Chapter 1. Introduction to Power Systems

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Chapter

1

Introduction to Power Systems

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1.1 Objective

This chapter presents a general introduction to power system and its main elements.

1.2 Introduction to Power Systems a brief history[1]

In 1882 Edison inaugurated the *first central generating station in the USA*. The Edison plant fed a load of 400 lamps, each of them consuming the power of 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 specialised loads. This scheme used a 60-kW generator driven by a horizontal steam engine; the voltage of generation was 100V *direct current* (DC).

The first major *alternating current* (AC) station in *Great Britain* (GB) was at *Deptford*, where power was generated by machines of 10 000 h.p. and transmitted at 10 kV to consumers in London (see **Fig. 1.1**).

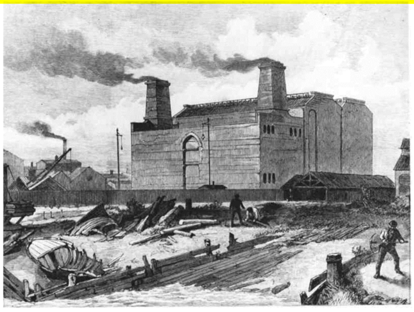

Fig. 1.1. Deptford Power Station built 1887. It was the first major station to use the new-fangled high voltage AC. It was rebuilt a number of times before it was decommissioned in 1983 and demolished in 1992. See more at https://londonist.com/2012/03/the-history-of-londons-power-stations

During this period the battle between the advocates of AC and DC, it was the *War of Currents era* (sometimes, War of the Currents or Battle of Currents). George Westinghouse and Thomas Edison became adversaries due to Edison's promotion of DC for electric power distribution against AC advocated by several European companies and Westinghouse Electric based in Pittsburgh, Pennsylvania, which had acquired many of the patents by Nikola Tesla.

Owing mainly to the invention of the *transformer* the supporters of AC prevailed and 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* (CEB) was created with the object of interconnecting the best of the 500 generating stations then in operation with a high-voltage network known as the Grid. The act tried to link the Britain most efficient power stations with consumers via a '*national gridiron'*. The CEB established the Britain *first synchronised AC grid*, running at 132 kilovolts (kV) and 50 Hertz (Hz), which by 1933 was a collection of local grids, with emergency interlinks, covering most of England.

Nationalisation of the electricity supply industry under terms of the *Electricity Act 1947* comes into effect in 1948.

The Electricity Act 1947 nationalised 505 separate electricity generation and supply organizations in GB on 1 April 1948, both privately owned and state-owned, and consolidated them into 14 area electricity boards of the new *Central Electricity Authority* that the Act created (also known as the *British Electricity Authority*), which subsequently became the *Central Electricity Generating Board*. Two organisations 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 the *generation* and the operation of the high-voltage transmission network or grid.

The electricity supply industry was in public ownership from 1948 to 1990. All of this changed radically in 1990 when the *British Electricity Supply Industry* was *privatized*.

For the first 80 years of electricity supply, the growth of the load was rapid at around 7% per year, implying a doubling of electricity use every ten years and this type of increase continues today in rapidly industrialising countries. However, in the USA and other industrialised 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 CO2, 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

[1] Source: B. M. Weedy, B. J. Cory, N. Jenkins, Janaka B. Ekanayake, Goran Strbac. (2012). Power Systems. Wiley

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.

1.3 Power System Definition

An electric power system is a network of electrical components used to supply, transmit and use electric power (see **Fig. 1.2**).

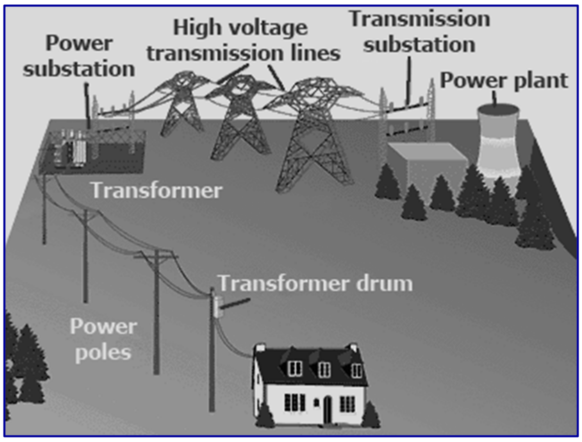

Fig. 1.2. Typical power system structure.

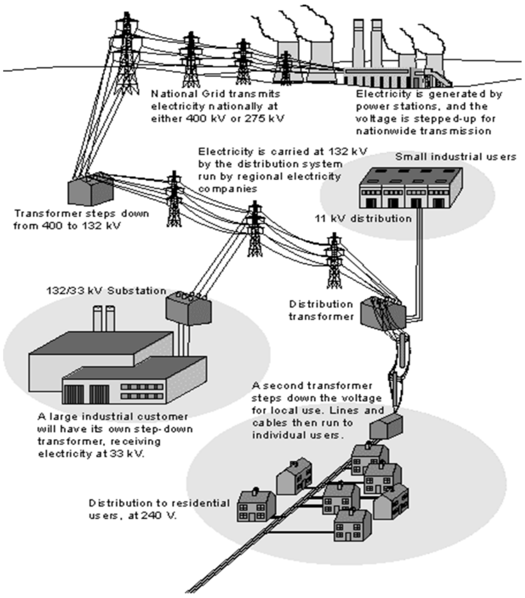

Fig. 1.3. Structure of a power system with special emphasis on voltage level used in GB.

Now a formal definition of the power system

(1) *(generating stations electric power system) The electric power sources, conductors, and equipment required to supply electric power. (PE/EDPG) IEEE 505-1977r*[2].

(2) *(electric) The generation resources and/or transmission facilities operated as an entity to meet load and/or interchange commitments. (PE/PSE) 94-1991w*[3]

(3) The generation resources and/or transmission facilities operated under common management or supervision to meet load and interchange commitments. (PE/PSE) 858-1993w[4] [3]

For more definitions, check: (2000). "*IEEE 100 The Authoritative Dictionary of IEEE Standards Terms Seventh Edition*." IEEE Std 100-2000[5].

The traditional power system is arranged as a hierarchy (see **Fig. 1.3**). Generators feed into a high voltage transmission system that facilitates bulk transfers of power over large distances. Connected to the transmission system are medium voltage distribution networks that take power from grid supply points and deliver it to the customers who are supplied a low voltage.

1.4 The structure of an electric power system

For a lot of its history, the electricity supply industry has operated as a set of vertically integrated monopolies within certain geographic areas. Many countries, notably but not only, the UK, have sought to bring competition to this industry in order to provide better value to consumers. The approach in the UK has been to unbundled the various functions within the industry and then use a combination of market mechanisms, and regulation are then used to enhance economic efficiency.

[2] IEEE Standard Nomenclature for Generating Station Electric Power Systems, ANSI/IEEE 505-1977

[3] IEEE Recommended Definitions of Terms for Automatic Generation Control on Electric Power Systems, ANSI/IEEE 94-1991

[4] ANSI/IEEE 858-1993, IEEE Standard Definitions in Power Operations Terminology

[5] Direct link: https://ieeexplore.ieee.org/document/4116787

There are *four functions* on the *supply-side*:

- Generation;
- Transmission;
- Distribution and
- Supply

moreover, one function on the *demand-side*:

- Consumption

The various functions are summaries in **Table 1.1**.

Table 1.1. Summary of main functions in the electrical power system in the context of GB.

Function	Method	Examples (GB)
Generation	Steam, gas, water or wind turbines driving alternators	nPower, E.On, British Energy, SELCHP, Barking Power
Transmission	275kV and 400kV overhead lines –"*the national grid.*"	National Grid (owner and operator), Scottish Power (owner)
Distribution	132kV, 33kV, 11kV overhead lines and cables	UK Power Networks, Scottish and Southern
Supply	Purchase of energy on the wholesale market, resell and bill	EDF Energy, E.On, British Gas
Consumption	Motors, heaters, lighting & supplies for electronic equipment	Industrial, commercial and domestic consumers

1.4.1 Generation

Electricity is produced by converting mechanical energy into electrical energy (*electromechanical conversion systems*). In the majority of cases, the mechanical energy is either obtained from thermal energy or provided by the flowing water. The main sources of *thermal energy* sources are coal, natural gas, nuclear fuel and oil. The use of *non-fossil fuels* such as wind, solar, tidal, and geothermal and biogas in electricity generation is also increasing. *Hydro-power* is the main non-thermal source of mechanical energy used in electricity generation. The conversion of mechanical to electrical energy is done using synchronous generators in the majority of power plants. Few wind generation systems use induction generators. The power is usually generated at low voltage, between 11 and 35 kV, and then fed into the transmission system using a step-up transformer. Electricity in GB is usually generated in power stations at about 22-25 kV[6]. (see **Fig. 1.4**)

