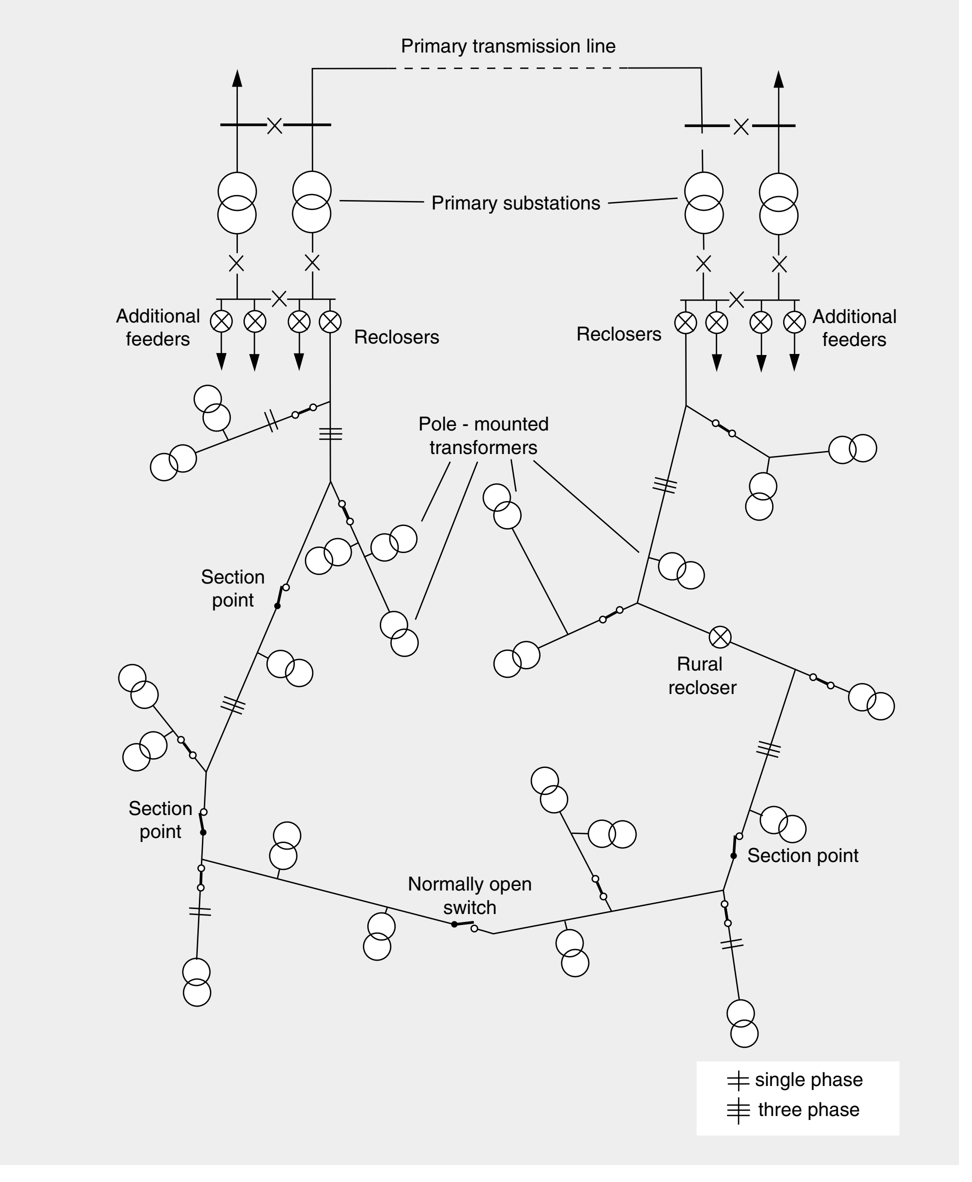

Figure 1.19 Typical rural distribution system

fuse-blowing characteristics where time grading is important. Section switches operated by radio or tele-command enable quick resupply routes to be established following a faulty section isolation.

Good earthing at transformer star points is required to prevent overvoltages at consumers' premises. Surge protection using diverters or arcing horns is essential in lightning-prone areas.

