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The story of Electricity Generation from pipelines to pylons

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Introduction

If ever you've wondered why mains electricity is a.c. (alternating current) not d.c. (direct current), or why pylons have three wires hanging down each side, or why mains power is a sine wave and not, say, a square wave, then this online feature is for you!

Back in 1999 I was a guest of National Power, as it was then known, a major owner/operator in Britain's power generation sector. One of their new Combined Cycle Gas Turbine (CCGT) power stations was under maintenance, and the entire station was laid bare. It was an ideal opportunity for me to delve into the innermost workings of a new power station to discover how they work. I could then plot the distribution of electricity, all the way from 400,000V (SuperGrid) power right down to the 230V a.c. domestic wall socket that's powering the PC I'm using right now.

National Power was extremely generous in its hospitality and I had unrestricted access to the entire power plant during a shutdown. I also saw how electricity was "traded" every day as each power station would "bid" for some business with Britain's National Grid. I learned a lot about electricity generation when researching this story, and I soon appreciated the gargantuan efforts that are made to deliver this essential utility right into our homes and factories.

The result was a 10,000 word general-interest feature – *Power Generation from Pipelines To Pylons* – which first appeared in EPE Magazine August and September 1999. I found this project immensely satisfying and interesting, and I hope you enjoy reading this web-enabled reprint.

You can read the full story on the following pages along with my photos and diagrams to help things along. I've also featured topics on electricity pylon function, (UK) fuse ratings and First Aid.

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Part 5: Neutral and Ground; Delta and Star connections. The supply to your home.

Part 6: Getting down to Earth; Electrical Safety considerations.

More resources:

- Electricity Pylons: an introduction
- First Aid Guidance
- Leaps & Volts: Safe Working Distances
- Fuses and Circuit Breakers

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Part 1: The evolution of electrical mains power, and where UK power comes from today.

In the UK we are fortunate enough to enjoy virtually uninterrupted electricity, provided by one of the world's largest interconnected electrical systems which links our power stations together to form the National Grid. The high quality of Britain's electricity supply is taken for granted by us all, although for both the micro-electronics enthusiast and the general public much mystique surrounds the way in which electrical power is created and delivered safely to our homes.

In this feature, supported by the expertise of the international power generation company National Power plc, Alan Winstanley describes the high technology involved in generating power - from a gas pipeline to the turbines and generators and then to the electricity pylon and beyond! We also examine in close-up some of the techniques related to the provision of a 230V supply directly to our housing and industry.

National Power generously granted the writer unlimited access to all parts of a modern 650MW gas-fired power station - Killingholme "A" - and provided a much-needed insight illustrating where our "juice" actually flows from. If ever you have wondered what "neutral" really means, why the earth (ground) plays such a vital role in safety, or why an electricity power station would ever need gas, or if you just want to brush up on some fundamental theory, this article provides background which is essential reading for electronics users and consumers everywhere.

National Power plc demerged on 2 October 2000 into two companies, International Power plc and Innogy Holdings plc. In 2002 the European firm RWE AG acquired Innogy Holdings plc. RWE Innogy owns many familiar British electricity brands, including National Power and Yorkshire Electricity. At the time of writing (Feb. 2011) Killingholme "A" power station is operated by Centrica. A neighbouring larger Killingholme "B" site is owned by E.ON.

Please note! This article is based on the British 230V electrical distribution system. In fact Britain built many such power grids around the world, so what's written here might apply where you live but there may be differences. However there are differences in terminology and voltages, so please bear that in mind. The term "earth" is often used in Britain to mean "ground" and can be used interchangeably. Some details about the commercial distribution of power in Britain have changed since this article was written.

Lights fantastic

The sight of electricity pylons marching alien-like across the countryside is an all too familiar one, yet in spite of their omnipresence it is easy to overlook the feats of heavy engineering and high technology surrounding us which are responsible for delivering electrical energy to illuminate and warm our homes, cook our food and entertain us, as well as powering our industries.

It is something of a paradox that the microelectronics enthusiast can utilise the very latest in silicon chips to create another technological masterpiece, yet if we are honest, many of us would admit to having only a fleeting knowledge about the electricity supply itself. We leave that sort of thing to electricians. We probably know (we think) that earth is, as its name suggests, connected to earth somewhere along the line, and perhaps the neutral is, er, somehow neutral. We know that the supply is "alternating", but how many have actually stopped to consider what this all really means? Or why it's like that to begin with?

After reading these articles you will know precisely how the electricity supply is generated, distributed and delivered. Although it is written with the UK 230V a.c. 50Hz. supply in mind, note that many similar principles are utilised abroad, so even if you do not reside in the UK you will find a considerable amount in common between the systems outlined here and those found in your own country (some of which are undoubtedly British-built).

The incandescent electric lamp was first produced in 1879 by Joseph Swan in England and Thomas Edison in the USA, and two years later Britain saw the advent of its first public electricity supply . Over the next fifty years some 600 supply undertakings with nearly 500

localised power stations would be created, operating at a variety of frequencies and both a.c. and d.c. voltages. In 1927 the Central Electricity Board (CEB) was appointed by statute, with a view to standardising frequencies, and also to implement an interconnection plan to improve efficiency and reduce waste. The plan involved hooking together a select number of power stations, and was completed in 1938. Later the industry was nationalised in 1948.

Over the last twenty or thirty years the power generation picture in the United Kingdom has been transformed, so to speak, having moved away from the once heavy reliance on Britain's rich supply of coal to a modern multi-fuelled power industry which is clean, efficient and dependable.

Until the early 1990's, power generation was undertaken and controlled by the Central Electricity Generating Board (the CEGB), which was primarily responsible for producing and selling power for onwards transmission to the regional electricity boards by the National Grid, the organisation which "owns the wires". From there it would be distributed to tens of millions of residential and commercial properties.

Privatisation and the arrival of market competition in 1990 introduced radical changes in the way the UK electrical supply market operated. The CEGB gave way to competing power companies - including National Power, PowerGen and the nuclear arm of the industry, British Energy. There are now some 30 or more power producers, many of which are independent or foreign owned power stations, competing for the business of nearly 23 million domestic customers. These and millions of commercial and industrial users are served by fourteen Regional Electricity Companies (RECs). The market for buying and selling electrical power has opened up at all levels, so much so that in the UK it is now possible to buy gas from electricity providers and vice versa.