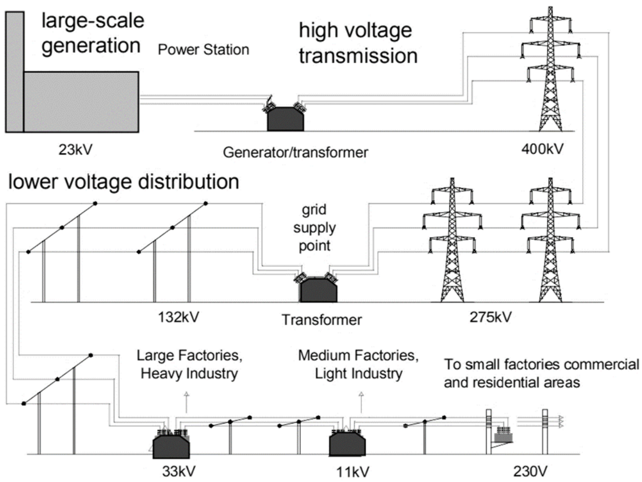

Fig. 1.4. Voltage levels and it uses inside a power system. Source: https://www.parliament.uk/documents/post/pn163.pdf

1.4.2 Transmission system

The electricity is generated in bulk in the generating stations and then transmitted over long distances to the load or demand points. *The transmission system interconnects all the generating stations and major load centres in the system*. It forms the backbone of the power system. Since the *power loss* in a transmission line is proportional to the square of line current ($P_{loss} = R_{TL}|I|^2$), the transmission lines operate at the highest voltage levels, usually 275 kV and upwards. Usually, the transmission network has a *meshed structure* in order to provide many alternate routes for the power to flow from the generators to the load points. This improves the reliability of the system.

High voltage (HV) transmission lines are terminated at *substations* (see **Fig. 1.5**). Very large industrial customers may be provided power directly from these substations. At these substations, the voltage is stepped down to a lower level and fed into the sub-transmission system. This part of the transmission system connects the high voltage substation through the step-down transformers to distribution substation. Typically, the *sub-transmission* voltage levels are from 66 kV to 132 kV. Some large industrial consumers may be served directly from the sub-transmission

[6] https://www.thebigbangfair.co.uk/media/49868/ngrid_be-the-source_how-electricity-made-transmitted-v2.pdf

system. The transmission lines connect the neighbouring power systems at transmission levels, thus forming a grid. The grid is the network of multiple generating resources and several layers of the transmission network.

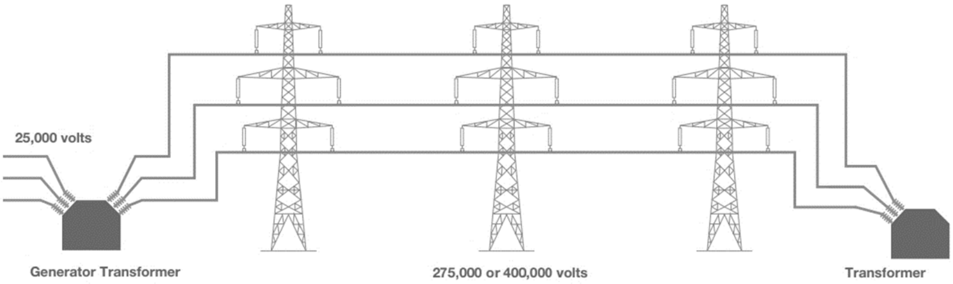

Fig. 1.5. A demonstrative example of the transmission system, using GB voltages. National Grid transmits electricity at high voltage throughout England and Wales on a system made up of 7,000 kilometres of overhead lines, 600 kilometres of underground cables and some 300 substations[7].

1.4.3 Distribution system

The distribution represents the final stage of power transfer to the individual consumer (see **Fig. 1.6**). The distribution network is generally connected in a *radial structure*. The primary distribution voltage is typically between 11kV and 33kV. Small industrial customers are supplied by *primary feeders* at this voltage level. The *secondary distribution feeders* supply residential and commercial at 415/240 V. Small generating plants located near the load centres are usually connected to sub-transmission or distribution system directly.

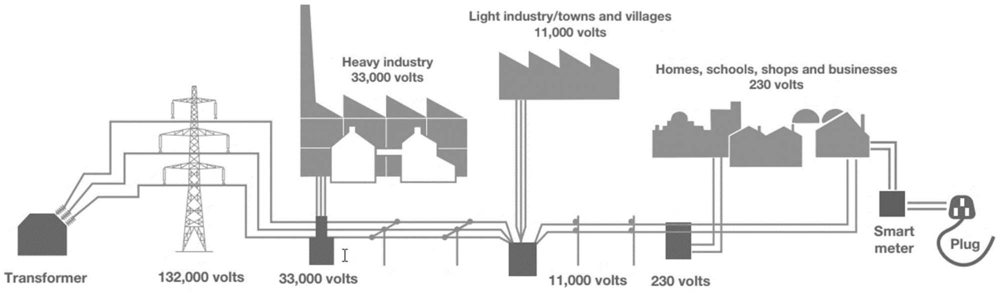

Fig. 1.6. Typical distribution system structure showing the GB voltage levels. Distribution Network companies distribute the energy in their licence areas throughout England and Wales[7].

A power system operates in a normal state if the following conditions are satisfied:

- The bus voltages are within the prescribed limits.
- The system frequency is within the specified limits.
- The active and reactive power balance exists in the system.

However, *the system load varies continuously* and hence, in order to ensure satisfactory system operation, proper controls have to be provided in a power system.

1.5 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 power balance between generation and demand must be carefully enforced. However, this aspect has been changing the recent time with more and more penetration of energy storage devices in the power network. A short discussion of that will be presented in future sections.
- The electricity sector creates major environmental impacts that increasingly determine how a plant is installed and operated.
- The generating stations are often located away from the load resulting in transmission over considerable distances.

1.6 Generation Sector and Energy conversion

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*.

[7] https://www.thebigbangfair.co.uk/media/49868/ngrid_be-the-source_how-electricity-made-transmitted-v2.pdf

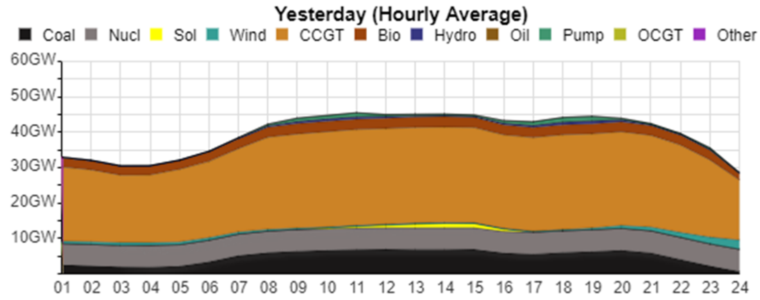

Fig. 1.7. Hourly demand profile (2018. Year on hourly average) in the GB system. Minimum: 30.429 GW maximum: 47.041 GW average: 40.869 GW. Source: http://gridwatch.co.uk/

Coal, uranium, oil, gas, hydro, wind and solar are the main sources of energy used in the generation of electricity in England and Wales. Much of the electricity is produced *in thermal power stations*.

Electricity generation in the UK in 2017[8] was broadly stable compared to the previous two years at 336 TWh, with a continuation of *the shift in fuel mix away from coal*. Unlike previous years, *this shift has tended towards growth in renewable generation aided by the increase in renewable capacity*.

In 2017, *the share of renewables' generation increased* to 29.3% from 24.5% in 2016. This increase resulted from a 12.8% increase in renewables' generation capacity in 2017, reaching 18.3 GW (de-rated to reflect intermittency), accounting for 22% of generating capacity.

Low carbon electricity's share of generation increased from 45.6% to a record 50.1%. This increase was driven by the increase in renewables generation, as nuclear generation decreased by 1.9% compared to 2016.

Total electricity supply fell by 1.0% to 353 TWh, as net imports decreased by 16.8% to 14.8 TWh. The UK remained a net importer of electricity in 2017, with net imports contributing 4.2% of electricity supply – this was slightly lower than the 5.0% of supply in 2016. Final consumption decreased by 1.0% to 301 TWh in 2017, largely as a result of decreases in the domestic and commercial sectors due to warmer weather.