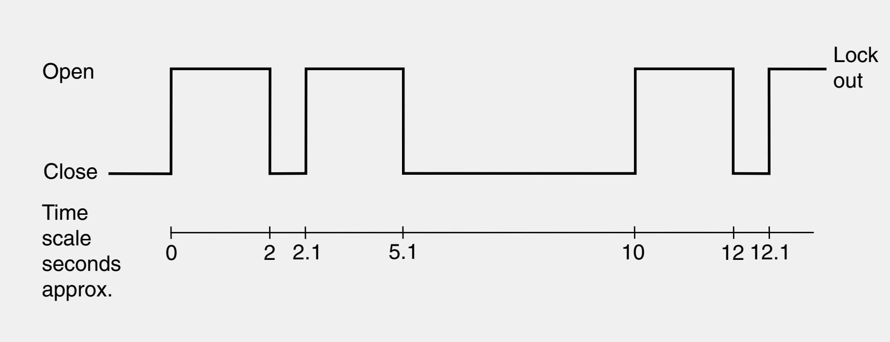

Figure 1.20 Sequence of operations for a recloser

1.8.3.2 Suburban Systems

These are a development of the rural system into ring mains, with much of the network underground for amenity reasons. The rings are sectionalized so that simple protection can be provided. Loads range between 2 and 10 MW/mile^2 (0.8–4.0 MW/km^2).

In high-density housing areas, the practice is to run the L.V. mains on either side of each road, interconnected at junctions by links for sectionalizing (see Figure 1.21). At appropriate points this network is fed by step-down transformers of 200–500 kVA rating connected to an H.V. cable or overhead line network. Reinforcement is provided by installing further step-down transformers tapped from the H.V. network. It is rare to up-rate L.V. cables as the load grows.

Short-circuit levels are fairly low due to the long H.V. feeders from the bulk supply points. With the increasing cost of cables and undergrounding works, but with improved transformer efficiency and lower costs due to rationalization and standardization, an economic case can be made for reducing the L.V. network and extending the H.V. network so that fewer consumers are supplied from each transformer.

1.8.3.3 Urban (Town or City) Systems

Very heavy loadings (up to 100 MW/mile^2 or 40 MW/km^2) are usual, especially where high-rise buildings predominate. Extensive heating and air-conditioning loads as well as many small motors predominate. Fluorescent lighting reduces the power factor and leads to some waveform distortion, but computer and TV loads and power electronic motor drives now cause considerable harmonics on all types of network.

Again, a basic L.V. grid, reinforced by extensions to the H.V. network, as required, produces minimum costs overall. The H.V. network is usually in the form of a ring main fed from two separate sections of a double busbar substation where 10–60 MVA transformers provide main supply from the transmission system (see Figure 1.22). The H.V. network is sectionalized to contain short-circuit levels and to ease protection grading. A high security of supply is possible by

