POWER SYSTEMS: AN INTRODUCTION
INTRODUCTION

This article gives a broad outline of a typical electrical power system, such as we would expect to find in most countries. The objective will be to develop a basic understanding of the topic, so that even the non-technical with no knowledge of electrical engineering will obtain a basic appreciation of:

- What an electrical power system is.
- How electricity is generated.
- How electricity is delivered to customers.
- How an electrical power system can be considered to be a collection of interacting elements.

Each aspect of a power system relates to one aspect of our newly re-instated Power System Trainer, and to our suite of products that form the basis of our Power Systems Laboratory. This range is summarised in Appendix 1.

In addition, throughout this article, we will also highlight particular products from other TecQuipment ranges which have specific relevance to the Power industry, and these are summarised in the subsequent appendices.
WHAT IS AN ELECTRICAL POWER SYSTEM?

The following figure is a representation of a simple electrical power system. We shall look at each element of the system in turn and summarise the role that protection plays in each of the key stages of the power network.

![Schematic overview of a basic electrical power system](http://www.cescoorissa.com/power-delivery.html)

Figure 1 - Schematic overview of a basic electrical power system
(Source: http://www.cescoorissa.com/power-delivery.html)

Figure 1 shows a single power station delivering electrical power to a customer via substations (transformers) and transmission lines. This system is representative of electrical power systems around the world.

In practice, an electrical power system would be much more complex and extensive than shown. It would typically cover a very large geographic area and include many power stations, transmission lines, substations, and numerous customers of all types – domestic and industrial.

The whole of the UK for instance is covered by a single grid system that connects all customers to a large number of strategically positioned and interconnected power stations. In other parts of the world the grid system may cover the whole country, as in the UK, or be limited to only supplying a region, a city, part of a city or a town.
For simplicity and ease of understanding it is convenient at this point to consider an electrical power system to be a collection of different functional elements. Once the functions of these individual elements are understood it is then much easier to understand the operation of a complete electrical power system with all of the elements included and interacting.

**GENERATION**

Firstly, an electrical power system includes the means of generating electrical power.

**FIGURE 2 – A COAL-FIRED POWER STATION.**

Government plans to phase out coal in favour of gas as an energy source in the UK means that power stations such as this will either close or be converted to renewable fuels such as biomass.

Electrical power is produced in power stations containing the generators and all of the essential ancillary equipment needed to run, monitor and control them.

Consider the generation system represented by the next figure.

**FIGURE 3 – SINGLE GENERATOR SYSTEM**
It shows a single generator supplying a load that comprises a number of consumers. In practice, this would usually be a mix of industrial and domestic users. In such a system, the one generator would need to be rated to be able to supply the maximum possible load.

The single generator system has many practical and operational weaknesses. If the load demanded exceeds the maximum capacity of the generator, then it could be damaged and result in all of the consumers losing their electrical supply. Also, when maintenance is required the generator would need to be stopped, leaving all consumers without electrical power for the duration of the maintenance period.

Single generator systems are convenient and cost-effective for relatively small local consumers, such as remote towns or villages. They are also appropriate for use as emergency standby generators in factories, hospitals, etc, in the event that the regular supply fails. Single generator systems are not suitable for supplying large systems, such as the electrical supply for a town or city that includes many households, factories, hospitals, schools, etc.

The following figure represents a multiple generator system where the consumers are now divided into three groups or regions, usually determined by geographic area. In this system, each region has its own dedicated generator.

![Figure 4 - Multiple Generator System](image)

**FIGURE 4 - MULTIPLE GENERATOR SYSTEM**

The generators do not have to be as large as in the single generator example given previously because they are each sharing the total load. Also, if a fault occurs or maintenance is required, then not all of the consumers will lose their electrical power.

It is still not a perfect system. If any one of the regional generators should be overloaded, it is not possible to transfer power from a generator that is lightly loaded. Also, some consumers would still experience a total loss of power in the event of an overload, a fault or when maintenance is required.

The next figure shows a generator system where the outputs from all of the generators are connected to a single busbar by suitably rated heavy-duty cables. The consumers’ groups are also connected to the same busbar.
A busbar is literally a copper bar used in power stations to combine the outputs from all of the generators and then distribute the power to the consumers. Because of the magnitude of the electric current that a busbar will have to conduct, it is a substantial, very large copper bar.

With this system, all of the generators can be used to share all of the loads of the consumers in all of the consumer groups/regions. The generators can be relatively small and easier to control.

There is just one more step needed to make the system fully practicable. It must be possible to add or remove generators or consumers from the busbar. This may be for routine maintenance or to protect the equipment from overloads or faults.

The next figure shows the generators and consumers connected to a busbar with circuit-breakers in each of the connecting cables.

Circuit-breakers are heavy duty switches that are used to open or close electrical power circuits. They allow engineers to disconnect (isolate) or connect each of the generators or consumer groups to the busbar.

In normal operation, all circuit-breakers will be closed and the three generators will be supplying electrical power to the three consumer regions.

**FIGURE 5 – MULTIPLE GENERATOR SYSTEM CONNECTED BY A COMMON BUSBAR**

**FIGURE 6 – MULTIPLE GENERATOR SYSTEM CONNECTED BY A COMMON BUSBAR WITH CIRCUIT BREAKERS**
If generator $G_A$ needs to be serviced, circuit-breaker $A_1$ is opened to stop it supplying electrical power to the system. Once isolated from the rest of the system, the generator can be safely brought to a standstill to allow technicians to work on it in safety.

Likewise, if a fault occurs in the Consumers B region, then opening circuit-breaker $B_2$ will remove the fault from the system. This will also remove all of the consumers in the region covering the Consumers B region. Once the fault has been rectified, closing circuit-breaker $B_2$ will re-connect the Consumers B region to the system and the consumers will receive their electrical supplies once more.