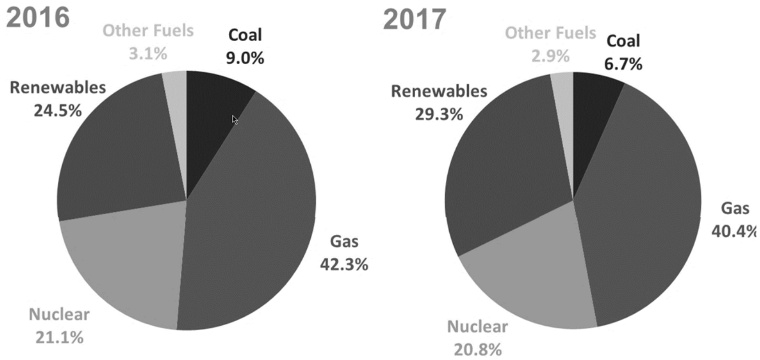

Fig. 1.8. Shares of electricity generation, by fuel[8]. A historical series of fuel used in the generation on a consistent, energy supplied, fuel input basis is available at Table 5.1.1 on the BEIS section of the GOV.UK website and accessible from the Digest of UK Energy Statistics home page: www.gov.uk/government/collections/digest-of-uk-energy-statisticsdukes

[8]Source: https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/736152/Ch5.pdf

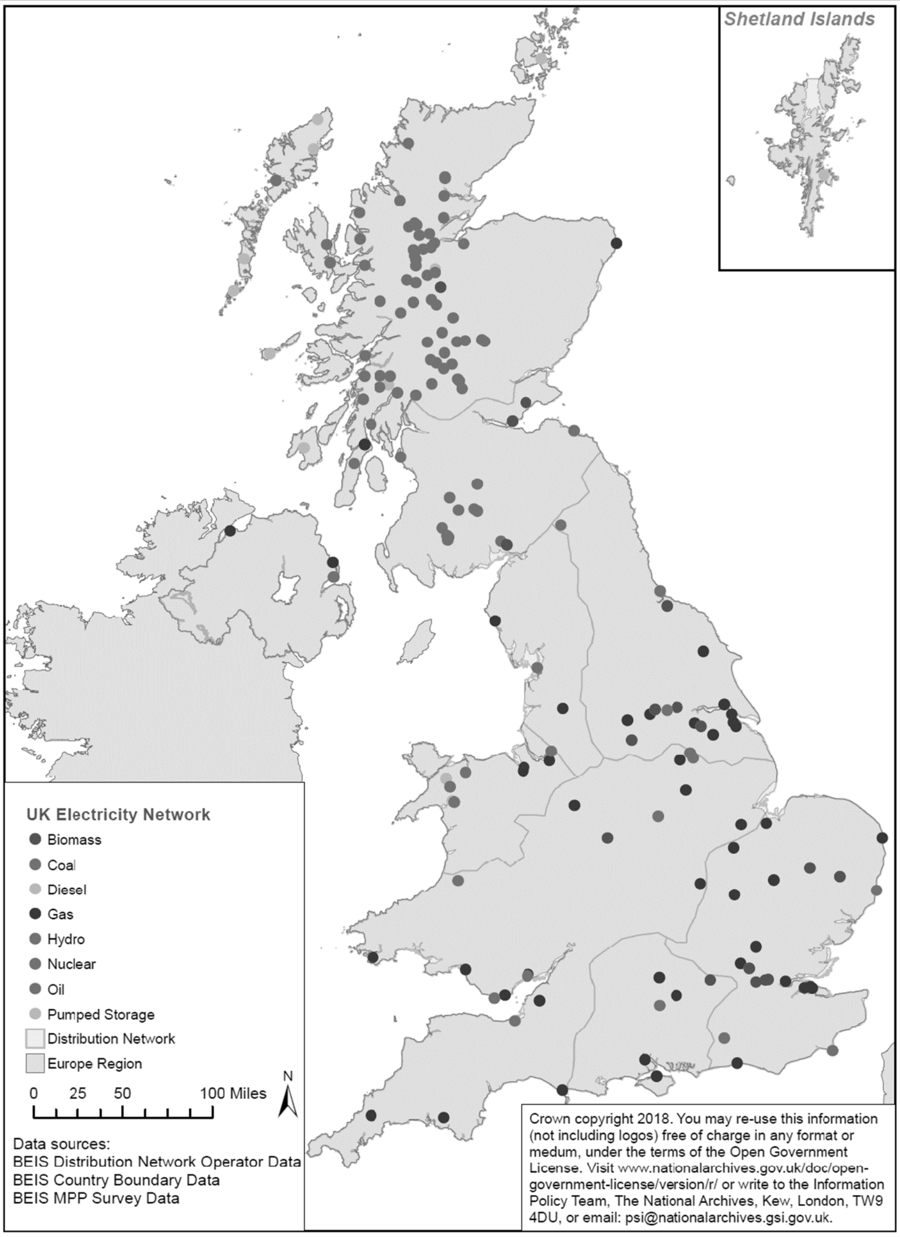

Fig. 1.9. Illustrative map showing the geographical location of the major power stations in the UK (operational May 2018).

1.6.1 Energy Conversion using Steam

The *steam-electric power station* is a power station in which the electric generator is steam driven. The combustion of *coal, gas* or oil in *boilers* produces *steam*, at high temperatures and pressures, which is passed through steam turbines which drives an electrical generator. After it passes through the turbine, the steam is condensed in a condenser. The greatest variation in the design of steam-electric power plants is due to the different fuel sources. *Nuclear fission* can also provide energy to produce steam for turbines.

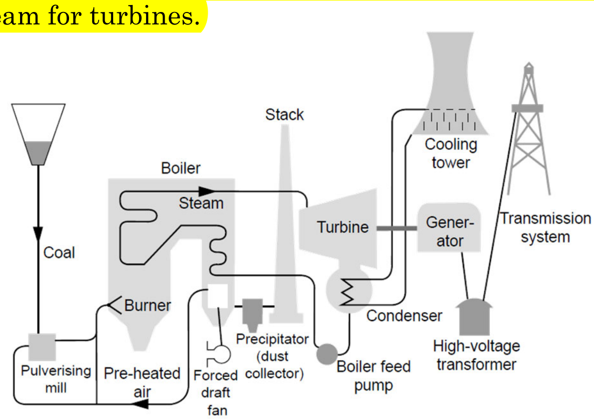

Fig. 1.10. Schematic diagram showing the main component in view of a coal-fired steam generating station.

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.

Drax power station is large biomass and coal-fired power station in North Yorkshire, England, capable of co-firing petcoke[9]. It has a 2.6 GW capacity for biomass and 1.3 GW capacity for coal. Its name comes from the nearby village of Drax. It is situated on the River Ouse between Selby and Goole. Its generating capacity of 3,906 megawatts (MW) is the highest of any power station in the United Kingdom, providing about 6% of the UK's electricity supply.

1.6.2 Energy Conversion Using Water

Perhaps the oldest form of energy conversion is by the use of *water power*. The technology behind hydropower is fairly simple, but taming the power of water is a major challenge. 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. *Hydropower plants are expensive to build* but *inexpensive to operate*.

Unfortunately, the *geographical conditions* necessary for hydro-generation are not commonly found, especially in Britain. As of 2017[10], hydropower accounts for around 1.8% of Britain's total electricity supply and 18% of our renewable energy. This makes it our fourth most-generated renewable energy source after wind power, bioenergy and solar power. The vast majority of hydropower in the UK is generated in Scotland and Wales in hydroelectric power plants, located within reservoirs and dams across the Scottish Highlands and Welsh countryside. *Dinorwig Power Station* in north-west Wales is the largest hydropower plant in the UK by far. It has a total capacity of 1,728 megawatts which is enough to power a whopping 2.5 million homes. In Scotland, the Cruachan Power Station in Argyll and Bute can generate 440 megawatts of hydroelectric power and power up to 225,000 homes.

In most developed countries, all the suitable hydroelectric sites are already fully utilised. *The Three Gorges Dam* in Hubei, China, has *the world's largest instantaneous generating capacity (22,500 MW)*, with *the Itaipu Dam* in Brazil/Paraguay in second place (14,000 MW). Despite the large difference in installed capacity these two power stations generate nearly equal amounts of electrical energy during the course of an entire year - Itaipu 103.1 TWh in 2016 and Three Gorges 98.8 TWh in 2014, because the *Three Gorges experiences six months per year when there is very little water available to generate power*, while the Paraná River that feeds the Itaipu has a much lower seasonal variance in flow. The power output of the Three Gorges reaches 125 TWh in years of high feed availability.

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 impart significant energy.

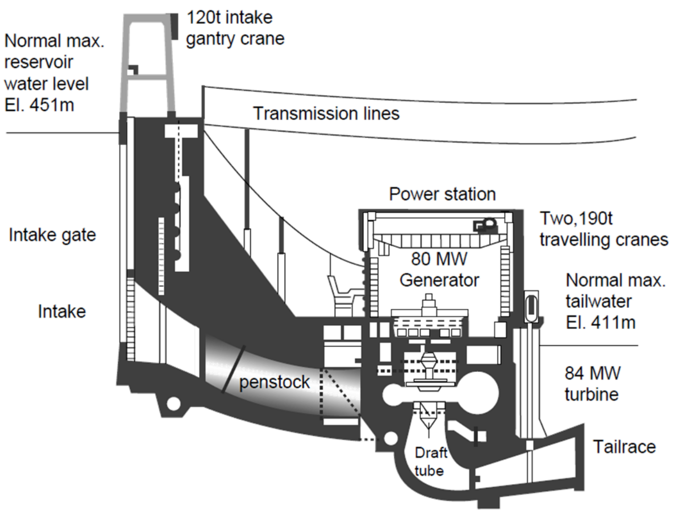

Fig. 1.11. Schematic diagram showing the main components in a typical hydropower station.

1.6.3 Gas turbines

With the increasing availability of *natural gas* (methane, CH_4) 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 the following figure.