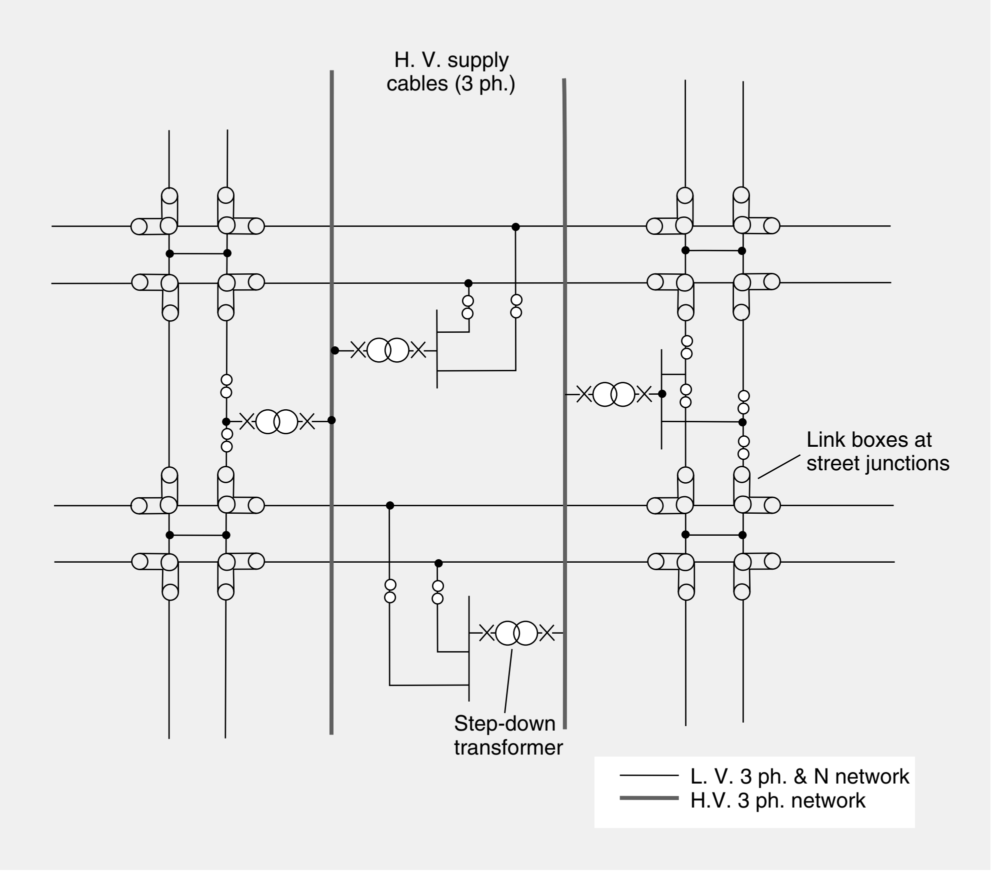

Figure 1.21 Principle of suburban distribution system

overlapping H.V. rings so that the same L.V. grid is fed from several transformers supplied over different routes. Failure of one portion of the H.V. system does not affect consumers, who are then supported by the L.V. network from adjacent H.V. supplies.

In the UK transformers of 500 or 1000 kVA rating are now standard, with one H.V. circuit breaker or high rupturing capacity (HRC) fuse-switch and two isolators either side to enable the associated H.V. cable to be isolated manually in the event of failure. The average H.V. feeder length is less than 1 mile and restoration of H.V. supplies is usually obtainable in under 1 h. Problems may arise due to back-feeding of faults on the H.V. system by the L.V. system, and in some instances reverse power relay protection is necessary.

In new urban developments it is essential to acquire space for transformer chambers and cable access before plans are finalized. High-rise buildings may require substations situated on convenient floors as well as in the basement.

Apart from the supply of new industrial and housing estates or the electrification of towns and villages, a large part of the work of a planning engineer