The opening or closing of the circuit-breakers will be achieved either manually or automatically. The open/closed status of circuit-breakers may be controlled by protection relays so that the operation is not only automatic, it is also very fast.

Note that busbars and circuit-breakers are used throughout electrical power systems to combine, distribute and control the flow of power from the power stations to their consumers.

For the vast majority of electrical users, it is usual for their electricity to be supplied from a centrally operated generating system. This comprises many power stations, each including a number of generators and a network or grid of transmission lines. This centrally operated and controlled system is the type of electrical power system covered by this article and the equipment in TecQuipment’s Electrical Power Systems range (see Appendix 1).

In most large power stations, the source of mechanical power for the generator (also termed the prime mover) would almost certainly be a steam turbine.

**ENERGY FROM FOSSIL FUELS**

Power generation is achieved through the burning of fossil fuels such as coal, oil or gas. Other fuels can also be used where they are locally available and in sufficient quantities. For example, peat is used as the fuel of choice in many countries because it is available in large quantities and cheaper than transporting fuels to the power station from distant sources. The burning process releases the chemical energy that is stored in the fuel. This produces the heat needed to convert water into high-energy steam. The steam drives power turbines to produce the rotary power needed to rotate the generators.

The steam-driven power turbines connect to electrical generators to form turbine/generator sets, also called turbo-alternators. These turbo-alternators convert the mechanical energy of the turbine into electrical energy at the output of the generators. The generators will be designed to produce electricity of the correct specification in terms of the voltage amplitude, waveform (sinusoidal) and frequency (50 or 60 Hz). The generators will also be rated to supply the required levels of current and power.
Figure 7 – One of the 6x 660 MW Generators in the Turbine Hall at Drax Power Station, North Yorkshire, UK

This photo was taken in 2006, before a major contract was signed with Siemens to replace all the turbines as part of a modernisation project aimed at increasing the plant’s efficiency. This has resulted in one million tons less CO₂ released into the atmosphere every year. (Source: https://creativecommons.org/licenses/by-sa/2.0/deed.en)

A modern commercial power station would include a number of turbo-alternators, typically producing over 500 MW each. The total electrical power output from a power station would be the sum of all the generators running at any particular time.

The following figure shows the multi-bladed rotor of a steam turbine. Note the workmen in the picture to appreciate the size of this machine.
The shaft will be supported and run on journal bearings. TecQuipment’s Theory of Machines products relating to this include the TM25, TM1001, TM1022, TM1002, TM1005 and TM1027 (see Appendix 2).

Large steam-driven turbines include a large mass of material. It takes time, therefore, for a cold turbine to reach its operating temperature after steam is first introduced. Because of the high operating temperatures involved, turbines cannot be started quickly from cold without the risk of permanent damage or failure due to the expansion of critical components as the generator warms up and expands.

From cold, it can take up to approximately six hours before a steam-driven turbo-alternator can safely produce electricity. This includes the time it will take for the steam generation plant to be brought up to its operating temperature and to produce the amount of steam required.

TecQuipment’s Heat Transfer products relating to this include the TD1002 (see Appendix 3).

From ‘hot-standby’, where the turbine and its associated plant are maintained at working temperatures, this time can be reduced to approximately two hours. Because generators cannot be instantly switched on to produce electricity, accurate anticipation of changes in demand is needed if the generators are to meet customer’s demands at all times.

Steam generator systems also require time to respond to changes in demand while they are running. An increase in demand requires more steam to be produced. This is achieved by increasing the flow rate of water into the boiler and increasing the fuel to the burners. Because
of the relatively large response time of steam-driven generator systems, it is necessary to anticipate future changes in demand, whether it be an increase or a decrease.

Once the steam has passed through the turbines and given up most of its energy, it is no longer useful to the generation process. At this stage, the steam is still hot and contains valuable energy.

Cooling towers are then used to convert the steam into relatively low temperature water. This ‘cooled’ water can then be safely discharged into a local river or similar.

Fossil fuel power stations can be easily recognised by their characteristically shaped cooling towers emitting clouds of steam, as shown below.

![A Cooling Tower](image)

**FIGURE 9 – A COOLING TOWER**

A combined heat and power plant (CHP) is a power station, as described previously, but where the waste heat produced from the electricity generating process is captured and utilised as the source of heat for both industrial and domestic purposes.

TecQuipment’s heat exchanger products relating to this include the TD1, TD1005, TD360, TE93 and TD1007 (see Appendix 3).

CHP, also called ‘cogeneration’, increases the overall efficiency of the power generation system to as much as 70-90%, compared with the 35-52% that is possible from conventional electricity generation. Furthermore, because CHP plants are usually relatively small and supply electricity locally, CHP can also avoid transmission and distribution losses.
CHP plants help towards reducing greenhouse gas emissions to the atmosphere. Global targets to reduce carbon dioxide emissions, following initiatives such as Kyoto and Doha, could be partially achieved by developing more CHP plants.

A further step towards the environmental efficiency of CHP plants is where household and industrial waste is burned to provide the primary source of energy in the generation process. Using this otherwise useless material not only saves on burning valuable oil, gas or coal, it also converts a material that is unpleasant and difficult to dispose of into an inert ash that can be safely dumped or used in the building industries.

CHP plants, and other forms of embedded generation, such as solar panels, can pose some interesting power network challenges into the network. These can be simulated using TecQuipment’s Power System Trainer (PSS1) with a Second Generator (PSS3) connected (see Appendix 1 for details of these products).

In smaller power generation plants, the prime mover could be a gas turbine or a diesel engine. These smaller types of prime mover are commonly used in ships, emergency back-up systems for buildings, and for portable electrical systems, for example.