[9] Petcoke (petroleum coke) is the coke that, in particular, derives from a final cracking process—a thermo-based chemical engineering process that splits long chain hydrocarbons of petroleum into shorter chains—that takes place in units termed coker units. (Other types of coke are derived from coal.)

[10] https://theswitch.co.uk/renewable-energy/hydroelectric-power

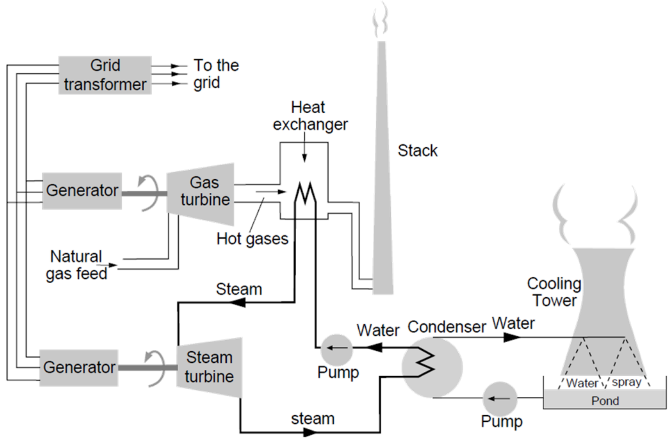

Fig. 1.12. Schematic diagram showing the main components of a combined-cycle gas turbine (CCGT) power station.

Combined efficiencies of new CCGT generators now approach 50-60%. That is, from an overall efficiency of say 34% (*simple cycle*), to possibly an overall efficiency of 62% (*combined cycle*), 84% Theoretical efficiency (*Carnot cycle*).

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 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.

Pembroke CCGT power plant is located in west Wales, UK. It was built with an estimated investment of £1bn and was officially opened on 19 September 2012. With a total generating capacity of 2,160MW and thermal efficiency of 60%, it is one of the largest and the most efficient CCGT power plants in the UK. Pembroke power station is owned and will be operated by RWE npower, an integrated energy company based in the UK.

1.6.4 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, U_{238} (99.3% by weight) and U_{235} (0.7%). Only U_{235} is fissile, that is when struck by slow-moving neutrons its nucleus splits into two substantial fragments plus several neutrons and 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.

As of 23 April 2014, the IAEA report there are 450 nuclear power reactors in operation operating in 31 countries. Nuclear power in the UK generates around a quarter of the country's electricity as of 2016, projected to rise to a third by 2035.

The UK has 15 operational nuclear reactors at seven plants (14 *advanced gas-cooled reactors* (AGR) and *one pressurised water reactor (PWR)*), as well as nuclear reprocessing plants at Sellafield and the *Tails Management Facility* (TMF) operated by Urenco in Capenhurst. The UK reactors are generating about 21% of its electricity but almost half of this capacity is to be retired by 2025.

EDF Energy owns and manages the seven currently operating reactor sites, with a combined capacity of about 9 GW. Six new plants are proposed to be built in the next few decades. All nuclear installations in the UK are overseen by the *Office for Nuclear Regulation*.

PWRs constitute the large majority of the world's nuclear power plants (notable exceptions being Japan and Canada) and are one of three types of *light water reactor* (LWR), the other types being *boiling water reactors* (BWRs) and *supercritical water reactors* (SCWRs). An *Advanced Gas-cooled Reactor* (AGR) is a type of nuclear reactor designed and operated in the United Kingdom. These are the second generation of *British gas-cooled reactors*, using graphite as the neutron moderator and carbon dioxide as coolant. They have been the backbone of the UK's nuclear generation fleet since the 1980s.

Hinkley Point C nuclear power station (HPC) is a project to construct a 3,200 MWe nuclear power station with two EPR reactors in Somerset, England. The proposed site is one of eight announced by the British government in 2010,[4] and in November 2012 a nuclear site licence was granted. On 28 July 2016 the EDF board approved the project, and on 15 September 2016, the UK government approved the project with some safeguards for the investment. The plant, which has a projected lifetime of sixty years, has an estimated construction cost of between £19.6 billion and £20.3 billion.

Table 1.2. Power nucelar reactors operating in the GB power system[11].

Plant	Type	Present capacity (MWe net)	First power	Expected shutdown
Dungeness B 1&2	AGR	2 x 520	1983 & 1985	2028
Hartlepool 1&2	AGR	595, 585	1983 & 1984	2024
Heysham I 1&2	AGR	580, 575	1983 & 1984	2024
Heysham II 1&2	AGR	2 x 610	1988	2030
Hinkley Point B 1&2	AGR	475, 470	1976	2023
Hunterston B 1&2	AGR	475, 485	1976 & 1977	2023
Torness 1&2	AGR	590, 595	1988 & 1989	2030
Sizewell B	PWR	1198	1995	2035
Total: 15 units		**8883 MWe**		

Most AGR units are running at significantly less than original or design capacity. Since 2006 Hinkley Point B and Hunterston B have been restricted to about 70% of normal MWe output because of boiler-related problems requiring that they operate at reduced boiler temperatures. In 2013 these two stations' power increased to about 80% of normal output following some plant modifications

In a PWR, the primary coolant (water) is pumped under high pressure to the reactor core where it is heated by the energy released by the fission of atoms. The heated water then flows to a steam generator where it transfers its thermal energy to a secondary system where steam is generated and flows to turbines which, in turn, spin an electric generator. In contrast to a boiling water reactor, the pressure in the primary coolant loop prevents the water from boiling within the reactor. All LWRs use ordinary water as both coolant and neutron moderator.

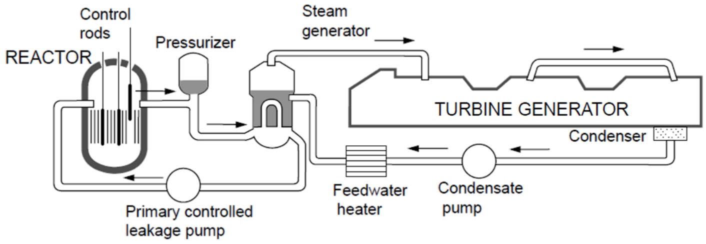

Fig. 1.13. Schematic diagram showing the main components of a PWR.

A BWR uses demineralised water as a coolant and neutron moderator. Heat is produced by nuclear fission in the reactor core, and this causes the cooling water to boil, producing steam (see **Fig. 1.14**).

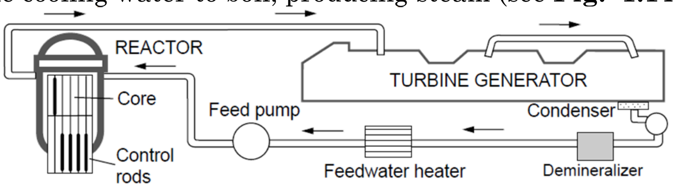

Fig. 1.14. Schematic diagram showing the main components of a BWR.

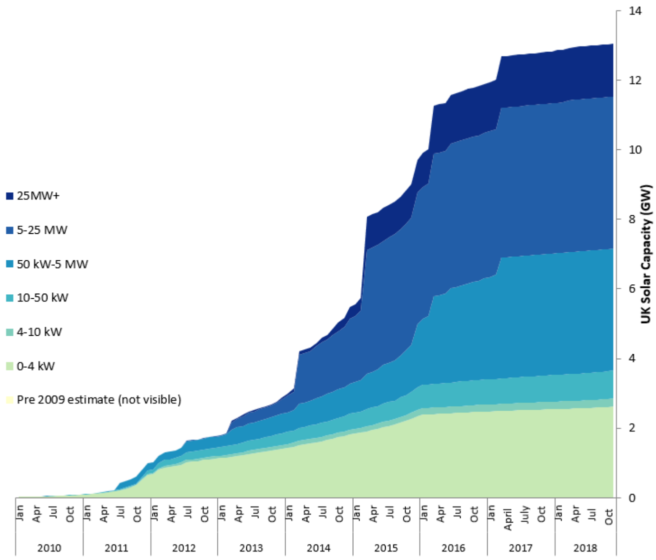

Fig. 1.15. UK Solar Deployment by Capacity (updated monthly). Source: https://www.gov.uk/government/statistics/solar-photovoltaics-deployment

[11] http://www.world-nuclear.org/information-library/country-profiles/countries-t-z/united-kingdom.aspx

1.6.5 Solar Energy-Photovoltaic Conversion

Photovoltaics (PV) is the conversion of light into electricity using semiconducting materials that exhibit the photovoltaic effect, a phenomenon studied in physics, photochemistry, and electrochemistry. A photovoltaic system employs solar panels, each comprising some solar cells, which generate electrical power.

The main process of the PV 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.

UK solar PV installed capacity at the end of 2017 was 12.8 GW, representing a 3.4% share of total electricity generation. The all-time peak generation from photovoltaics was 9.34 GW on 14 May 2018.