Over the many decades in which we have enjoyed virtually uninterrupted electrical supplies, the power providers have gained vast experience of the likely demands which will be placed upon them at any one time by their customers. This enables the power distribution companies to plan ahead and allocate daily the various power generation resources that will be available to meet the forecasted demands. Fig. 1 shows how according to National Power various fuel types are available in "layers" to meet this demand, which in the UK totals nearly 70,000 Megawatts (MW) (1999). The graph also shows how the resources are divided amongst various fuel types.

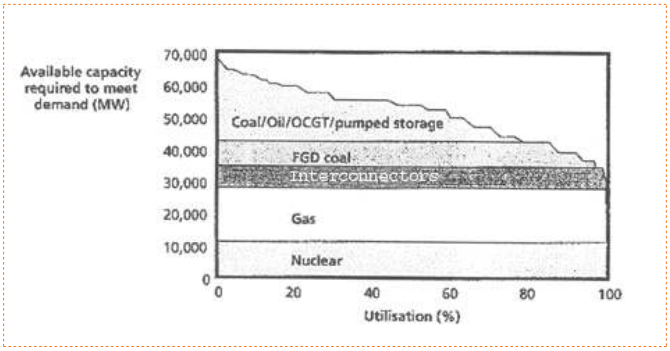

Fig 1 UK Electricity plant portfolio (98/ 99) showing how different sources of power are brought on-stream as demand increases. Nuclear is 'on all the time' whilst coal-oil and pumped storage (hydro) are used to 'top up' the capacity available. *National Power*

Underpinning the country's supply capability are both gas and nuclear fuel sources which produce a constant 30,000MW between them (1999) and form the bedrock of Britain's available capacity. Also providing nearly 5,000MW of capacity are what are termed "interconnectors", which relate to the connections made by the National Grid to both Scotland and France: yes, a certain proportion of our power is imported, though the same wires could be used to export surplus electricity as well. Roughly 2,000MW of interconnected power is available via the Cross-Channel Link, a pair of undersea 45 km long cables completed in 1986.

The rest of the UK's electrical capacity is provided by coal, oil, OCGT (open-cycle gas turbine) and hydro-electric power, noting from Fig. 1 that the capacity of these sources dwindles in terms of utilisation: they form the buffer which is primarily used for the "top up" needed to meet peak surges. For most of the time, we rely on nuclear power, gas-fired power plants and imported electricity (the 'interconnects') which are 100% utilised.

The daily demands for electrical power rise and fall during the day, and the weather and many other events - such as the advertising breaks in favourite TV soaps - can trigger a huge surge in demand when Britons head for the electric kettle. These TV-related surges are known as "TV pick ups". The average Brit. will also decide to turn on the electric lights in the evening only when a commercial break occurs!

It is the function of the National Grid Control Centre, based at Reading, to match the demands placed by its customers with the available capacity and to cope with anticipated TV pick ups. According to National Grid figures (to 1999), the largest recorded TV pick-up of 2,800MW occurred in the World Cup Semi Final in July 1990 (England v. West Germany). To maintain stability the control process may also require electricity production to be reduced when demand falls: the funeral of Princess Diana caused a major drop of 1,000MW in normal power consumption when all daily activity stopped in the UK.

The task of matching supply and demand is called "generation despatch" and involves not only the National Grid being kept posted by data links showing the availability of power from all its suppliers, but also at what price: electricity is bargained in Pounds per MegaWatt Hour and power generation companies have to commit to a price for filling half-hour slots for the 24 hours ahead. This bidding process occurs every morning when the power plants notify the National Grid of their availability and pricing for the day.

As you would expect in a privatised market economy, the "bulk" price charged by generators varies depending on demand. On a typical November day (for example) it could rise from around £33 ($54)

per MegaWatt Hour (MWH) to roughly £45 ($74)/ MWH at peak times of the day - which, incidentally, is at tea time, when demand peaks dramatically at 17:30 hours. By way of comparison, depending on one's location a domestic electrical "unit" costs (at 1999 figures) 6.45 pence (10.6 cents), which equates to œ64.50 or $106.42/ MWH. In 2011 they are nearly double that.

Trends from preceding weeks, months and even years are taken into account as well and forecasts are accurate to within a couple of percentage points. Any event which is forecast to trigger a rise in power demand - say a televised World Cup - is brought into the equation, as are other factors including weather forecasts, seasonal trends and even the day of the week.

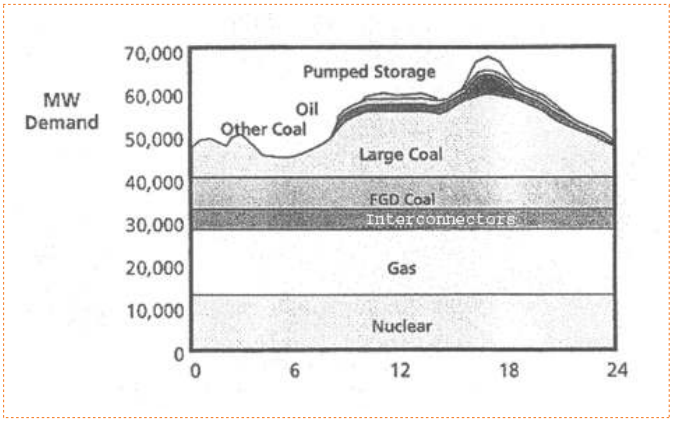

Fig 2 How a 24-hour demand, peaking at 17.30 hours, is met by the electricity industry. *National Power.*

In Fig. 2 above, National Power illustrates how peak demands over a typical 24 hour period are gradually topped up as more plant is brought on stream to cope, culminating with the short-term use of pumped storage (water caverns) to generate hydroelectric power at peak times (around 6 p.m.). Note that nuclear and gas-fired power provides a constant output, and only as demands soar will larger coal and oil-fired stations be brought onto the system to meet peak surges. A "pumped storage" installation in Dinorwig, Wales can also be brought on stream within ten seconds, to cater for daily peaks in demand, and this cushion has helped to reduce the need to have spare generator plant constantly running to meet unanticipated surges in demand, see Fig. 3 below. All power plants are identified in an "order of merit' table which highlights the individual cost of power generated by the various power plants.