TecQuipment’s Thermodynamic products relating to this include the GT100, GT185 and TD300 (see Appendix 3).

Steam turbines or other types of engines and motors are not the only prime movers that are used to drive generators.

**HYDROELECTRIC ENERGY**

The exploitation of water to drive industrial processes dates back nearly two and a half thousand years, when simple water wheels were developed in the Eastern Mediterranean, primarily to grind flour. Later on, water wheels were increasingly used in a variety of industrial processes, and watermills are still used today in many countries.

Hydroelectric power stations use water turbines to extract energy from water falling from a height to a lower level - the actual process is one of converting potential energy into electrical energy.

The following figure shows a typical layout of a hydroelectric power station.
Water flowing from the reservoir to the outflow at a lower level releases its energy to the turbine which then drives the generator to produce electrical power.

The generator driven by the power turbine operates on the same principles as the steam turbine driven generator – it is only the prime mover that is different.

Hydroelectric power stations need to be situated in hilly or mountainous areas where a dam can be built across a river valley. This creates a head of water that provides the energy required to drive the power turbines.
The turbines can be accelerated from standstill to produce electrical power in less than two minutes – or 30 seconds if the turbines are already spinning. There is no warm-up period needed.

For hydroelectric power stations to produce electricity all year round, the volume of water in storage above the dam must be sufficiently large to last through any dry season. Where water is not plentiful, electrical power can only be generated for short periods of time, or during seasonal periods of rainfall.

The turbines used in hydroelectric power stations are mostly of the Pelton type.

The industrial sized Pelton turbine shown in the following figure may be built to a larger scale than we use in TecQuipment’s products but the appearance, theory and operating principles are exactly the same.

![Industrial Pelton Turbines](https://creativecommons.org/licenses/by-sa/3.0/deed.en)

**FIGURE 12 - INDUSTRIAL PELTON TURBINES**
(Source: [https://creativecommons.org/licenses/by-sa/3.0/deed.en](https://creativecommons.org/licenses/by-sa/3.0/deed.en))

TecQuipment’s Fluid Mechanics products relating to turbines include the H18, H19, MFP101 and H8 (see Appendix 4).

Hydroelectric power stations include extensive and complicated systems for transporting water from the reservoir to the discharge point via the turbine.
To design and manage these systems, electrical power engineers need to also be knowledgeable about non-electrical topics. These include: the principles and operation of pumps of all types, fluid friction, pipe friction, energy losses in pipes, impact of jets, laminar/turbulent flow, hydrostatics, Reynolds number, pipe surge, and cavitation, for example.

TecQuipment’s Fluid Mechanics products relating to these topics include the H47, H83, MFP101b, H31, H7, H34, H16, H408, H8, H215, H2, H11, H314, H405, TE86 and H400 (see Appendix 4).

A relatively new innovation in hydroelectric power generation is the pumped storage system.

Essentially, a pumped storage power station is the same as a hydroelectric power station. The difference is how they are managed and operated. During the night, when demand for electricity is relatively low, the generators are used as electrical motors with electricity to drive them being supplied from the grid. These motors power the turbines to operate as pumps that deliver water from a lower reservoir to a reservoir at a higher level.

During the day water is allowed to fall from the upper reservoir to the lower reservoir via the turbine. This produces the mechanical power needed to rotate the generator and so produce electrical power.
FIGURE 14 - THE GRAND’MAISON DAM, ISÈRE, FRANCE

At 1,800 MW capacity, this is the largest pumped storage power station (PSPS) in Europe (Source: https://creativecommons.org/licenses/by-sa/3.0/deed.en)

The turbines used in pumped storage power stations are mostly of the Kaplan type because they can be operated as turbines or as pumps.

The next figure shows an industrial-sized Kaplan turbine being assembled. Rotating the adjustable vanes changes the mode of operation from a pump to a power-absorbing turbine.

FIGURE 15 - A KAPLAN TURBINE FOR A HYDROPOWER PLANT
(Source: https://creativecommons.org/licenses/by-sa/4.0/deed.en)

TecQuipment's Fluid Mechanics products relating to Kaplan turbines include the H18, H19, MFP101 and H8 (see Appendix 4).
NUCLEAR ENERGY

Nuclear power stations use the energy released by disintegrating uranium atoms (a process called nuclear fission) to produce steam. The rest of the power generation process is exactly the same as that given for the fossil fuel power station.

Figure 16 - Bruce Nuclear Generating Station, Ontario, Canada

This is the world’s largest operational nuclear power station at 6,232 MW. The Kashiwazaki-Kariwa Nuclear Power Plant in Niigata Prefecture in Japan has a larger generating capacity, but was shut down following the Fukushima disaster and has yet to be restarted fully.
(Source: https://en.wikipedia.org/wiki/Bruce_Nuclear_Generating_Station)

The popularity of nuclear power stations is declining because of fears concerning the length of time the spent fuel remains radioactive, the cost of storing it, and the decommissioning of old power stations. In particular, major nuclear disasters such as Three Mile Island in 1979, Chernobyl in 1986 and Fukushima Daiichi in 2011 have highlighted the catastrophic effects that can occur when the worst happens. Nevertheless, despite this, and despite the huge construction costs and timescales involved, many countries are actively pursuing the construction of new or replacement reactors as part of their strategic energy requirements.

A well-designed electrical power system would typically include a variety of fossil fuel, hydroelectric and other types of generators. Engineers can choose to have the slower to respond fossil fuel power stations in continual operation to satisfy the base level of power requirements. The faster responding hydroelectric/pump storage systems would be used as and when required to satisfy the transient requirements of the grid.
CLIMATE CHANGE AND RENEWABLE Energies

In the face of the threat posed by global warming and climate change, renewable sources of energy that are sustainable and friendly to the environment are being increasingly developed and used to provide an ever growing proportion of the electrical power used in many countries.