1.6.6 Wind Generators

Wind power is the use of air flow through wind turbines to provide the mechanical power to turn electric generators. Wind power generation is a serious alternative to burning fossil fuels; there is plentiful, renewable, widely distributed, clean, produces no greenhouse gas emissions during operation, consumes no water, and uses little land. A *wind turbine* (WT) or alternatively referred to as a *wind energy converter*, is a device that converts the wind's kinetic energy into electrical energy.

A *wind farm* (WF) consists of many individual WTs, which are connected to the electric power transmission network. *Onshore wind* is an inexpensive source of electric power, competitive with or in many places cheaper than coal or gas plants. *Offshore wind* is steadier and stronger than on land, and offshore farms have less visual impact, but construction and maintenance costs are considerably higher. Small onshore wind farms can feed some energy into the grid or provide electric power to isolated off-grid locations.

The some of the biggest turbines are (January 2019): MHI Vestas V164-9.5MW, Siemens Gamesa SG 8.0-167 DD, Goldwind GW154 6.7MW, Senvion 6.2M152, GE Haliade 150-6MW.

The *Gansu Wind Farm in China* is the largest wind farm in the world, with a target capacity of 20,000 MW by 2020. The largest offshore wind farm in the world begins is located on the Cumbrian coast, UK (6 Sep 2018). The *Walney Extension* is 12 miles off the north-west coast of England in the Irish Sea, generating a capacity of 659 megawatts, and is located between northern England and the Isle of Man. It has 87 turbines, each around 190 metres tall. It is covering an area roughly equal to 20,000 football pitches; it produces enough green energy to power around 600,000 homes. The previous largest offshore wind farm is the London Array off the Kent coast in the Thames Estuary. It said that by 2030, between a fifth and a third of the UK's electricity could come from offshore wind power.

1.7 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. There are many energy storage technologies already available:

- Pumped Storage
- Compressed-Air Storage
- Secondary Batteries
- Fuel Cells
- Hydrogen Energy Systems
- Superconducting Magnetic Energy Stores (SMES)
- Flywheels
- Supercapacitors

Planning applications in the UK to install just 2MW of battery storage capacity in 2012 have soared since then to a cumulative total of 6,874MW in 2018. (92% of applications for storage projects are approved the first time)[12].

The UK's 'largest' grid battery storage facility is in Hertfordshire (July 2018). The 50MW battery storage facility is located at Bishop's Stortford in Hertfordshire. It is a 4,500sqm site and was built by the contractor for UK company Statera Energy, which owns and operates the site. Housed in seven custom-built 'E-houses', the facility includes 27 inverters, 150,000 lithium-ion battery cells, and is connected to a nearby 400kV substation via a 132kV grid connection. It is capable of delivering up to 60MVA of power and utilises technology provided by SMA Sunbelt Energy, a fully owned subsidiary of German energy storage specialist SMA Solar Technology AG.

1.8 Single Line Diagram

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*. A *one-line diagram* or *single-line diagram* (SLD) is a simplified notation for representing a three-phase power system.

[12]https://www.renewableuk.com/news/425522/Energy-storage-capacity-set-to-soar-300-UK-based-companies-involved-in-new-sector.htm

Certain conventions for representing items of plant are used. It is typically some standardisation could be used for representing symbols in a one-line diagram or single-line diagram. The most used standard includes:

- International Electrotechnical Commission (IEC). IEC 60617 - Graphical Symbols for Diagrams[13].
- BS EN 60617-12:1999, IEC 60617-12:1997 Graphical symbols for diagrams.
- IEEE Standard American National Standard (ANSI). "Graphic Symbols for Electrical and Electronics Diagrams" (Including Reference Designation Letters)[14].

Fig. 1.16 shows a very limited example of main symbols used at the one-line diagram or single-line diagram

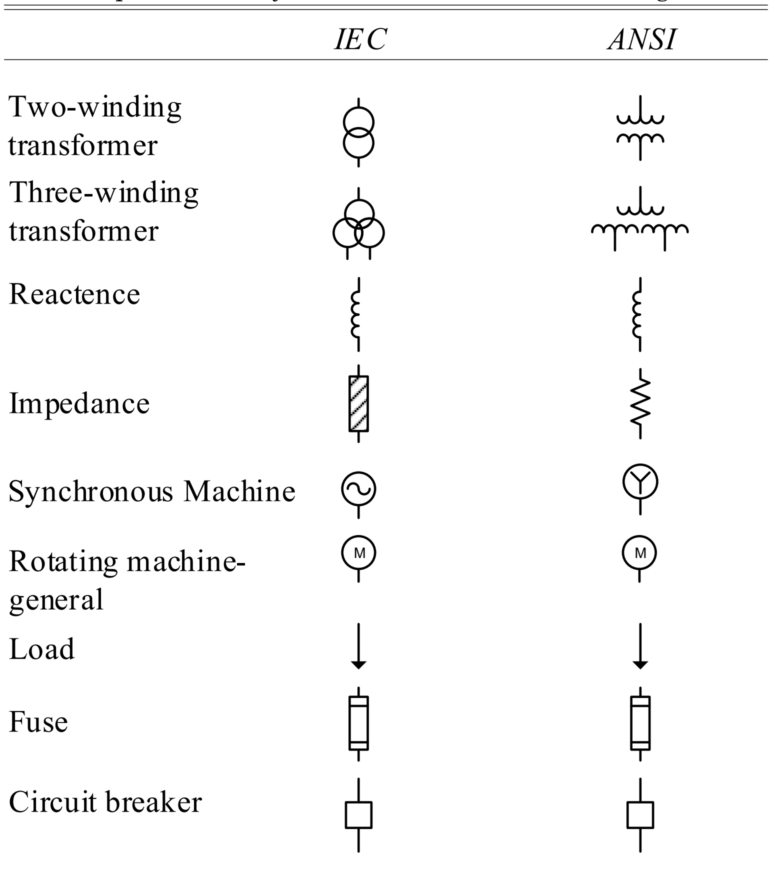

Fig. 1.16. Symbols for representing the components of a three-phase power system.

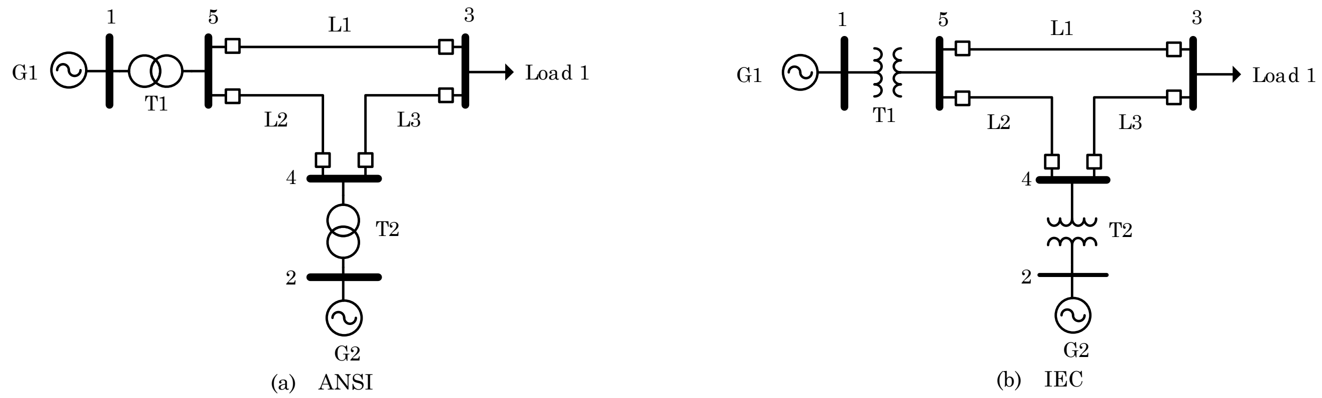

Fig. 1.17. An illustrative example of a single-line diagram of a simple power system: two synchronous generators (G1 and G2), two two-winding power transformers (T1 and T2), one load (Load 1), three transmission lines (L1, L2, L3) and six circuit breakers.

1.9 Transmission System

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 using 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.

- *Overhead lines* (OHLs) are used by electricity transmission companies as the default preferred solution for connections between power stations, distribution companies and bulk electric power users. With air as *the main insulating medium*, overhead lines are designed using a balance between energy to be transported, security, costs and electrical mechanical, civil performance and environmental trade-offs[15]. An OHL route

[13] http://std.iec.ch/iec60617
[14] https://ieeexplore.ieee.org/document/985670
[15] https://www.nationalgrid.com/sites/default/files/documents/37783-ETYS%202014%20Appendix%20E%20-%20Technology.pdf

consists of *one or more conductors* suspended by *towers*. The conductors are connected to the towers with *insulators*, which are traditionally made using cast iron caps encapsulating glass or porcelain. The conductor insulation is provided by air, so OHLs are generally considered to be the most cost-effective method of HVAC transmission.