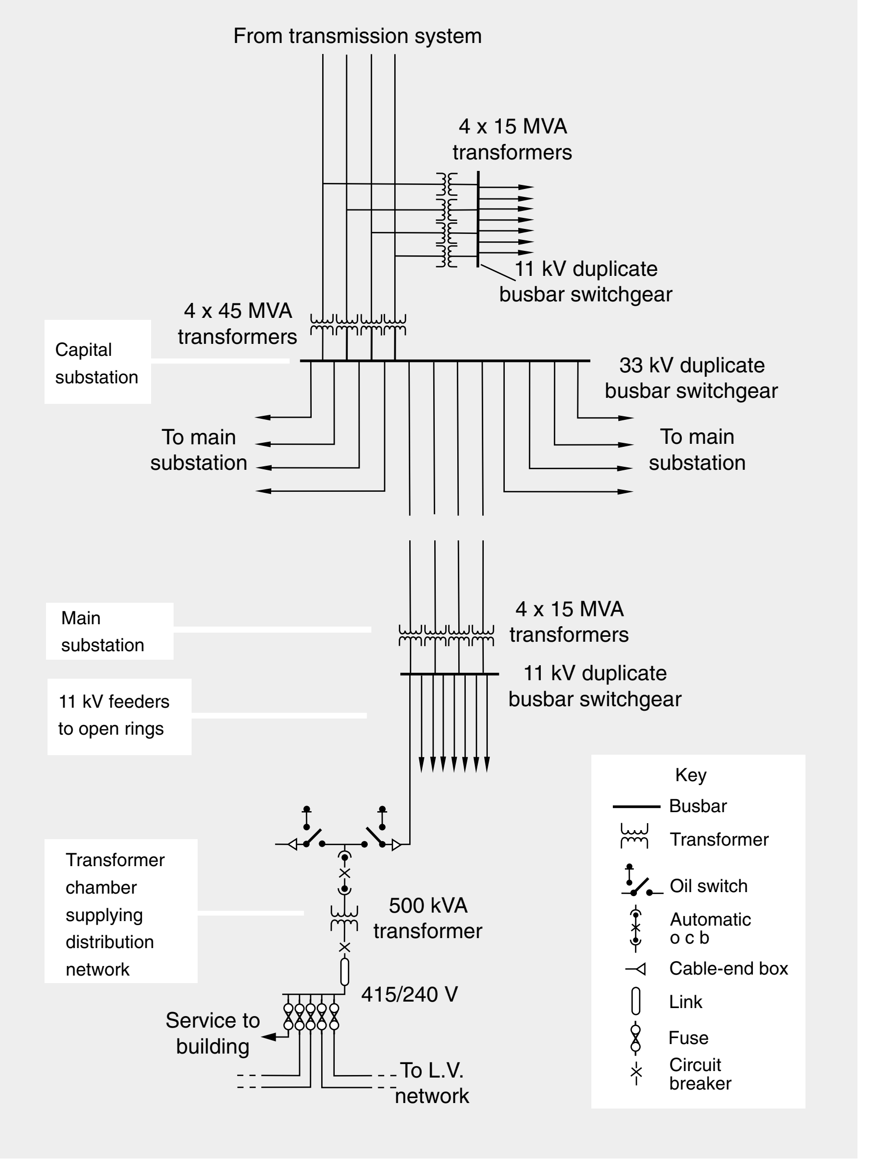

Figure 1.22 Typical arrangement of supply to an urban network–British practice

is involved with the up-rating of existing supplies. This requires good load forecasting over a period of 2–3 years to enable equipment to be ordered and access to sites to be established. One method of forecasting is to survey the demand on transformers by means of a maximum-demand indicator and to treat any transformer which has an average load factor of 70% or above as requiring up-rating over the next planning period. Another method is to analyze consumers' bills, sectionalized into areas and distributors and, by surveys and computer analysis, to relate energy consumed to maximum demand. This method can be particularly useful and quite economic where computerized billing is used. The development of the Smart Grid is leading to much greater monitoring being installed on the 400 V network and control on the 11 kV system.

In practice, good planning requires sufficient data on load demands, energy growth, equipment characteristics, and protection settings. All this information can be stored and updated from computer files at periodic intervals and provides the basis for the installation of adequate equipment to meet credible future demands without unnecessary load shedding or dangerous overloading.

1.8.4 Typical Power Systems

Throughout the world the general form of power systems follows the same pattern. Voltage levels vary from country to country, the differences originating mainly from geographical and historical reasons.

Several frequencies have existed, although now only two values – 50 and 60 Hz – remain: 60 Hz is used on the American continent, whilst most of the rest of the world uses 50 Hz, although Japan still has 50 Hz for the main island and 60 Hz for the northern islands. The value of frequency is a compromise between higher generator speeds (and hence higher output per unit of machine volume) and the disadvantage of high system reactance at higher frequencies. Historically, the lower limit was set by the need to avoid visual discomfort caused by flicker from incandescent electric lamps.

The distance that a.c. transmission lines can transfer power is limited by the maximum permissible peak voltage between conductor and ground. As voltages increase, more and more clearance must be allowed in air to prevent the possibility of flashover or danger to people or animals on the ground. Unfortunately, the critical flashover voltage increases non-linearly with clearance, such that, with long clearances, proportionally lower peak voltages can be used safely. Figure 1.23 illustrates this effect.

The surge impedance of a line, described for a lossless line where the resistance and conductance are zero, is given by $Z_0 = \sqrt{L/C}$, where L is the series inductance and C is the shunt capacitance per unit length of the line. When a line is terminated in a resistive load equal to its surge impedance then the reactive power I^2X_L drawn by the line is balanced by the reactive power generated by the line capacitance V^2/X_C. The surge impedance loading is V^2/Z_0, typical values are shown in Table 1.5.

The curve given in Figure 1.24 shows that, in practice, short lines are usually loaded above their surge impedance loading (SIL) but, to ensure stability is maintained, long lines are generally loaded below their SIL. A useful rule-of-thumb to ensure stability is to restrict the phase difference between the sending and receiving end voltages of an EHV transmission circuit to 30°. Lower voltage circuits will have much smaller phase angle differences.