Solar Energy

Photovoltaic (PV) cells that convert sunlight directly into electricity are one option.

![PV panels on a typical house in the UK](https://creativecommons.org/licenses/by-sa/2.0/)

These can be used in large arrays of many millions of panels, covering tens of square kilometres, or in smaller systems to supply power to single households or businesses. Photovoltaic arrays are becoming more and more widespread, and are increasingly being used to provide clean energy, thereby helping to reduce non-sustainable energy consumption. Excess energy produced by solar arrays can be fed back into the grid.

Another way of capturing solar energy is to use the thermal energy of sunlight. Solar thermal systems range from small domestic systems, which are often used to provide heated water for indoor heating and swimming pools, to vast arrays such as the concentrated solar power (CSP) complexes in Spain. One design uses an array of mirrors, called heliostats, which track the sun and concentrate the sunlight at a fixed point on a large ‘power tower’. This immensely concentrated energy is used to melt salt to store the thermal energy, which can then be converted into electricity when it is required. Another design is the parabolic trough array which uses a similar idea to concentrate thermal energy in pipes containing molten salt in tubes running along the focal axis of long linear reflectors in arrays covering vast areas of ground.
The PS10 was the world’s first commercial solar power tower. (Source: https://en.wikipedia.org/wiki/PS10_solar_power_plant#/media/File:PS20andPS10.jpg)

Figure 19 – A Parabolic Trough Reflector at Harper Lake, California, USA
WIND ENERGY

Wind power is becoming increasingly popular because, once a wind turbine has been installed, the running costs are extremely low and there is no pollution.

Figure 20 - Clouds form in the wake of Denmark’s Horns Rev windfarm, one of the world’s largest offshore wind farms
(Source: https://creativecommons.org/licenses/by-nd/2.0/)

Wind turbines are, of course, totally dependent upon there being wind of the required strength. If there is no wind, then there can be no power generation.

For efficiency, wind turbines are often located on high ground or out to sea to maximise the availability and strength of the wind available. A good site for a single wind turbine usually means it is a good site for many wind turbines – a wind farm.

TecQuipment products relating to solar power and wind turbines include the TE4, TE38, TE39, TD1003 and the AF100 (see Appendix 5).
TIDAL ENERGY

Another renewable energy scheme for electricity generation uses the immense power of the oceans and rivers. Tidal energy turbines are being increasingly used to convert the energy contained in coastal waters into electrical energy.

FIGURE 21 - SIHWA LAKE TIDAL POWER STATION, GYEONGGI PROVINCE, KOREA, THE LARGEST IN THE WORLD AT 254 MW
(Source: https://creativecommons.org/licenses/by/2.5/deed.en)

Suitable locations for tidal energy schemes are limited because, to be cost-effective, the tidal stream needs to be high and last for many hours in a day.

Power is generated during the incoming and outgoing tides but not at slack water when the tidal flow is too low to turn the turbines. An important consideration when choosing a location for a tidal energy complex is that it does not interfere with shipping routes or with fishing activities.

Energy can also be extracted from the sea using wave power generation. In these systems, wave motion drives specially shaped floats that are connected to generators to produce electricity. Because the sea is in constant motion, these generators are able to produce electrical power continuously, and in increasing amounts as the waves become higher and more frequent.
GEOTHERMAL ENERGY

The heat from thermal springs has been exploited since Palaeolithic times, and is used in a variety of ways to provide direct heating to homes and businesses around the world.

![Figure 22 - It’s not just humans who exploit geothermal energy! Japanese Macaques bathing in the hot springs of Jigokudani Monkey Park, Nagano Prefecture, Japan](https://pixabay.com/en/snow-monkeys-macaque-japanese-1394883/)

The conversion of this heat to electricity relies on the extraction of high-temperature steam from deep underground to spin steam turbines, and this is being used increasingly by a number of countries as a low-carbon alternative to burning fossil fuels. The USA is currently the largest producer of geothermal electricity in the world, followed by the Philippines and Indonesia – together they account for 58% of global geothermal electricity production (2010 data).

![Figure 23 - Iceland’s Nesjavellir geothermal power station](Photo: Gretar Ívarsson, geologist at Nesjavellir)

Geothermal plants account for more than 25 per cent of the electricity produced in Iceland.

(Photo: Gretar Ívarsson, geologist at Nesjavellir)
Thermoelectric generators, which use the Seebeck effect to convert heat into electricity, are small scale devices compared to the kinds of generation plants we have discussed up until now, although they do have a place in the power industry in converting waste heat into power, thus increasing the efficiency of the power station.

TecQuipment products relating to geothermal energy include the TD1008 (see Appendix 5).

We have now covered the most common methods that are used to generate electricity. We will now consider the next stage in the process, that of delivering electrical power to customers.

See Appendix 8 for an overview of the role that different fuels play in global energy consumption, as well as the growth of renewable energies.
TRANSFORMATION

Modern large turbo generators produce immense amounts of electrical energy. Generators over 1000 MW will typically be generating tens of thousands of volts and producing currents in the tens of thousands of amps. A 1000 MW turbo generator, for example, may be producing 37 kA at 27 kV in a typical large power station. Distributing these currents straight to the network would introduce very high levels of losses, and incur massive costs in terms of the size of conductors that would be required to carry such massive currents. It is for this reason, therefore, that the voltages are stepped up considerably, thereby reducing the current that needs to flow in the grid.