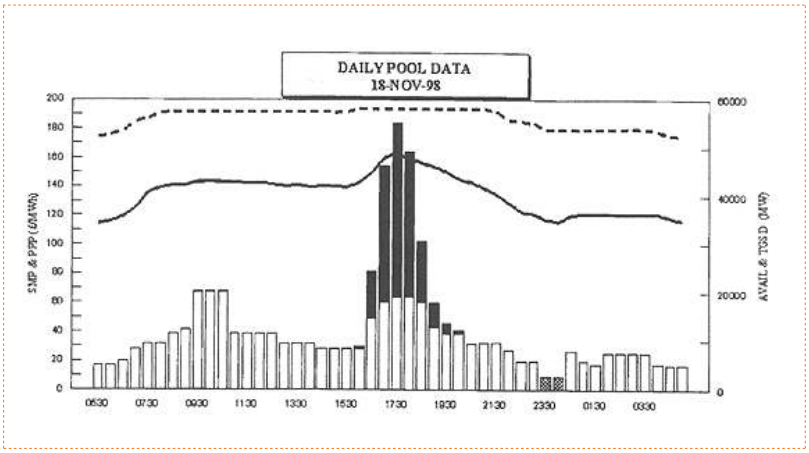

Fig. 3 Daily demands are bought by the National Grid in half-hour blocks from electricity producers. The graph, produced daily, depicts several factors including the purchase price of electricity (1998). *National Power*

Hence there are low merit (high cost) and high merit (low cost) plants which depend on the type of fuel used. In addition, the National Grid will take into account the dynamic parameters of the plant, such as loading rates, and whether the turbines are hot or cold. It can be cheaper to run a more expensive "hot" machine than a cheaper cold machine.

Killingholme "A" CCGT Power Station

In the remaining sections, we'll examine how electrical energy is generated, transmitted and delivered to your home. The feature offers a broad-interest view of both electricity generation as well as distribution, and is designed to offer an insight into electrical power divided in two stages: from gas pipeline to electricity pylon, and then examining how electricity is delivered directly into your home.

In particular we will be looking at one of Britain's newer gas-fired power stations: National Power's Killingholme "A" is situated on the banks of the River Humber. Killingholme "A" was National Power's first gas turbine plant commissioned in 1993.

This 650MW plant runs as a "base load" operation, which means that Killingholme "A" provides a constant output that forms some of the everyday "bread and butter" of the United Kingdom's electrical capacity. Its performance won Killingholme "A" the National Power Availability Prize.

National Power has strong international links and is heavily involved with the export of technological know-how, including the construction and joint operation of power plants in other countries, notably the USA, Europe and China. The power station at Killingholme also has an impressive array of links with local educational and environmental projects, having funded a wide variety of nature conservation drives in association with both local and national authorities. A new fully staffed visitor's centre, an educational garden and close associations which have been carefully nurtured with neighbouring schools and further education help ensure that Killingholme "A" plays an environmentally aware and responsible role in the community.

National Power generously granted the writer unlimited access to the entire power plant and the author is extremely grateful for the abundant levels of assistance which have been provided by Station Manager Keith Ulyett and National Power engineer Richard Power. Both offered much enthusiastic help and hospitality during the preparation of this special feature. The writer has spent several days on-site, including a day during a major outage (overhaul) when several key parts of the power plant were in the process of being stripped down for inspection and maintenance. This was therefore a timely opportunity to delve into the inner workings of a power plant.

The power station subsequently changed hands and at the time of writing (Feb. 2011) is now operated by Centrica Energy.

Next, transformer and power transmission basics are explored.

On to Part 2

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Part 2: The problem of electrical power distribution: transformer basics explained.

From Pipelines to Pylons

Killingholme "A" is a gas-fired power station. Why gas? When the UK electricity marketplace was forcibly opened up to competition in 1990, the switch from coal to gas became all the rage in what became known as "the dash for gas". Whilst coal-fired power stations battled with the logistics of being constantly fed by trainloads of cheap coal, not to mention the enormous cost of upgrading plant to meet pollution targets, one thing which is still in plentiful supply is natural gas, provided from rigs in the nearby North Sea.

Several new power stations were therefore constructed in this locality, some being independently owned and others being built by both National Power and PowerGen. A gas fired power station is far cheaper and much more compact to build than a comparable coal-fired station, producing less carbon dioxide and virtually non-existent levels of sulphur dioxide, the compound which gives rise to acid rain.

Since the region's petro-chemical industries are handsomely served by major underground gas pipelines, then if there is an immediate need to construct power plants quickly and efficiently, gas is an obvious choice for fuel. Furthermore, by purchasing "off the shelf" power plant rather than attempting to design everything in-house, National Power enjoyed a greater choice of supplier and shorter lead times during the dash for gas.

Before we delve under the bonnet of Killingholme "A", it is worth relating a few fairly fundamental principles of electricity, which actually have a most profound impact on the way in which electricity must be distributed. When scaled up to the level of national electricity distribution, it soon becomes apparent why milliohms suddenly matter and kilovolts really count. A set of rules different from those which the microelectronics enthusiast usually concentrates on, exists in the field of generating and transmitting power and even the hardened electronics enthusiast cannot help being filled with awe when confronted with a 400,000V transformer or a 10,000 Amp circuit breaker!

Long distance transport

When electric current needs to be conducted over large distances (e.g. dozens of miles), several issues arise. The primary problem is that of unwanted electrical resistance, which results in heating effects (I^2R) that are proportional to the *square* of the current: if a length of wire has a known resistance, then doubling the current will *quadruple* the power dissipated in the form of heat. Wasting power in this way is inefficient and equates directly to increased costs, so it is highly desirable to reduce these heating effects.