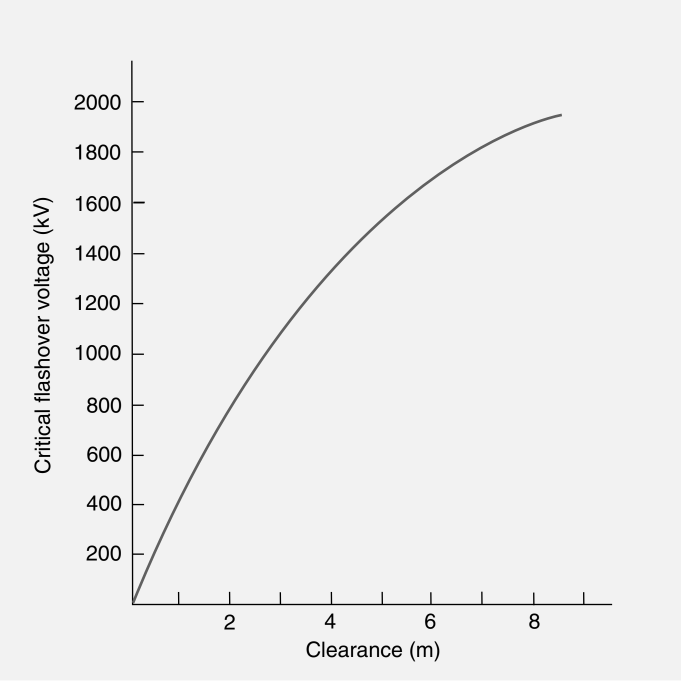

Figure 1.23 Critical flashover voltage for V-string insulators in a window tower (Figure adapted from Edison Electric Institute)

The highest a.c. voltage used for transmission is around 750 kV, although experimental lines above 1000 kV have been built.

The topology of the power system and the voltage magnitudes used are greatly influenced by geography. Very long lines are to be found in North and South American nations and Russia. This has resulted in higher transmission voltages, for example, 765 kV, with the possibility of voltages in the range 1000–1500 kV. In some South American countries, for example, Brazil, large hydroelectric resources have been developed, resulting in very long transmission links. In highly developed countries the available hydro resources have been utilized and a considerable proportion of new generation is from wind. In geographically smaller countries, as exist in Europe, the degree of interconnection is much higher, with shorter transmission distances, the upper voltage being about 420 kV.

Systems are universally a.c. with the use of high-voltage d.c. links for specialist purposes, for example, very long circuits, submarine cable connections, and back-to-back converters to connect different a.c. areas. The use of d.c. has been limited by the high cost of the conversion equipment. This requires overhead line lengths of a few hundred kilometres or cables of 30–100 km to enable the reduced circuit costs to offset the conversion costs.