This is achieved by the use of step-up transformers at the power station, which convert the high voltages generated into very high voltages. In the UK, our main transmission voltage is 400 kV, nearly 20 times the voltage produced by a large turbo generator. In other countries, the transmission voltages may be up to 800 kV.

**FIGURE 24 - A GOOD EXAMPLE OF A LARGE POWER TRANSFORMER, OF 200 MW CAPACITY, MANUFACTURED BY SIEMENS, ONE OF THE LEADING GLOBAL MANUFACTURERS OF LPTs**

These large power transformers (LPTs) operate in exactly the same way as the smallest transformers which we all use on a daily basis. Our mobile phone chargers, for example, are just much smaller versions of the massive transformers used in power stations, only in the case of a phone charger, we are stepping down from the mains voltage (in the UK, for example, this is 240 V) to around 5 V which our phones operate on. The operating principles and the fundamental construction of LPTs are essentially the same, however, as they are for these small transformers.
The transformer core comprises a myriad of very thin iron plates, less than 1 mm thick, precision cut and assembled to reduce internal losses and noise. These cores are surrounded by massive copper windings, again, precision made. Voltage control systems are utilised to match the grid and generator voltages. Cooling systems are built in to dissipate the large amount of heat generated in the transformer, and the whole assembly is typically immersed in an insulating, oil-filled tank. In all, an LPT can weigh several hundred tons, cost millions of pounds, and take several years to design and build. Unlike our mobile phone chargers, however, most LPTs are designed and made to specific one-off requirements.

With the electricity now transformed up to very high voltages, it can be efficiently transmitted over the grid and distributed to consumers.

Note that the actual level of power does not change when the electricity is boosted. Although the voltage is being increased to a high level, the current is being reduced proportionally. It is the reduction of the current that improves the efficiency of the transmission process by reducing the power losses in the conductors (Joule’s Law explains this phenomenon).

Note also the size of the insulators that have been used. Because the voltages used are so high it is essential that the insulation is also high, especially in wet/damp weather. This is to ensure that the electricity does not find alternative paths to flow along.

A further point to note is that transformation also occurs at the other end of transmission lines, where the very high voltages now need to be progressively stepped down until it reaches the level of the mains voltage, which is typically in the 100 V to 240 V region, depending on the country. At the same time, the electricity supply is progressively distributed through a branching system of transformer substations until it reaches individual consumers.
TRANSMISSION

Once the transformers have boosted the voltage, the electrical power is transmitted to consumers typically via overhead cables, as shown in the next figure. This is termed ‘transmission’.

![High voltage transmission lines](image)

**FIGURE 25 – HIGH VOLTAGE TRANSMISSION LINES**

In built-up areas, such as in towns and cities, it is common practice for the transmission cables to be laid underground. Although this is a significantly more expensive solution, the aesthetic advantages are clear.

The transmission network generally uses alternating current (AC), and operates at very high voltages, typically between 115 kV and 765 kV – the maximum voltage varying from country to country, depending upon local regulations and requirements. In the UK, for example, the main transmission network runs at 400 kV, which is stepped down to 275 kV at a regional level.

The vast majority of countries in the world operate a synchronous transmission grid at either 50 Hz or 60 Hz throughout the entire country, but in some cases, most notably Japan, different frequencies are employed in different regions. This has its origin going back to the end of the 19th century, when the very first generators were purchased for Tokyo and Osaka – each city...
choosing different manufacturers whose generators operated at different frequencies. Thus the eastern half of Japan now runs at 50 Hz, while the western half runs at 60 Hz. These are joined together by four large frequency converters.

High voltage direct current (HVDC) lines are utilised for submarine cables, owing to the limitations of AC cables underwater and the large reactive losses incurred over relatively small distances (in the tens of kilometres underwater). Where power needs to be transmitted above ground over very long distances, HVDC transmission is also used, as the costs involved in HVDC transmission are lower over long distances than for AC, despite the converter stations being more costly. Electrical losses are also lower in HVDC networks.

Because of the large size of the cables needed to transmit large amounts of power, weight is a key consideration in any network. Aluminium is used as the principal conductor, often strengthened by steel – its lighter weight being more advantageous structurally and economically than copper, despite its marginally poorer electrical qualities.

Transmission lines are typically supported by many vertical structures, called pylons, positioned along their length. The cables are attached to the pylons via long ceramic insulators to avoid inadvertent earthing of the current.

TecQuipment products relating to structures include the STR4, STR5, STR8, STR12, STR14, STR17 and STF2 (see Appendix 6).

Transmission lines connect all of the power stations together to form a grid system that covers the local area, region or the whole country. Transmission is an essential part of the power system because power stations are not usually located near to customers. The reasons for this are:

- Power stations need economic and convenient supplies of water and fuel: near a river for availability of cooling water, and a coal or oil field for fuel would be ideal. Coastal power stations are also popular because fuel from other countries can be delivered directly and cheaply via ships.
- For efficiency, power stations are large. It is not efficient for each customer (a small town for instance) to have its own power station.
- Nobody wants to live next door to a power station!
DISTRIBUTION

FIGURE 26 - THE NATIONAL GRID OF GREAT BRITAIN (Note that this does not show the interconnections that link Britain to Ireland and to northern Europe) (Source: National Grid Plc - http://www.northwestcoastconnections.com/bgo/overview.asp)
The figure shows the location of power stations and the network of transmission lines that connect them together to form the National Grid. The Grid also connects all major centres of population, where the majority of electricity consumers are located – domestic and industrial.

At strategic points, electricity is taken off the grid at local sub-stations. Transformers reduce the voltage to the required levels for distribution via busbars and circuit-breakers for use by consumers. The consumers, the actual users of the electrical power, can be domestic households, schools and colleges, hotels, hospitals or industrial organisations.