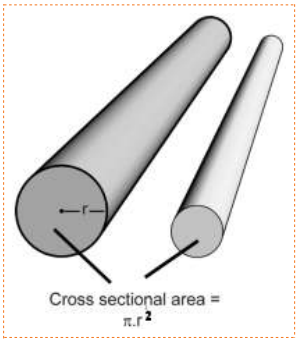

Fig. 4 The resistance of a conductor is related to the cross-sectional area (CSA): the smaller the diameter, the higher the resistance.

Since a conductor's resistance is directly proportional to its cross-sectional area, then in order to overcome the resistance inherent in long-distance power lines, the cross-sectional area of a conductor could obviously be increased (Fig. 4, left). This will reduce its resistance to current but will obviously increase costs because of the greater volume of conductor needed.

The solution is to step up the voltages being transmitted to much greater levels - tens or hundreds of thousands of volts. The higher the operating voltage, the lower the current, then the smaller the cross sectional area of power lines can be, to deliver the same level of power. This saves material costs, but then introduces yet another factor: the cost of insulating the environment from these extremely high voltages.

Transmitting electrical power economically around the country, then, is a finely-calculated compromise between several factors if power is to be transmitted efficiently and also at the most economical price: too thin a wire and the I^2R heating losses become unacceptable; however too thick a wire results in a formidably high material cost; lastly, too high a voltage implies a greater cost in insulation and other technologies. It is also cheaper to suspend lengthy cables overhead than bury them underground (where heat dissipation and insulation become a problem).

Fig. 5 below shows the economics of this simple relationship in a graph. Incidentally, in case you've always wondered, those power transmission lines found hanging from pylons are usually made of aluminium alloy.

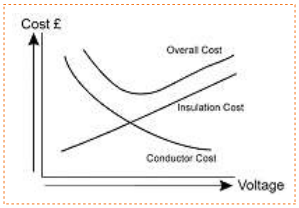

Fig. 5 Illustrating the simple relationship between the cost of providing a supply versus the voltage and insulator costs.

Transformation

In order to transmit electrical power over considerable distances, great reliance is made on the **transformer**. Every reader will be familiar with a transformer, and exactly the same principle of "stepping up" or "stepping down" an alternating voltage is used throughout the power distribution network. It would of course not be at all feasible to route high d.c. voltages on overhead or underground cables due to the magnitudes of current involved. Imagine trying to transport 80 amperes per house at 230V a.c. [UK] and you can imagine that the conductors would have to be impossibly thick - several metres in diameter - to transmit such power levels to an entire town. (The Cross Channel Link does however run at d.c., as a way of separating the English and French power transmission systems: converter stations at both ends then produce alternating currents for onwards transmission.)

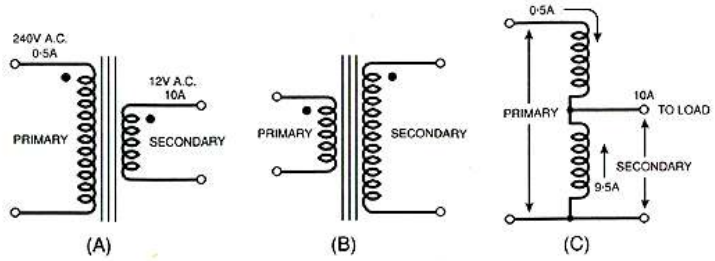

Fig. 6(a) Step-down transformer symbol. The "spot" indicates the direction (start/ finish) of a winding (b) Step-up transformer (c) Auto-transformer

The main function of a transformer is of course to step an alternating voltage up or down. Fig. 6 (above) shows the familiar circuit symbol of a typical mains transformer that would be found in a constructional project or consumer equipment. It consists of two or more coils wound on a laminated steel core. The primary winding can be considered as the input and the output is taken from the transformer's secondary winding. It is also often important to know the direction or phase of the windings: in electronics a spot-mark may sometimes be used to identify one end of each winding, or they may be labelled as, say, 230V [UK] and 0V on the primary, and 12V and 0V on the secondary winding.

Whether the transformer will increase (step up) the alternating voltage applied to the primary, or reduce it (step down) depends on the ratio of the number of turns of both windings. Regardless of which type the transformer actually is, at a simple level it can be assumed that the power (V x I) across the primary is roughly the same as that across the secondary. A step-down transformer (used in ordinary mains adapters for example) might have a 230V a.c. primary and, say, a 12V a.c. secondary. The turns ratio is therefore approximately 20:1. If the voltage across the primary is Vp and that across the secondary is Vs, then Vp/ Vs = Np/ Ns, where Np and Ns are the numbers of turns in the primary and secondary windings. As shown in Fig. 6a, the primary power (230V x 0.5A watts) is the same as the secondary (12V x 10A).

Therefore, the primary of a typical step-down mains transformer is at a **higher voltage** but carries a **lower current** than the secondary. The power (voltage x current) is the **same** in both windings. Importantly, this means that **thin wire** can be used for the high voltage side. However the secondary circuit operates at a **lower** voltage but a **much higher** current. A thicker gauge wire is needed on the secondary, to cope with these higher currents.

The **auto-transformer** can be considered as a single winding with a tapping made somewhere along its length. One terminal is therefore common to both the primary and the secondary. Scaled-down versions are used in workshops or laboratories, and have a moving contact which can be rotated to produce a variable a.c. voltage.

A key advantage of the auto transformer is that the secondary winding does not "see" all of the secondary current, which means that less copper wire is needed when compared with the classic "double wound" transformers of Fig. 6a and 6b. The use of auto transformers is quite widespread in the power industry, and these are classed as voltage transformers (VTs). One disadvantage to be remembered at consumer level is that they do not provide complete safety isolation from the mains.

A third type of transformer is also utilised in the power generation industry, in order that current flow can be measured. Since it would be impractical to directly measure the many kilo-amperes which can flow in certain parts of the electricity generation system, a **current transformer** (CT) is used to enable readings or measurements to be taken. A "doughnut" or toroidal-shaped secondary coil can be placed over a conductor which passes through the centre; the current-carrying conductor can then be deemed to be the "primary" of a current transformer whose secondary current can then be directly measured, or used in conjunction with protection equipment.