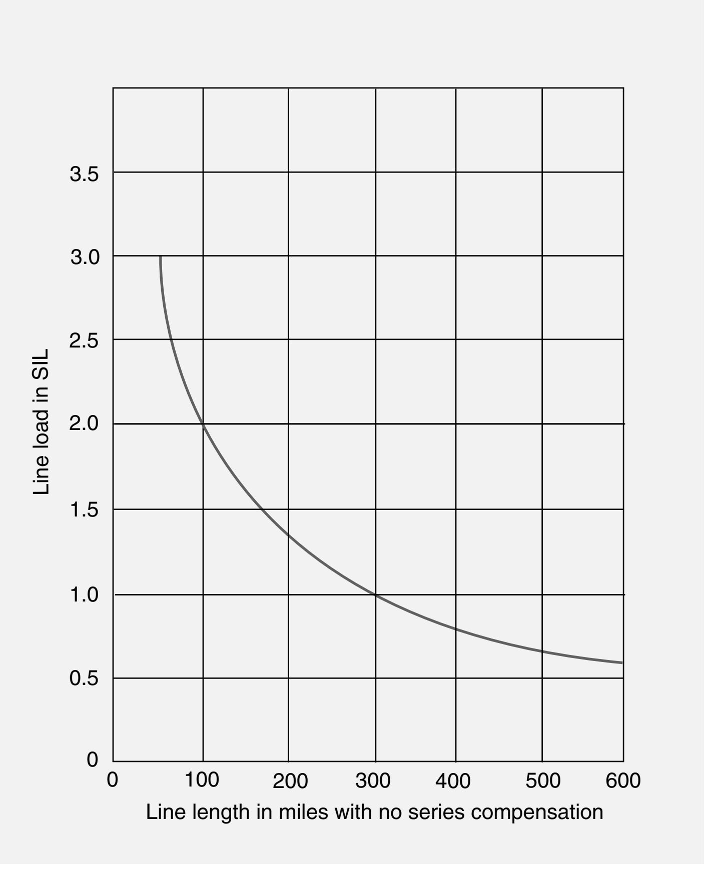

Figure 1.24 Practical transmission-line capability in terms of surge-impedance loading (SIL) (Figure adapted from Edison Electric Institute)

1.8.4.1 USA

The power system in the USA is based on a comparatively few investor owned generation/transmission utilities responsible for bulk transmission as well as operating and constructing new generation facilities when needed. Delivery is to smaller municipal or cooperative rural distribution companies or to the distribution arm of the transmission utility. The industry is heavily regulated by Federal and State Agencies and the investor profits are carefully controlled.

The loads differ seasonally from one part of the country to another and load diversity occurs because of the time zones. Generally, the summer load is the highest due to extensive use of air-conditioning (Figure 1.1(a) and (b)). Consumers are supplied at either 110 V, 60 Hz, single phase for lighting and small-consumption appliances but at 220 V for loads above about 3 kW (usually cookers, water-heaters and air-conditioners). This type of connection normally uses a 220 V centre-tapped transformer secondary to provide the 110 V supply.

1.8.4.2 UK

Here, the frequency (as in the whole of Europe) is 50 Hz and the residential supply is 230–240 V single phase. The European standard is now 230 V, but with ±10% tolerance this voltage can vary between a maximum of 253 V and a minimum of 207 V; equipment and appliance designers must take this allowed variation into account or beware! Most commercial and industrial loads are supplied at 400–415 V or higher voltages, three phase. The winter load produces the highest peak because of the preponderance of heating appliances, although it is noted that the summer load is growing due to increasing use of air-conditioning in commercial and industrial premises.

1.8.4.3 Continental Europe

Many continental countries still mainly have combined generator/transmission utilities, which cover the whole country and which are overseen by government control. Increasingly these systems are being ‘unbundled’, that is they are being separated into different functions (generation, transmission, distribution), each individually accountable such that private investors can enter into the electricity market (see Chapter 12). Interconnection across national boundaries enables electrical energy to be traded under agreed tariffs, and limited system support is available under disturbed or stressed operating conditions.

The daily load variation tends to be much flatter than in the UK because of the dominance of industrial loads with the ability to vary demand and because there is less reliance on electricity for heating in private households. Many German and Scandinavian cities have CHP plants with hot water distribution mains for heating purposes. Transmission voltages are 380–400, 220, and 110 kV with household supplies at 220–230 V, often with a three-phase supply taken into the house.

1.8.4.4 China and the Pacific Rim

The fastest-growing systems are generally found in the Far East, particularly China, Indonesia, the Philippines and Malaysia. Voltages up to 500/750 kV are used for transmission and 220–240 V are employed for households. Hydroelectric potential is still quite large (particularly in China) but with gas and oil still being discovered and exploited, CCGT plant developments are underway. Increasing interconnection, including by direct current, is being developed.

1.9 Utilization

1.9.1 Loads

The major consumption groups are industrial, residential (domestic) and commercial. Industrial consumption accounts for up to 40% of the total in many industrialized countries and a significant item is the induction motor. The percentage of electricity in the total industrial use of energy is expected to continue to increase due to greater mechanization and the growth of energy intensive industries, such as chemicals and aluminium. In the USA the following six industries account for over 70% of the industrial electricity consumption: metals (25%), chemicals (20%), paper and products (10%), foods (6%), petroleum products (5%) and transportation equipment (5%). Over the past 25 years the amount of electricity per unit of industrial output has increased annually by 1.5%, but this is dependent on the economic cycle. Increase in consumption of electricity in industrialized countries since about 1980 has been no more than 2% per year due largely to the contraction of energy-intensive industries (e.g. steel manufacturing) combined with efforts to load manage and to make better use of electricity. Residential loads are largely made up of refrigerators, fridge-freezers, freezers, cookers (including microwave ovens), space heating, water heating, lighting, and (increasingly in Europe) air-conditioning. Together these loads in the UK amount to around 40% of total load.