**FIGURE 27 – INDUSTRY, ONE OF THE MAJOR CONSUMERS OF ELECTRICAL POWER**

In addition to the mainland grid, there are also undersea interconnections to northern France, Northern Ireland, the Isle of Man, the Netherlands and the Republic of Ireland.

Whatever or whoever the consumers are, they all have the same requirement, to receive a reliable and good quality supply of electricity when they need it.

The power used by each customer has an effect on the generators and all other components in the system. The total demand on the power system is the sum of all the individual consumers.

Electrical power engineers, technicians and control room operatives have to be effective and efficient in managing and operating an electrical power system. To do this, they need to receive and interpret up-to-date information concerning the operation of all parts of the system. They also need to have the experience and skills to understand the interactions and interdependencies between all of the components of the system, to be able to react as required to changing situations.

Modern power systems are monitored and controlled from central control rooms. This may cover a local town/city or the whole of a nation’s electrical power grid.

The next figure shows a typical electrical power system control room, with panels containing controls, displays and indicators. With these, engineers can monitor and control the performance of a complete electrical power system, from generation to utilisation.
In Appendix 1, we will look at TecQuipment’s Power System Trainer (PSS1). The PSS1 is designed to provide engineers, technicians and control room operators with realistic facilities that allow them to monitor and control the all the elements of an electrical power system. It includes all the main parts of an electrical power system, from supply (generation) to demand (utilisation). Each part includes dedicated industrial-standard protection relays that do specific jobs, from generator protection to distance protection on transmission lines, and distribution transformer protection.

Other TecQuipment products relating to control systems include the CE103, CE105, CE107, CE110, CE111, CE117, the TE3300 range and the TE37 (see Appendix 8).
UTILISATION

In the UK, the Electricity Supply Regulations permit:

- Variations of voltage not exceeding 10% above and below the nominal 400 kV, 275 kV and 132 kV and not exceeding 6% at lower voltages.
- Variations in frequency not exceeding 1% above and below 50 Hz, a range of 49.5 to 50.5 Hz. Over a 24-hour period, the regulations require that the average frequency is exactly 50 Hz.

Both the voltage and frequency are affected by changes in load and some compensation is required to keep the grid within regulatory limits.

This is where technical and operational expertise is most needed because instantaneous decisions and actions have to be made throughout the day to keep the whole system within the specified limits as the load changes.

Day to day changes in demand due to the weather or the season are predictable. Unpredictable or extreme events can affect the demand profile.

The next figure shows the electrical power consumption profile of a typical working day. It clearly shows the demand increasing as people wake up in the morning and then start to work. The loading remains relatively constant during the working day and then reduces consistently towards the end of the evening. It then starts to picks up in the early morning as people prepare for another working day.

**Figure 29 – A graph showing a typical weekday demand profile in the UK**
(Source: www.mpoweruk.com/electricity_demand.htm)
There will be some variations from day to day, weekends and holidays for instance, but in general the daily load cycle is very predictable and the total grid generating capacity can be planned in advance for each day.

The increased use of electricity in winter for lighting and heating in the home increases the load on the power system, particularly in the early morning and early evening. The daily profile is fairly similar, however, and as a result, can be fairly accurately predicted by the National Grid.

![Graph showing weekday demand profile](Source: www.theenergycollective.com/robertwilson190/228281/can-solar-keep-uk-s-lights)

**Figure 30 – A graph showing how the typical weekday demand profile in the UK varies during the year**

The variation of load demanded from the grid at any time of the day has to be planned in advance if the consumers are to continue to receive the quality of electricity they expect.

As explained previously, it is not possible for a generator to instantaneously respond to changes in demand. In the case of steam turbine driven generators – the providers of the majority of the electrical power in most networks – the response time is in the order of hours rather than seconds.

It is a statutory requirement that such a surge of power demanded should have minimal effect on the whole grid. Electrical power systems engineers have to plan their responses in advance to ensure that enough generators are on-line and ready to produce electricity at the time when it is needed. It would not be economical to have all generators running at maximum capacity 24 hours a day, every day.
In the UK, teams of experts are employed by power generation companies to predict what the load on the system will be at any time during the day. They use their experience to identify all circumstances that would have an effect on the load. This includes studying television programme schedules to identify the start and end of popular programmes that would have a similar effect on load demand, such as the England v Germany 1990 FIFA World Cup semi-final example shown below, when a surge in demand of 2800 MW hit the UK Grid. This is equivalent to over a million kettles being switched on at the same time.

![Power Demand Surge during the 1990 FIFA World Cup Semi-Final](image)

**FIGURE 31 – POWER DEMAND SURGE DURING THE 1990 FIFA WORLD CUP SEMI-FINAL.**

This event was one of the largest of its kind in the UK. When this kind of event relates to demand surges as a result of TV coverage, it is referred to as ‘TV pick-up’. The 1990 semi-final is the largest recorded TV pick-up in the UK. (Source: [www.wordsinspace.net/urban-media-archaeology/2011-fall/2011/10/12/tv-pick-ups/](http://www.wordsinspace.net/urban-media-archaeology/2011-fall/2011/10/12/tv-pick-ups/))

Other events can cause even bigger pick-ups for the National Grid than television coverage. During the solar eclipse of August 11, 1999, there was a record fall followed by a sharp rise in demand of 3000 MW, as millions of people left their homes and workplaces to observe the phenomenon.

Anticipating and managing such events is a highly involved process, and requires well-designed systems that are effectively managed. Electrical power engineers and technicians who design and build such systems, and control room operatives who operate and manage them, need knowledge, experience and skill to achieve this level of operation. The success of this activity in the UK is such that we hardly ever experience an interruption in our electricity supplies. In many countries, however, ‘brown-outs’ and ‘black-outs’ can be a daily occurrence.
Brown-outs are caused by generators having difficulty in supplying the demanded load. Lights dim noticeably, circuit-breakers open, and some electrical equipment fails to operate (PCs for instance).