A series of CTs and VTs are used to constantly monitor the circuits of the power station; an enormous voltage transformer with a 15.75kV primary is positioned directly to measure the output of each generators. Transformers are also instrumental (literally) in alerting the power generation and distribution companies to any losses which may occur further downstream in the electrical grid.

In the power generation industry, thin wires at high voltages are used to transport power economically over great distances. Transformers will then be utilised at sub-stations in order to step down the voltages to something more appropriate, using thicker, more expensive wires to carry these higher "secondary" currents. We will look at the aspects of three phase power transmission and distribution later on.

Next, the basics of gas turbines and power generation are described along with unique photos taken during a shut-down.

On to Part 3

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Part 3: How a CCGT power station works. Turbines introduced.

Talking turbines

Having introduced these fundamental electrical aspects, let's return to our power station at Killingholme "A" and explore in more detail where electrical power actually comes from. Our adopted power station is fuelled by gas brought in from the North Sea and transported in an underground pipeline. The actual compound area where the natural gas arrives contains just a little surface pipework and is remarkably ordinary-looking, all things considered!

National Power's Killingholme "A" plant is known as a Combined Cycle Gas Turbine (CCGT) plant, which utilises gas turbines to drive electrical generators. In a CCGT plant, surplus heat created by the gas turbines is further utilised to produce steam. This drives a steam turbine to generate yet more electricity. The steam turbine is driven by "waste" heat from the gas turbine which results in a vast improvement in overall power plant efficiency. A diagram explaining the overall process is shown in Fig. 7. **| Click here to enlarge |**

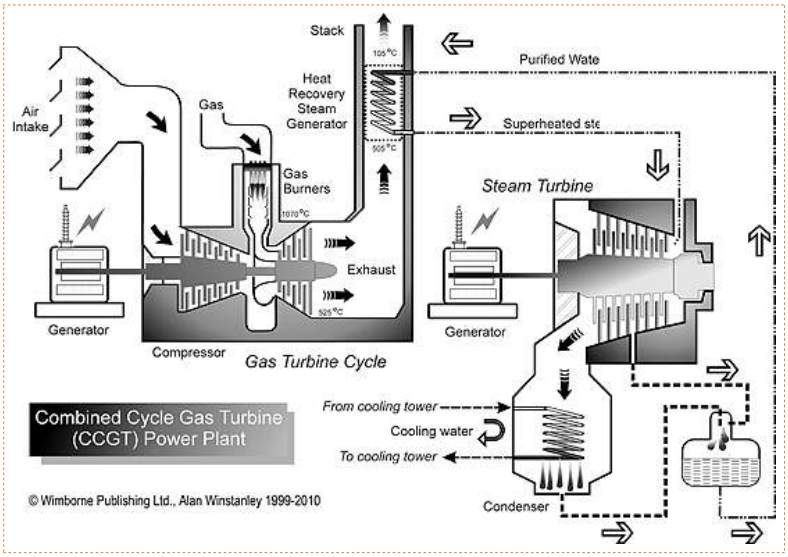

Fig. 7 Schematic representation of a Combined Cycle Gas Turbine (CCGT) power plant. A gas turbine drives a generator and the exhaust is used to heat purified water and generate superheated steam. A steam turbine is then used to generate more electricity. A cooling tower enables the steam to be condensed back into purified water. See text for more details. (*Adapted from original ABB material.*) © Copyright.

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A 3D cutaway illustration of this type of CCGT power station is available, with key to identify major areas. (Courtesy National Power.)

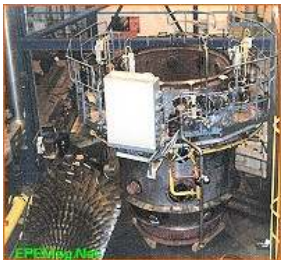
| Click here to enlarge |

Large grilles on the front of the building are actually air inlets for the gas turbines. Each turbine requires about half a tonne of air per second, so atmospheric air is sucked in and compressed by many stages of spinning blades located at the front of each turbine shaft.

The resultant high pressure air is "swirled" along with natural gas within a combustion unit fitted on top of the turbine. Within this "silo combustor" are 54 separate burners which act as gas jets. The burning mixture reaches temperatures of over 1,000°C.

Photographed during shut-down, a silo combustor bank of 54 gas turbine burners undergoing maintenance.

The other two silos removed from the gas turbines, during a shutdown.



A gas turbine during inspection, with the stripped-out turbine compressor blades nearby.

A gas turbine being inspected and serviced. The combustor bank (above) fits where the technician is working.

The gas turbine opened up, with the turbine and compressor blades removed.

The turbine blade assembly completely removed. Note the size of the technicians for comparison.

The steam turbine under maintenance.

The rotor of the steam turbine.

Steam turbine blades

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In the same way that in an internal combustion engine the petrol/ air mixture ignites and expands to force down a piston, the resulting continuous expanding force from the burning gas mixture passes over and spins the gas turbine blades. These drive a generator through a shaft, which also drives the air compressor blades.

In A Spin

Looking at the generator in more detail, it is much easier to use stationary coils rather than attempt to rotate them, so the electrical generator consists of a comparatively small rotating electromagnet (the rotor) surrounded by a series of large fixed coils (stators) in which electrical energy is induced. They output up to 145 megawatts at 15.75kV. The Killingholme power plant has three gas-turbine driven generators plus a steam turbine as well. We look in greater detail at what happens to the generator's output later on.

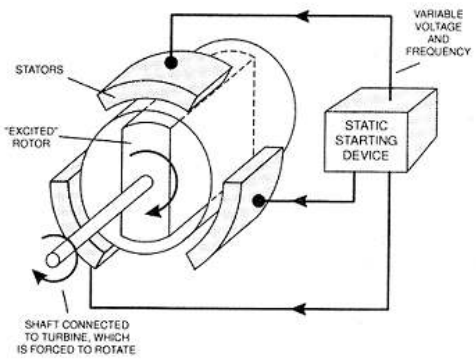

Fig. 8 A static starting device (SSD) is used to convert a generator into a "starter motor" (consuming 4MW). This causes the rotor to spin, which in turn, turns over the turbine.