The commercial sector comprises offices, shops, schools, and so on. The consumption here is related to personal consumption for services, traditionally a relatively high-growth quantity. In this area, however, conservation of energy measures are particularly effective and so modify the growth rate.

Quantities used in measurement of loads are defined as follows:

Maximum Load: The average load over the half hour of maximum output.

Load Factor: The units of electricity exported by the generators in a given period divided by the product of the maximum load in this period and the length of the period in hours. The load factor should be high; if it is unity, all the plant is being used over all of the period. It varies with the type of load, being poor for lighting (about 12%) and high for industrial loads (e.g. 100% for pumping stations).

Diversity Factor: This is defined as the sum of individual maximum demands of the consumers, divided by the maximum load on the system. This factor measures the diversification of the load and is concerned with the installation of sufficient generating and transmission plant. If all the demands occurred simultaneously, that is, unity diversity factor, many more generators would have to be installed. Fortunately, the factor is much higher than unity, especially for domestic loads.

Table 1.5 Surge impedance loading and charging MVA for EHV overhead lines. The range of values at each line voltage is due to variations in line construction

Line Voltage (kV)	Surge Impedance Loading (MW)	Charging MVAr per 100 miles
230	132–138	27–28
345	320–390	65–81
500	830–910	170–190
700	2150	445
750	2165	450

Data from Edison Electric Institute.

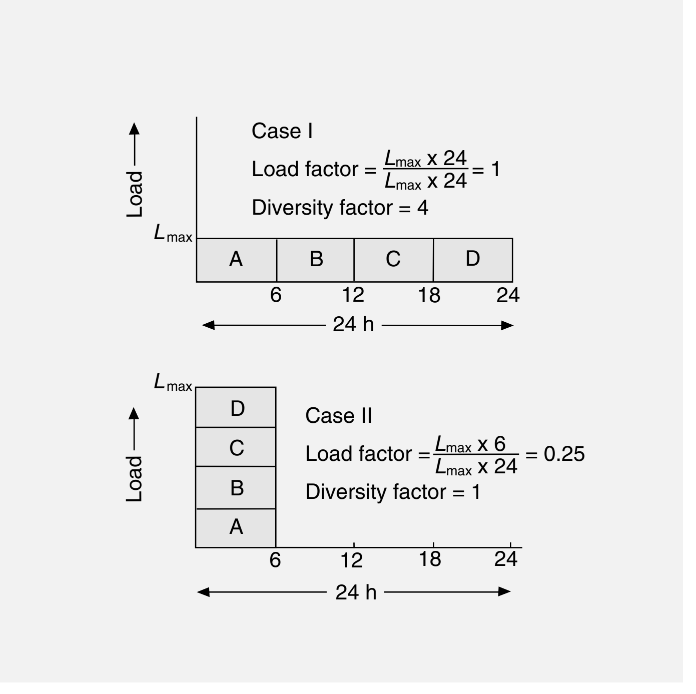

Figure 1.25 Two extremes of load factor and diversity factor in a system with four consumers

A high diversity factor could be obtained with four consumers by compelling them to take load as shown in Case I of Figure 1.25. Although compulsion obviously cannot be used, encouragement can be provided in the form of tariffs. An example is the two-part tariff in which the consumer has to pay an amount dependent on the maximum demand required, plus a charge for each unit of energy consumed. Sometimes the charge is based on kilovoltamperes instead of power to penalize loads of low power factor.

1.9.1.1 Load Management

Attempts to modify the shape of the load curve to produce economy of operation have already been mentioned. These have included tariffs, pumped storage, and the use of seasonal or daily diversity between interconnected systems. A more direct method is the control of the load either through tariff structure or direct electrical control of appliances, the latter, say, in the form of remote on/off control of electric water-heaters where inconvenience to the consumer is least. For many years this has been achieved with domestic time switches, but some schemes use switches radio-controlled from the utility to give greater flexibility. This permits load reductions almost instantaneously and defers hot-water and air-conditioning load until after system peaks.