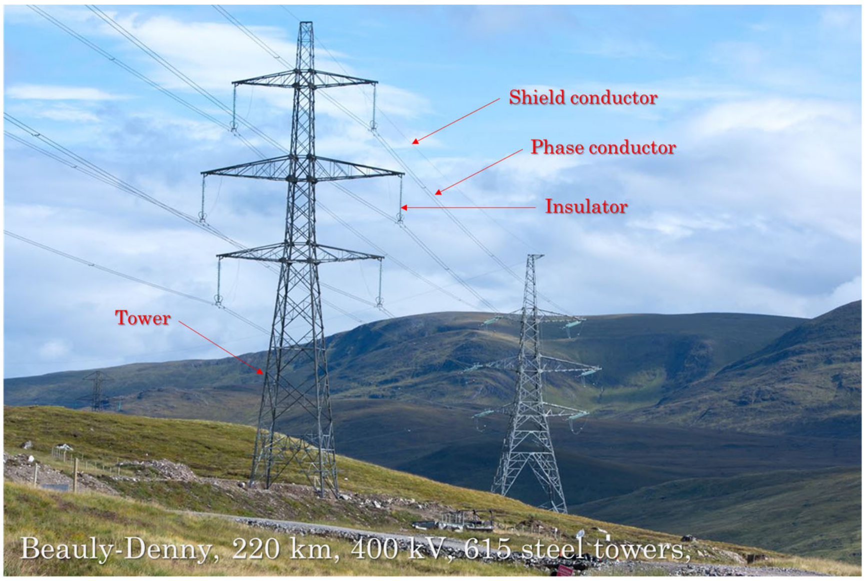

Fig. 1.18. An illustrative example of the main components of an OHL. https://www.ssen-transmission.co.uk/projects/beauly-denny/

- *Underground cables* are used by electricity transmission and distribution companies across the world. Along with OHLs cables provide the connections between power stations and bulk electricity power users and at lower voltages in some countries provide connections between distribution centres and the end consumer.

The primary reason that power is transmitted at high voltages is to increase efficiency. As electricity is transmitted over long distances, there are inherent energy losses along the way. High voltage transmission minimises the amount of power lost as electricity flows from one location to the next.

A typical existing 400 kV line can transfer about 600 MW power, 800 kV line can do between 1,200 MW and 2,400 MW and 1,200 kV transfer 6,000-8,000 MW (it is an illustrative example, numbers may slightly change for specific transmission lines designs).

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.

Ultrahigh-voltage (UHV) electricity transmission has been used in China since 2009 to transmit both AC and DC electricity over long distances separating China's energy resources and consumers. 1,200 KV is the highest voltage proposed in power transmission, is expected to be used in a 380 km long 1,200 kV transmission line from Deoli to Aurang, China.

The world’s first ±1100 kV UHVDC (ultra-high voltage direct current) transmission line was put into operation on January 2019, marking the project with the highest voltage, the biggest transmission capacity, the longest transmission distance and the most advanced in technology in the world. The transmission line starts from the Changji converter station in northwest China’s Xinjiang Uygur Autonomous Region, and ends in the town of Guquan in east China’s Anhui Province, straddling 3,293 km and having a transmission capacity of 12 million kW.

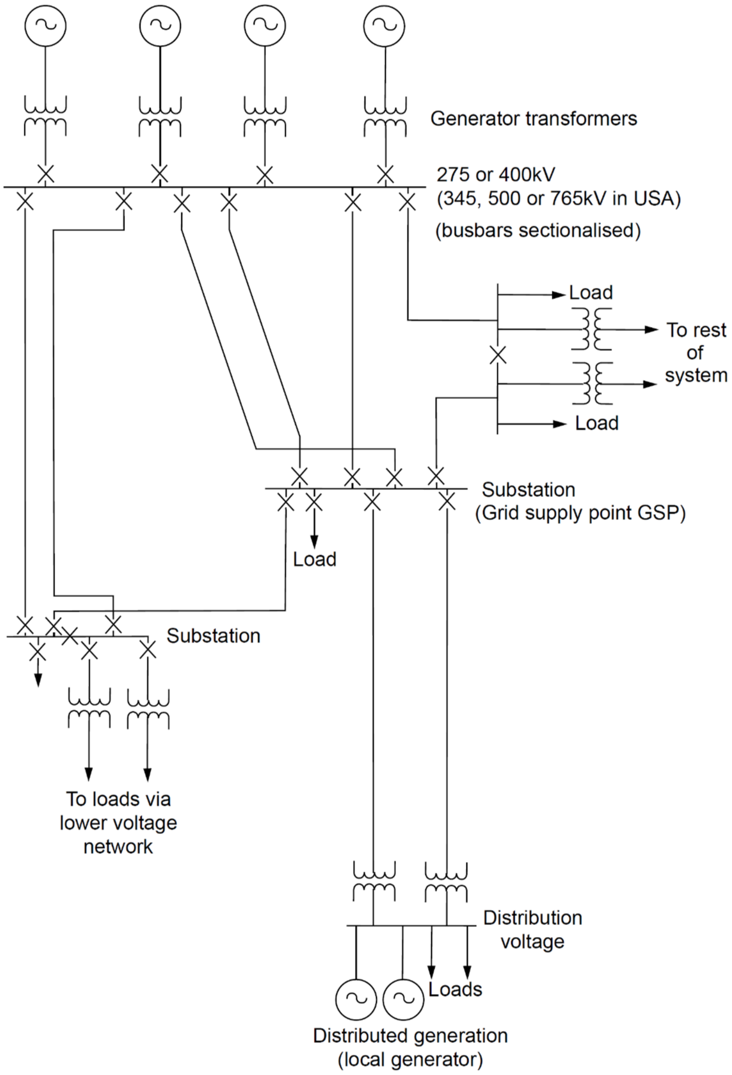

Fig. 1.19. Part of a typical power system

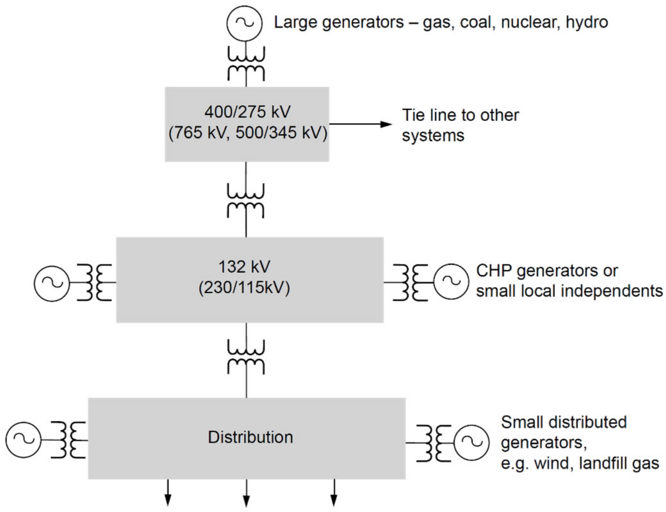

Fig. 1.20. Schematic diagram of the constituent networks of a supply system. USA voltages in parentheses.

1.9.1 Interconnections

Interconnection allows an alternative path to existing between generators and bulk supply points supplying the distribution systems. This provides security of supply should anyone path fail.

The interconnections of power systems offer the following advantages.

(a) *Quality:* The voltage profile of the transmission network improves as more generators contribute to the system, resulting in an increased total system capability. This also improves the frequency behaviour of the system following any load perturbation due to increased inertia of the system.

(b) *Economy:* In interconnected systems, it is possible to reduce the total set of generating plants required to maintain the desired level of generation reserve. This results in the reduction of operational and investment costs. Also, operational (including plant start-ups and shut down) and generation scheduling of units can be more economically coordinated.

(c) *Security:* In case of emergency, power can be made available from the neighbouring systems and each system can benefit even when individual spinning reserves may not be sufficient for isolated operation.

1.10 Distribution System

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/433V in Britain or 4.16 kV/220V 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.

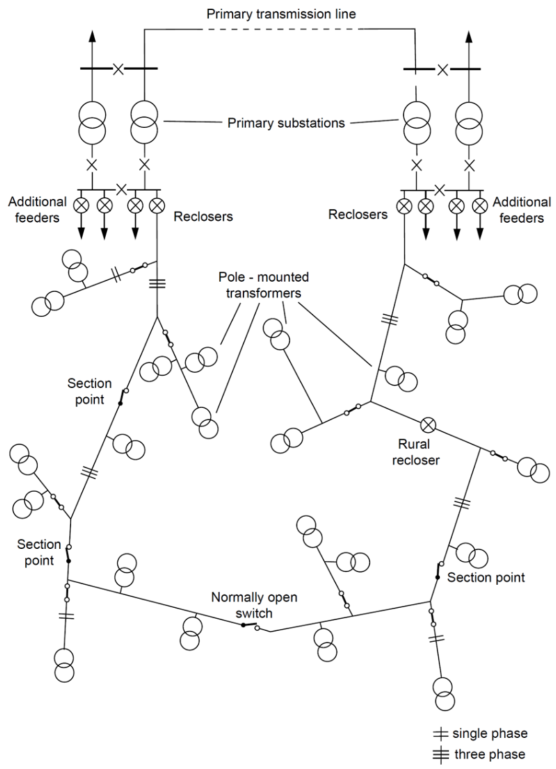

Fig. 1.21. An illustrative diagram of a typical rural distribution system.