To start the system, a "static starting device" (SSD) is utilised (Fig. 8) in which the generator is actually used *in reverse*, as a starter motor (consuming some four megawatts of power in the process!). Acting as an induction motor, the stator is energised by a variable voltage, variable frequency a.c. supply; the generator's inner rotating windings are powered with a d.c. current (called "exciting" the rotor) through brushes and moving contacts called sliprings. Variations on this theme include the use of rectified a.c. exciters, or brushless excitement systems which use a.c. generators and eliminate the need for sliprings altogether.

At a certain point, the rotor's magnetic field "locks" together with the field created in the stator, and the generator (still behaving as a motor) achieves *synchronous operation*: the two magnetic fields are synchronised with each other. Then the supply to the stator is increased in frequency, which causes the rotor to be dragged along at a higher rotational speed. Thus the shaft is forced to rotate.

At 2,500 r.p.m. the gas turbine manages to sustain itself and the SSD is disabled, the turbine's compressor blades now spinning fast enough to maintain the combustion process. The rotor's speed will then be automatically governed up to the critical speed of 3,000 r.p.m. and electricity can then be generated. To give you an idea of scale, the rotor shaft typically weighs 100 tonnes and is machined from one solid casting. It will become apparent later why a speed of 3,000 r.p.m. is significant to electricity users!

Power Bonus

The power generation process does not stop at the gas turbine. Having passed over the spinning gas turbine blades, the exhaust gases still have a temperature of some 500°C. Rather than letting this go to waste, in a CCGT system this is put to further use in a heat exchange boiler or "heat recovery steam generator" (HRSG).

Each heat exchanger contains over 100 kilometres of finned tubing, which functions like a heatsink in reverse: the hot exhaust gas is used to heat water which is pumped through the core of the heat exchanger. The water turns to steam. The chimney-like structures or stacks vent exhaust from the gas turbines after it's passed through the heat exchanger.

The "bonus" superheated steam produced by the heat recovery steam generators is completely free of water vapour and is invisible, and is piped to a steam turbine to drive a fourth 227 MW generator. The steam exhausted from this turbine is condensed by passing it over a bank of titanium tubing through which cooling water is pumped (originally extracted from the nearby River Humber). The resultant condensed water is extremely pure and is recycled for use back in the heat recovery boilers, to be heated back into steam again.

Lastly, the cooling water that has now been heated by the steam turbine's condenser, has to be cooled down and this is achieved in a cooling tower, where it is spraying it over a large surface area in the face of a rising column of air. The cooled water is then pumped back to the steam turbine's condenser for re-use. Sometimes water vapour is produced during this cooling-down process which will be seen billowing from power station cooling towers. As readers will know, coal-fired power stations rely on steam turbines and require much larger cooling towers for reducing the temperature of their condenser cooling water.

In a CCGT plant, it can be seen that much use is made of recycling and utilising the by-products of the combined cycle process. Exhaust heat from the gas turbine is used to create steam which generates "bonus" power with a steam turbine; the steam is then condensed back into water for further use in the heat exchanger, where it is re-heated by the gas turbine's exhaust to make more steam. The heat recovery cycle has a phenomenal effect on throughput: it increases the overall efficiency of the plant from approximately 33% to 50% or so.

In Part Four, the fundamentals of three-phase electricity are explored and we delve more deeply into our adopted CCGT power station, along with more photos.

On to Part 4

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The story of Electricity Generation from pipelines to pylons

| Introduction | Part 1 | Part 2 | Part 3 | Part 4 | Part 5 | Part 6 |

Part 4: Generators, frequency control, pylons, three phase distribution

Let's return to the process of electrical power generation and examine it in greater detail. Previously it was mentioned that each of the three gas turbines in our adopted power station drives an a.c. generator; a steam turbine drives a fourth. A power generator consists of an electromagnet (*rotor*) which is rotated directly by the turbine shaft. Each revolution of the turbine turns over the generator once. The rotor is surrounded by *stator* coils in which the moving rotor induces a voltage that will ultimately be delivered to the consumer.

The generator's electromagnetic rotor is d.c. controlled and since the rotor's currents are lower than those in the stator coils, it is easier to engineer the moving contacts (the sliprings and brushgear) which are needed to power or "excite" the rotor.

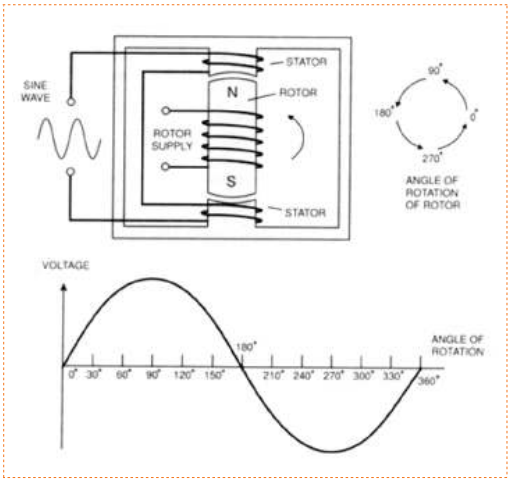


Fig. 9 A sinewave is produced in the stator coil by the spinning rotor. The voltage level depends on the rotor's angle of rotation, and it reverses polarity every 180°

If a simple two-pole rotor is used, this could be likened to a simple electromagnet having a North and a South Pole. The spinning electromagnet induces a voltage in the stator coil each time it passes by, and the stator voltage will therefore reverse polarity with every half-revolution of the rotor. The voltage level generated in the stator coil depends on how far the rotor has travelled during one revolution (its rotational angle).

Figure 9 (above) shows why a sine wave is generated. If the voltage is plotted against the angle of rotation, then the stator voltage peaks at 90 degrees of rotation, falls back to zero after 180 degrees and then peaks in the reverse direction at 270 degrees before completing a full cycle at 360 degrees. Because it delivers **alternating voltage**, this generator is more correctly called an **alternator**. (A **dynamo** produces a **d.c.** voltage instead.)