1.9.1.2 Load Forecasting

It is evident that load forecasting is a crucial activity in electricity supply. Forecasts are based on the previous year's loading for the period in question, updated by factors such as general load increases, major new loads, and weather trends. Both power demand (kW) and energy (kWh) forecasts are used, the latter often being the more readily obtained. Demand values may be determined from energy forecasts. Energy trends tend to be less erratic than peak power demands and are considered better growth indicators; however, load factors are also erratic in nature.

As weather has a much greater influence on residential than on industrial demands it may be preferable to assemble the load forecast in constituent parts to obtain the total. In many cases the seasonal variations in peak demand are caused by weather-sensitive domestic appliances, for example, heaters and air-conditioning. A knowledge of the increasing use of such appliances is therefore essential. Several techniques are available for forecasting. These range from simple curve fitting and extrapolation to stochastic modelling. The many physical factors affecting loads, for example, weather, national economic heath, popular TV programmes, public holidays, and so on, make forecasting a complex process demanding experience and high analytical ability using probabilistic techniques.

Problems

1.1 In the U.S.A. in 1971 the total area of right of ways for H.V. overhead lines was 16 000 km^2. Assuming a growth rate for the supply of electricity of 7% per annum calculate what year the whole of the USA will be covered with transmission systems (assume area to approximate 4800×1600 km). Justify any assumptions made and discuss critically why the result is meaningless.

(Answer: 91.25 years)

1.2 The calorific value of natural gas at atmospheric pressure and temperature is 40 MJ/m^3. Calculate the power transfer in a pipe of lm diameter with gas at 60 atm (gauge) flowing at 5 m/s. If hydrogen is transferred at the same velocity and pressure, calculate the power transfer. The calorific value of hydrogen is 13 MJ/m^3 at atmospheric temperature and pressure.

(Answer: 9.4 GW, 3.1 GW)

1.3 a. An electric car has a steady output of 10 kW over its range of 100 km when running at a steady 40 km/h. The efficiency of the car (including batteries) is 65%. At the end of the car's range the batteries are recharged over a period of 10 h. Calculate the average charging power if the efficiency of the battery charger is 90%.

b. The calorific value of gasoline (petrol) is roughly 16 500 kJ/gallon. By assuming an average filling rate at a pump of 10 gallon/minute, estimate the rate of energy transfer on filling a gasoline-driven car. What range and what cost/km would the same car as (a) above produce if driven by gasoline with a 7 gallon tank? (Assume internal combustion engine efficiency is 60% and gasoline costs £3 per gallon)

(Answer: (a) 4.3 kW; (b) 2.75 MW, 77 km, 27p/km)

1.4 The variation of load (P) with time (t) in a power supply system is given by the expression,

$$P(kW) = 4000 + 8t - 0.00091t^2$$

where t is in hours over a total period of one year.

This load is supplied by three 10 MW generators and it is advantageous to fully load a machine before connecting the others. Determine:

a. the load factor on the system as a whole;
b. the total magnitude of installed load if the diversity factor is equal to 3;
c. the minimum number of hours each machine is in operation;
d. the approximate peak magnitude of installed load capacity to be cut off to enable only two generators to be used.

(Answer: (a) 0.73 (b) 65 MW (c) 8760, 7209, 2637 h (d) 4.2 MW)

1.5 a. Explain why economic storage of electrical energy would be of great benefit to power systems.
b. List the technologies for the storage of electrical energy which are available now and discuss, briefly, their disadvantages.
c. Why is hydro power a very useful component in a power system?
d. Explain the action of pumped storage and describe its limitations.
e. A pumped storage unit has an efficiency of 78% when pumping and 82% when generating. If pumping can be scheduled using energy costing 2.0 p/kWh, plot the gross loss/profit in p/kWh when it generates into the system with a marginal cost between 2p and 6p/kWh.
f. Explain why out-of-merit generation is sometimes scheduled.

(Answer: (e) Overall efficiency 64%; Profit max. 2.87p/kWh; Loss max. 1.25 p/kWh)

(From Engineering Council Examination, 1996)