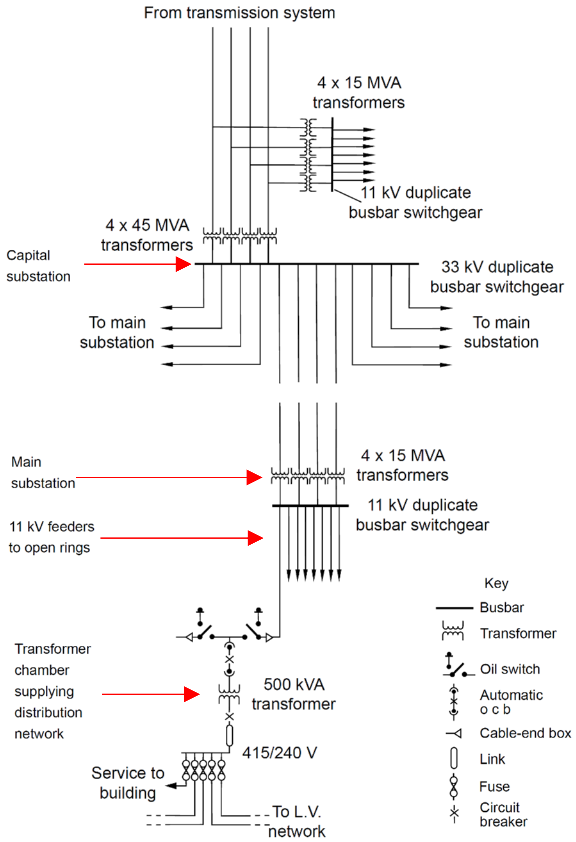

Fig. 1.22. An illustrative diagram of a typical arrangement of supply to an urban network–British practice.

Electricity distribution networks carry electricity from the high voltage transmission grid to industrial, commercial and domestic users. There are 14 licensed *distribution network operators* (DNOs) in Britain, and each is responsible for a regional distribution services area. The 14 DNOs are owned by six different groups.

The DNO groups and individual DNOs are[16]:

Electricity North West Limited

- Northern Powergrid: Northern Powergrid (Northeast) Limited, Northern Powergrid (Yorkshire) plc
- Scottish and Southern Energy: Scottish Hydro Electric Power Distribution plc, Southern Electric Power Distribution plc
- ScottishPower Energy Networks: SP Distribution Ltd, SP Manweb plc
- UK Power Networks: London Power Networks plc, South Eastern Power Networks plc, Eastern Power Networks plc
- Western Power Distribution:
  - Western Power Distribution (East Midlands) plc
  - Western Power Distribution (West Midlands) plc
  - Western Power Distribution (South West) plc
  - Western Power Distribution (South Wales) plc

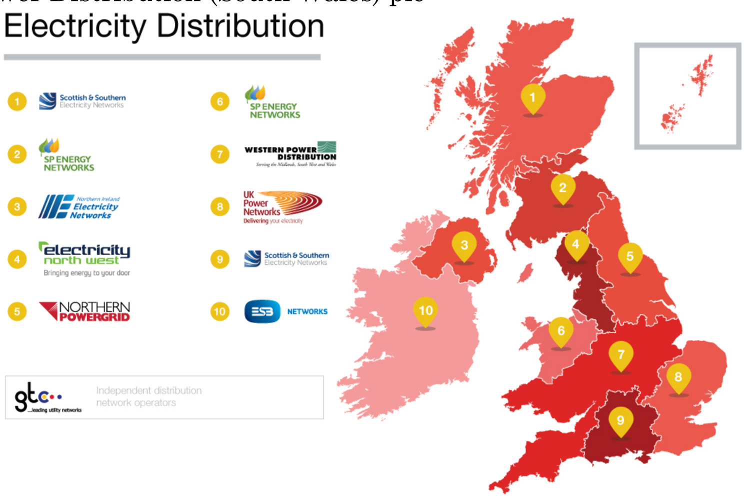

Fig. 1.23. Electricity distribution map of GB, showing the geographical area of each company[17].

[16] https://www.ofgem.gov.uk/electricity/distribution-networks/gb-electricity-distribution-network

[17] http://www.energynetworks.org/info/faqs/electricity-distribution-map.html

1.11 Electricity Grid Operation

A grid system is expected to provide a secure source of energy whenever a customer demands it. The grid operator must balance the demand with the supply of energy from various generators.

There is a daily pattern of load variation that is reasonably predictable. It is different at weekends and different from one season to the next. The highest demand is in the early evening of a winter weekday. The absolute peak varies slightly from year to year depending on the weather conditions. On 1 March 2018 during the cold snap, transmission system peak demand reached 50.7GW. On 29 October 2018, GB experienced the lowest overnight minimum demand (20.1 GW) seen during Greenwich Mean Time (the winter period). This was the result of high wind generation and warmer than normal temperatures.

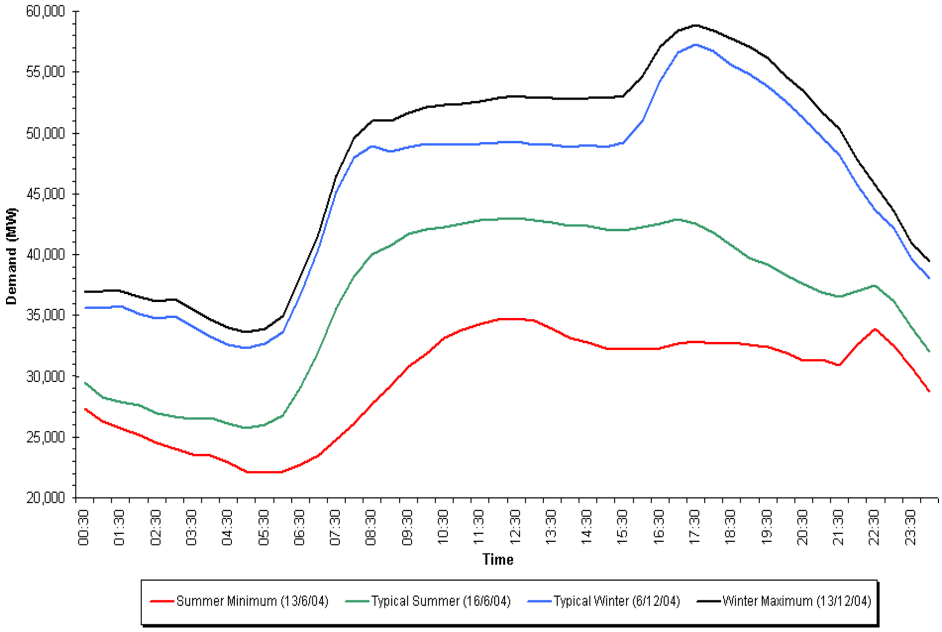

Fig. 1.24. Typical demand profile (MW) during 24-hours in GB. Seasonal variation is depicted.

The system operator must plan for unusual demand patterns such as "*television pick-up*"[18]. This is the sudden increase in load when a popular television programme ends. This can provoke a rise of 1,000 MW in demand in a matter of a few minutes. Major television events create even larger changes. The largest events are over 2,000 MW. Most TV events can be predicted reasonably well based on previous experience. It is highly unusual events that cause problems. It would also seem that the more diverse TV and entertainment market that now exists means that the TV pick-up is less severe because the audience for each TV programme is less. The largest ever TV pick-up in the UK was 2,800 MW of demand after the penalty shootout in an England v. Germany world cup semi-final in 1990.

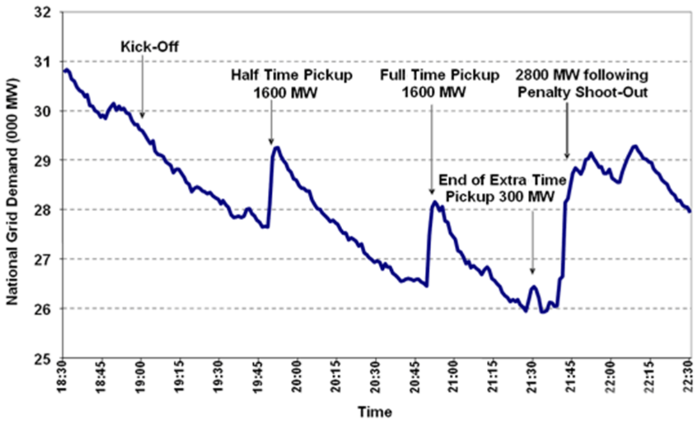

Fig. 1.25. An example of the phenomenon of "*TV pickup*" a very British problem, in this case, the 1990 World Cup England v's Germany match[19]. 2,800MW – equivalent to 1,120,000 kettles (based on 1MW = 400 kettles).