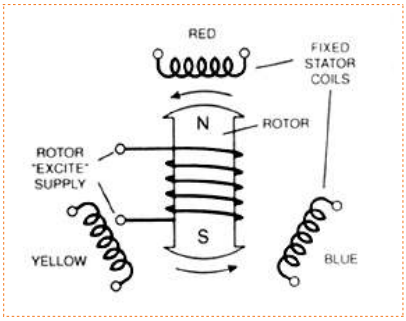


Fig. 10 A three-phase generator has three fixed stator windings spaced 120° apart around a spinning rotor, which itself is an electromagnet having North and South poles.

To get the most out of each revolution of the rotor, several stator coils are deployed so that multiple sine wave voltages are generated per revolution. In fact three coils are spaced at 120° apart (see Fig. 10) and the coils are designated by a colour code familiar to every electrician: they are **red**, **yellow** and **blue**. The generator windings produce 15.75kV (15,750V) between the phases.

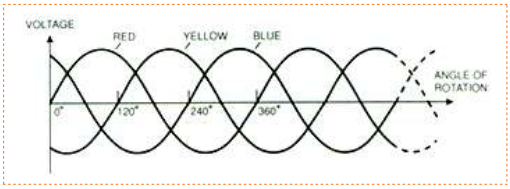


Fig. 11 Three phase electricity generated by the alternator of Fig. 10. The three phases are 120° apart.

Obviously each stator voltage will rise and fall as the rotor passes by, and the overall result can be plotted as a three-phase voltage in Fig. 11. It can be seen that the voltage in the blue phase is 120° behind the yellow phase, which lags 120° behind the red phase.

By increasing the rotor's speed, the voltages induced in the stator coils will occur more frequently, although the three phases will always be 120° apart. This simplified approach assumes that there is only one pair of magnetic poles on the spinning rotor as shown.

If the rotor spins once per second, then the a.c. voltage generated in each phase will have a frequency of 1 Hertz (1 Hz.), changing polarity every half second. The frequency of the generated voltage is calculated by:

Frequency in Hertz = (no. of pairs of poles x revs. per minute) / 60

From the above formula, a generator with one pair of poles as illustrated must rotate at **3,000 r.p.m.** to produce electricity at **50 Hertz**, which is the declared system frequency [UK].

The statutory limits defined in the Electricity Supply Regulations of 1937 are 50 Hz. +/- 1% (i.e. 49.5 - 50.5 Hz) although the National Grid (NGC) strives for a variation of no more than 0.1% as best practice. The turbines operate at this speed, 24 hours a day for months on end.

In the mid 1920's before electrical power generation was standardised in the UK, several frequencies could be used - anything from what was probably a migraine-inducing 25 Hz and must have been murder to read by, all the way up to 80 Hz. The Electricity Supply Act of 1926 resulted in a standardisation of supply frequency across Great Britain, at 50 Hz., although in the USA and elsewhere the supply has been set at 60Hz.

In fact most generators tend to have two poles although certain types e.g. hydro-electric generators may have four or more poles. This allows for a slower rotor speed of 1,500 r.p.m for a four pole machine which is more appropriate for the medium involved, whilst still generating a 50Hz sine wave.

Frequency Control

The actual method of controlling the supply frequency ultimately boils down to speeding up or slowing down all the generators on the system, by increasing or decreasing their load. The frequency of the voltage is the power station's ultimate yardstick of quality, and frequency itself plays a much more fundamental role in the country's entire electricity system than may generally be realised. Great effort is made to maintain this value and to eliminate cumulative errors in the consumer's supply, which might otherwise affect electric clocks, time switches, audio equipment etc., and any minor change in frequency is compensated for later on, in order to enable frequency-sensitive equipment to catch up (or slow down).

All power plants interconnected by the National Grid can be considered as part of an enormous "pool" of electricity hooked together on an "infinite busbar", which runs at a set frequency. Every power station thus connected operates at this frequency.

If at this time a small isolated power station was not connected to the busbar, but was then hooked in later, the frequency of the existing "pool" would easily dominate the generator of the newly-connected power plant. The net result is that all parts of an interconnected system operate at the same frequency.

The operating frequency of the rest of the grid is thus physically applied to an individual generator, in what is effectively a contest of wills. Since a generator's stator is synchronised to its rotor (and turbine shaft), it is necessary to ensure that a gas turbine runs at a speed which enables the generator's frequency to be matched to the rest of the grid. Hence the challenge is to supply just enough fuel to the turbines to ensure that the generator runs at the prevailing system frequency adopted by the rest of the grid.

Any increase in the fuel supply will not necessarily cause the turbine to run any faster, because the generator is already synchronised or locked to the frequency of the grid: instead the turbine will simply be "loaded", which is undesirable.

If the overall amount of generated power is insufficient to meet the demands placed on the system by consumers, then every turbine/ generator on that system will tend to slow down because insufficient input energy is being supplied. Hence the frequency would start to fall.

The system frequency can therefore be best controlled by ensuring that the generator's MW output constantly matches the consumer MW demand. It is ultimately the demand placed on a generator by the rest of the system which determines whether a generator speeds up or slows down. This, in turn, contributes to the quality of the frequency of the system.

The best analogy of this is to consider a car which is being driven at a fixed speed. If the car encounters a hill it will slow down, making it necessary to open the throttle to maintain engine speed. If the hill levels out, the throttle can be closed again. If it goes downhill, the engine can be used as a brake to slow the car.

A power station may be requested by the National Grid Control Centre to run in a "frequency insensitive" mode, meaning that the power plant simply runs at a fixed load irrespective of frequency. Conversely, in "frequency-sensitive" mode, the plant will be expected to operate at an automatically-variable load at a particular target frequency which is being enforced at the time. This compensates for variations in the consumer demand and whether the system frequency is starting to rise or fall as a consequence.