Black-outs happen when no power is available to the customer at all. In some instances, a black-out is deliberately caused by the power engineers who choose to switch off power to some selected consumers so that the remaining consumers do not suffer from the effects of brown-outs.

**PROTECTION**

Protecting the whole electrical power system **AND** maintaining a healthy supply to the customer is an essential part of all power systems.

Excess loads on a system can be caused by either:

- too much power demanded by consumers for the generating capacity available, or
- a fault in the system that is causing excessive currents to flow. Such faults could include faults to earth, or line-to-line faults.

Faults or damage can occur in any part of an electrical power system. Most of the system equipment and plant is outdoors and exposed to the elements 24 hours a day, every day of the year. Wind, rain, snow and ice are just some of the environmental conditions that the system has to be resistant against.

Protection relays are included throughout electrical power systems to monitor their performance and to identify when a fault has occurred. In some circumstances, it is possible for the protection relays to report an imminent failure before it becomes significant.

The protection system needs to be selective. It is not desirable for the whole power system to be switched off every time there is a fault in just one part of it.

This selectivity allows the appropriate remedial action to be taken to protect the whole system, while ensuring that the minimum number of consumers are disrupted.

The requirement is to not only isolate faults in one part of the system, it is important that all other parts of the system continue to operate normally.

Circuit-breakers are strategically positioned throughout the electrical power system. They are controlled by the protection relays to operate when required, to isolate specific sections of the power system and so limit the level of damage or disruption to the system that a fault can cause.

The ability to protect the supply as well as the equipment itself is vital.
Lightning can potentially disrupt power systems over a wide area. It is estimated that, worldwide, there are 100 cloud-to-ground lightning strikes every second. This is a small fraction of the vastly greater number of cloud-to-cloud strikes, which can induce damaging transient surges in transmission and distribution networks.

(Source: https://creativecommons.org/licenses/by-sa/3.0/au/deed.en)

Lightning is an extreme cause of disruption and possible damage to an electrical power system. A fundamental requirement of an electrical power system is that it can withstand and recover from a lightning strike.

Fortunately, lightning storms tend to be relatively localised events in most cases, and will generally only affect fairly small sections of the supply grid at any one time. Solar magnetic storms, on the other hand, can affect the power supply networks across entire continents.
SUMMARY

We have covered the complete electrical power system from generation to utilisation. This of course is only scratching the surface of an immensely complex and detailed subject.

One of the main points that we hope you have gained from this article is that electrical power systems include the following elements working interactively together to provide the level and quality of electricity required by its consumers:

- Generation
- Transformation
- Transmission
- Distribution
- Utilisation
- Protection

In electrical power systems courses in universities and colleges, it is often easier for students to understand the principles involved with each of these elements separately. Only then can students progress towards studies of more complex systems, when several of these elements are interconnected and working together.

Appendix 1 details TecQuipment’s practical laboratory solutions for the teaching of electrical power systems principles and practices. These include studies into the individual elements of an electrical power system operating on their own, as well as a complete electrical power system with all the elements included.
APPENDIX I - THE POWER SYSTEMS RANGE

TecQuipment manufactures a comprehensive range of trainers to cover all the aspects of an electrical power system mentioned in this article, ranging from a suite of standalone Power Systems Laboratory (PSL) trainers which look at each of the aspects of power systems in turn (generation, transformation, transmission, distribution, utilisation and protection), through to an all-encompassing Power System Trainer (PSS1) that combines all these elements in one unit.
POWER SYSTEM TRAINER (PSS1)
A self-contained unit that simulates all parts of electrical power systems and their protection, from generation to utilisation.

SECOND GENERATOR (PSS3)
A self-contained motor and generator set that connects to the Power System Trainer (PSS1) for extra experiments in central and embedded generation.
POWER SYSTEMS LABORATORY

SALIENT POLE GENERATOR (PSL10)

Provides typical generator performance characteristics for experiments in generation, synchronising and paralleling, and load sharing.

Recommended ancillaries for further experiments:

- Power Factor Load Bank (PSA40)
- Two Channel Oscilloscope (OS2)
- Overcurrent and Earth Fault Relay (PSA10)
- Differential Protection Relay (PSA15)
- Directional/Non-Directional Overcurrent Relay (PSA20)
- Feeder Management Relay (PSA25)
Transformer Trainer (PSL20)

Investigates the principles and operating characteristics of single-phase and three-phase power and distribution transformers.

Recommended ancillaries for further experiments:

- Two Channel Oscilloscope (OS2)
- Differential Protection Relay (PSA15)
TRANSMISSION LINE SIMULATOR (PSL30)

Investigates short, medium and long transmission line performance in single-phase and three-phase systems.

Recommended ancillaries for further experiments:

- Power Factor Load Bank (PSA40)
- Overcurrent and Earth Fault Relay (PSA10)
- Feeder Management Relay (PSA25)
- Distance Protection Relay (PSA30)
**DISTRIBUTION TRAINER (PSL40)**

Shows how electricity is distributed and protected – investigates distribution through transformers, radial and ring-main circuits, and efficiency and regulation.

Recommended ancillaries for further experiments:

- Overcurrent and Earth Fault Relay (PSA10)
- Differential Protection Relay (PSA15)
- Directional/Non-Directional Overcurrent Relay (PSA20)
- Feeder Management Relay (PSA25)
HUB (PSLHB)

One of the great advantages of the PSL modules is that they can be interconnected to perform additional advanced experiments that would not be possible using the individual modules alone. This is achieved using the PSLHB Hub, which provides all the common connections between the individual modules.