An example of a highly unusual event causing the system operator to work hard to maintain a stable system was the two-minute silence at 11:00 am on 14th September 2001 in remembrance of the deaths on 11th September. In the minutes before and during the silence, some 2,500 MW of load was switched off. This requires two large power stations to be removed from the system very quickly. We can tell that this was not achieved quickly enough because the grid frequency rose above its target range. When generation exceeds demand, the excess energy builds up in the inertia of the generators and the frequency rises. The "missing" 2,500 MW of load reappeared over the next 5 minutes and because there was now a shortage of generation the frequency briefly dipped below its target range.

[18] TV pickup is a term used in the United Kingdom to refer to a phenomenon that affects electricity generation and transmission networks.
[19] https://daryanenergyblog.wordpress.com/2013/09/24/blackout-paranoia/

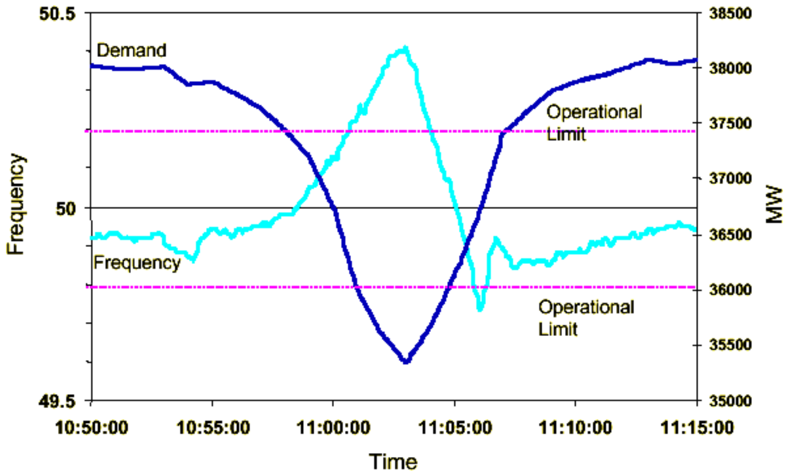

Fig. 1.26. Power demand during the Remembrance Day: 11:00 am on 14 September 2001.

A more recently, National Grid seems to have done a remarkably good job of managing some difficult demand pick-up and drop-off associated with the Royal Wedding. They would have looked back in the records more than 10 years for the last similar wedding but would have found direct comparison tricky because of the changes in TV viewing habits over ten years and the fact that this time a bank holiday was declared and last time it was a normal workday. Nonetheless, they managed to stop any large frequency excursions occurring despite swings in demand of more than 3,000 MW over an hour (actually a lot slower than a 2-minute silence).

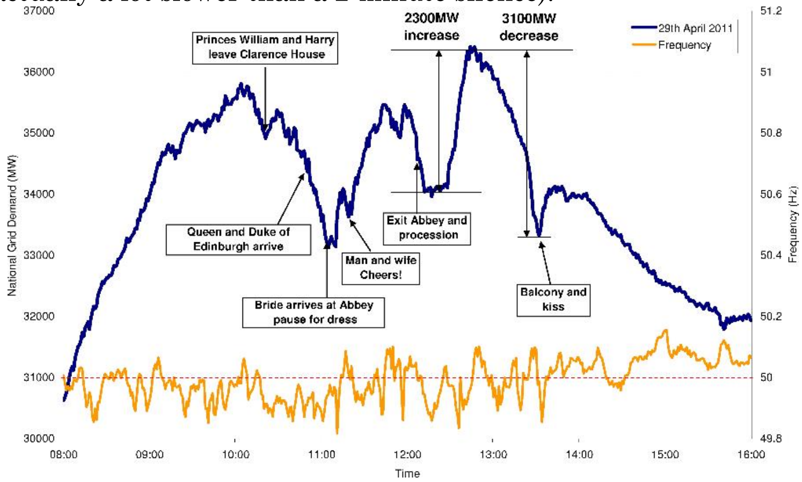

Fig. 1.27. Frequency and demand during the Royal Wedding 29 April 2011. Electricity demand: 1,600MW – 640,000 kettles.

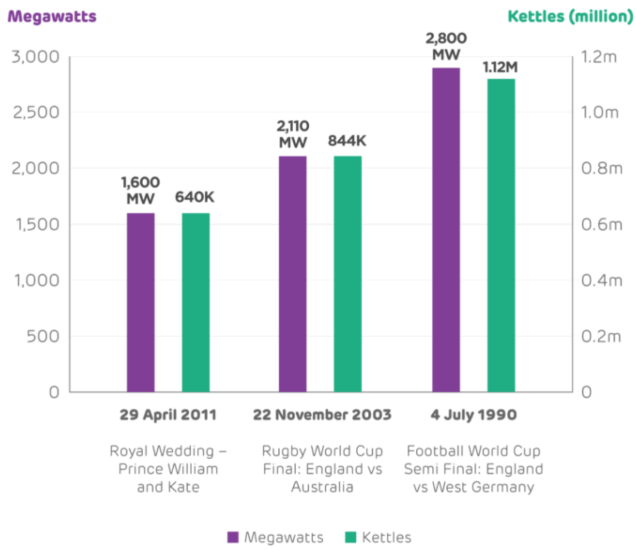

Fig. 1.28. The three biggest moments in the GB electricity system[20].

Faults in either generator or the transmission network itself cause system operators the greatest problems because these are very fast events. The GB system operators to a 1320 MW loss-of-in-feed standard. The large 2,000 MW coal-fired plant (such as Radcliffe-on-Soar or Drax) have four 500 MW turbine-generators run from two boilers with a double circuit connection to the grid. No single fault can cause all 2,000 MW to be lost in one go. The Sizewell B

[20] https://www.drax.com/technology/7-of-the-biggest-tv-moments-in-uk-electricity-history/

pressurised water reactor has two 660 MW turbine generators but only one steam circuit so the whole lot can get shut down in one go if there is a fault in the steam circuit. So National Grid carries enough reserve to deal with this loss if Sizewell B is running. In May 2008, Sizewell B did shut down unexpectedly which would have been OK but for the fact that a 500 MW generator at Longannet had also been lost unexpectedly about 2 minutes earlier. The loss of 1,993 MW of actual generation in such a short time was not covered by the reserve, and the frequency dropped below the operational limit (49.8 Hz) and then below the statutory limit (49.5 Hz) (a breach of National Grid's licence agreement unless an exceptional event). The frequency reached about 49.15 Hz before its fall was arrested. Then an unfortunate thing happened. A lot of small wind turbines other small generators (adding up to about 300 MW) disconnected 3 minutes later. These had been fitted with protection relays that interpreted a 3-minute under-frequency event as the break-up of the system and were shut down to prevent electrical islands forming. The result was that the frequency dropped even further and this led to automatic under-frequency load shedding. Put more bluntly, supply to parts of certain towns were shut off.

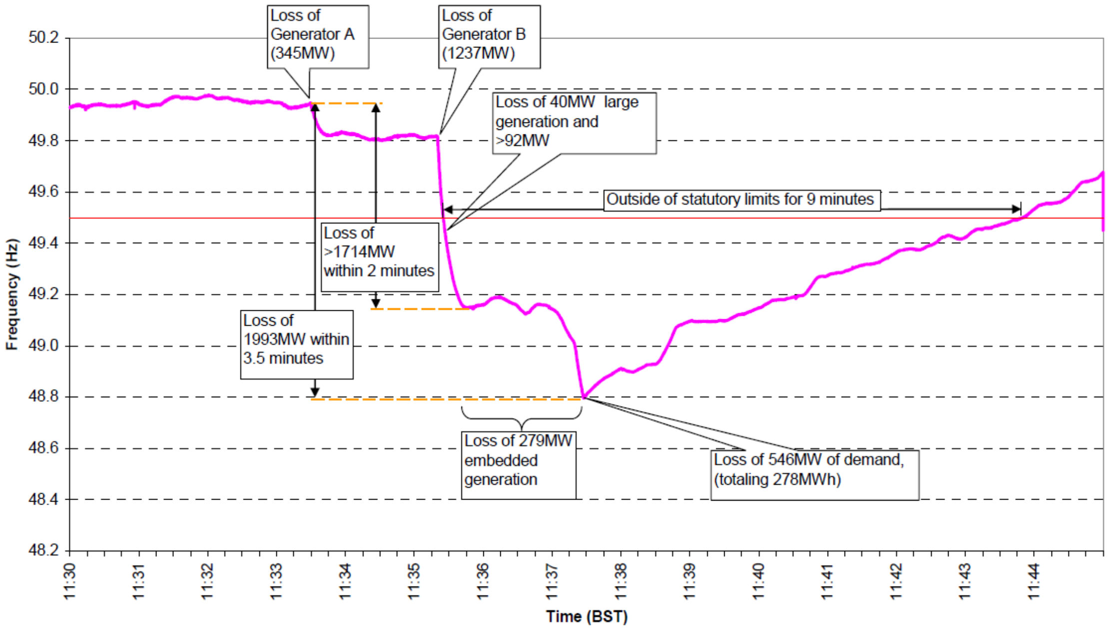

Fig. 1.29. Frequency Deviation following exceptional generation loss (1993MW).