SWITCHED BUSBAR MODULE (PSLSB)

The PSLSB Switched Busbar Module provides a convenient central test and control unit that provides common voltage and power ratings to the PSL modules. With the PSLSB, more advanced experiments can be performed in differential protection and unit protection.
PROTECTION AND RELAY TEST SET (PSL50)

For comprehensive investigations into the theory and practice of electrical power system protection.

Comes supplied with:

- Overcurrent and Earth Fault Relay (PSA10)
- Differential Protection Relay (PSA15)
- Directional/Non-Directional Overcurrent Relay (PSA20)
- Feeder Management Relay (PSA25)
- Distance Protection Relay (PSA30)
**THYRISTOR AND DIODE TRAINER (PSL60)**

A mobile unit that teaches the principles and applications of thyristors, diodes and converters in power circuits.

Comes supplied with:

- Two Channel Oscilloscope (OS2)
- Portable Load Bank – Resistive (PSA50)
- Portable Load Bank – Inductive (PSA60)
CIRCUIT BREAKER TRAINER (PSL70)
Compares different circuit protection devices and shows students how they perform.
Comes supplied with:

- Portable Load Bank – Resistive (PSA50)

3-PHASE TRANSFORMER (PSL80)
A mobile 3 kVA three-phase multi-tapped transformer for a wide range of single-phase or three-phase experiments.
Comes supplied with:

- Portable Load Bank – Resistive (PSA50)
- Portable Load Bank – Capacitive (PSA55)
- Portable Load Bank – Inductive (PSA60)
SINGLE-PHASE TRANSFORMERS (PSL90)
A set of three single-phase multi-tapped transformers for a wide range of single-phase or three-phase experiments.

Comes supplied with:
- Portable Load Bank – Resistive (PSA50)
- Portable Load Bank – Capacitive (PSA55)
- Portable Load Bank – Inductive (PSA60)
APPENDIX 2 - THEORY OF MACHINES

Journal Bearing Demonstration (TM25)

Static and Dynamic Balancing (TM1002)

Centrifugal Force (TM1005)

Governors (TM1027)

Balance of Reciprocating Masses (TM1022)

Whirling of Shafts (TM1001)
APPENDIX 3 – THERMODYNAMICS

Water-to-Air Heat Exchanger (TD1007)

Free and Forced Convection (TD1005)

Turbojet Trainer (GT100)

Forced Convection Heat Transfer (TD1)

Heat Transfer Experiment (TD1002)

Regenerative Engine Test Set (TD300)

Heat Exchangers (TD360)

Two-Shaft Gas Turbine (GT185)

Cross Flow Heat Exchanger (TE93)
APPENDIX 4 - FLUID MECHANICS (PUMPS AND TURBINES)

Pelton Turbine (H19)

Francis Turbine (H18)

Impact of a Jet (H8)

Hydraulic Ram Pump (H31)

Centrifugal Pump Test Set (H47)

Two-Stage (Series and Parallel) Pumps (H83)

Centrifugal Pump Module (MFP101)
APPENDIX 5 - FLUID MECHANICS (GENERAL)

- Friction Loss in a Pipe (H7)
- Reynolds Number and Transitional Flow (H215)
- Hydrostatics and Properties of Fluids (H314)
- Pipe Surge and Water Hammer (H405)
- Fluid Friction Apparatus (H408)
- Centre of Pressure (H11)
- Pipework Energy Losses (H34)
- Stability of a Floating Body (H2)
- Water Hammer Apparatus (TE86)
- Cavitation Demonstration Unit (H400)
- Losses in Piping Systems (H16)
- Reynolds Number and Transitional Flow (H215)
- Water Hammer Apparatus (TE86)
- Pipework Energy Losses (H34)
- Stability of a Floating Body (H2)
- Fluid Friction Apparatus (H408)
- Centre of Pressure (H11)
- Hydrostatics and Properties of Fluids (H314)
- Pipe Surge and Water Hammer (H405)
- Cavitation Demonstration Unit (H400)
- Losses in Piping Systems (H16)

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APPENDIX 6 - SOLAR ENERGY, HEAT PUMPS AND WIND ENERGY

- Photovoltaic Cells (TE4)
- Focusing Solar Energy Collector (TE38)
- Flat Plate Solar Energy Collector (TE39)
- Thermoelectric Device Demonstrator (TD1008)
- Subsonic Wind Tunnel (AF1300)
APPENDIX 7 - STRUCTURES

Suspension Cable Demonstration (STF2)

Bending Stress in a Beam (STR5)

Deflections of Beams and Cantilevers (STR4)

Buckling of Struts (STR12)

Pin-Jointed Frameworks (STR8)

Curved Bars and Davits (STR14)

Redundant Truss (STR17)
APPENDIX 8 – CONTROL

Thermal Control Process Apparatus (CE103)
Coupled Tanks Apparatus (CE105)
Engine Speed Control Apparatus (CE107)
Servo Trainer (CE110)

PLC Process (CE111)
Process Trainer (CE117)
Control and Instrumentation Study Station (TE37)

Process Training System – Pressure, Flow, Level, Temperature (TE3300 series)
Primary energy consumption per capita 2014
Tonnes oil equivalent

BP Statistical Review of World Energy 2015
© 2015 BP p.l.c.
ENERGY PRODUCTION BY FUEL

World electricity production by source from 1973 to 2013

1. Includes non-renewable wastes, electricity from chemical heat and other sources (e.g. fuels cells)

Source: International Energy Agency (IEA) 2015

RENEWABLE ENERGY GROWTH

Renewable Energy Growth in Major Economies

Source: Bloomberg New Energy Finance
WORLD RESOURCES INSTITUTE