The other key parameter is of course **voltage**. For consumers, the statutory limits on their 230V [UK] supply is +/- 6%. Unlike the system frequency, the voltage levels can vary in different parts of the transmission system. The voltage output of a generator is directly related to the rotor voltage - i.e. the excitation voltage, which is controlled by a complex automatic voltage regulation (AVR) system. Every aspect of the generator and the turbine's performance is constantly monitored by the power plant's fully computerised control room.

Onward transmission

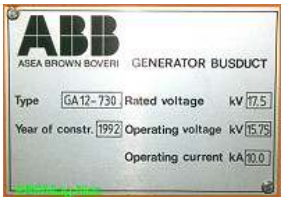
The next part of the electricity generation process relates to the way in which the power generated in the stator coils is transmitted to the user. Typically, the generator outputs 15.75kV and is rated for more than two hundred megawatts.

The three phases - red, yellow and blue - are carried outdoors from the generator using large ducts which resemble pipelines. These pipes are pressurised in order to prevent corrosion or water ingress. The ducts are also colour coded to identify the phases, and this same theme is used all the way through to the end-user's premises.

The power station's main circuit breaker enclosure. Ducts are lightly pressurised to prevent ingress of water etc.

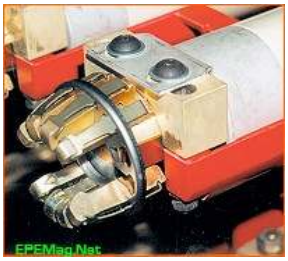
End-on view of the main circuit breaker housing - note the colour coded dots for each phase. They start here!

A circuit breaker 'bus duct' filled with a compound called SF6 (sulphur hexafluoride) to suppress arcing.



Not your average toggle switch rating...

High voltage circuit breaker contact bank



Circuit breaker contact (close-up)

One major problem is, how to actually switch such high magnitudes of voltage? Since these extremely high potential voltages can arc across considerable distances (see the section entitled "Leaps and Volts"), one can image the nightmarish problems of trying to switch many thousands of volts. The switchgear concerned must be able to withstand not only their full loads but six-fold overloads which occur when motors are starting; they must be capable of carrying or interrupting fault currents and must also cope with 17,500 Volts peak across the contact terminals. Evidently we are not talking 1/4" toggle switches here!

The solution lies in the use of special gas-filled circuit breakers. These are spring-loaded and motor driven and are designed to quench the high tension arc which develops between opening contacts. The compound sulphur hexafluoride (SF6) is used which is 6 times less conductive than air. Earlier types used oil-filled contacts or compressed air to snuff out the arc.

^ The three 3-phase lightly pressurised ducts leave the building and are connected to three 400kV transformers outdoors.

The 15.75kV (phase-to-phase) generator voltages are stepped up to 400kV by an external transformer - one per generator - for onwards transmission to the National Grid.

There are yet more amazing facts waiting to be "unearthed". Many readers will be aware that large transformers are oil-cooled in order to aid heat dissipation. In the largest types, oil is circulated by pumps and heat will be exchanged with a water-filled coolant circuit. The author was intrigued by several small instruments on these transformers: one small device - a **Hydran** - measures the level of hydrogen which accumulates in the oil.

The bank of three 400kV transformers outdoors

A single 400kV oil-cooled transformer

A "Hydran" detects the early presence of hydrogen gas in the transformer's cooling oil, warning of a developing fault.

A Buchholz relay mounted on each transformer detects any dangerous build-up of gases in the oil (e.g. due to a fault), and acts as a safety switch.

This digital counter displays the number of times (20) the transformer's been hit by lightning! Unfortunately the readout was obscured by the railings.

The 400kV transformer output is then switched by the open-air Banking Compound - the air here is full of buzzes and crackles.

In the event of a transformer internal failure (e.g. winding shorts, or contacts starting to burn out), hydrogen is one of the first gases to be produced, so by using a Hydran to test for this gas any trends can be spotted at an early stage.

A device known as a **Buchholz relay** is used as an automatic switch that responds to increasing levels of gas build-up in the oil. More accurate tests of oil samples are also undertaken by National Power and other gases such as acetylene can be measured over, say, a month and a good estimate made of the nature of an internal fault. Ultimately the oil can be drained and then the fault can be repaired.

Also worth mentioning is a small digital counter on the transformer's perimeter steel fence. It displayed "20": when this item was queried, the author was cheerfully told that this meant the transformer had been hit by lightning twenty times..... Oh, er, OK...

The Banking Compund is designed to switch the ultra high tension voltages generated by the power station: it's the stations multi-way on-off switch. An instrumentation building is nearby. Current transformers (CTs) monitor the output.

Note the open contacts mounted in mid-air - they rotate to connect the supplies on busbars.

An isolated area called the "*banking compound*" adjacent to the main power transformers contains an array of insulators and busbar isolating switches, which in my photos are open-circuit: on one of the author's visits, the entire system had been shut down for maintenance purposes and this is done by the physical act of rotating large isolators to break the circuit. (See Leaps and Volts page for a video.)

Usually though, when Killingholme "A" in full swing, the crackle of high tension voltages fills the air around this bus-bar area and you can almost feel the high tension above you. The same compound contains current transformers which monitors the station's output.

^ The power station's 400kV output is fed underground to a sub-station, from where it rises on pylons to be distributed around to the countryside. Note the "terminal tower", a special pylon that routes the overhead wires in the right direction. The stack on the left belongs to a neighbouring 1,000MW power station.

From there, the 400kV supply is fed underground to a nearby sub-station, before finding its way on to a transmission tower, the very first in a series of many hundreds which will be used to distribute the power around the countryside. Some of these feature in my photographs.

It's... Super Grid!

The enormous 400kV supply - known as the Super Grid (275kV in certain regions) will be found hanging off the largest of pylons (as a general rule, the larger the pylon, and the bigger the insulators , then the higher the voltage being carried). The same pylons also carry Super Grid voltages generated by other neighbouring power stations. If ever one wondered why there are three arms to each side of a pylon, the answer is now obvious: there is one wire per phase, with each tower usually carrying two circuits. Sometimes, wires may be electrically paralleled, which will be witnessed by two or more wires running next to each other to share the load. (See my separate feature, "Electricity Pylons").

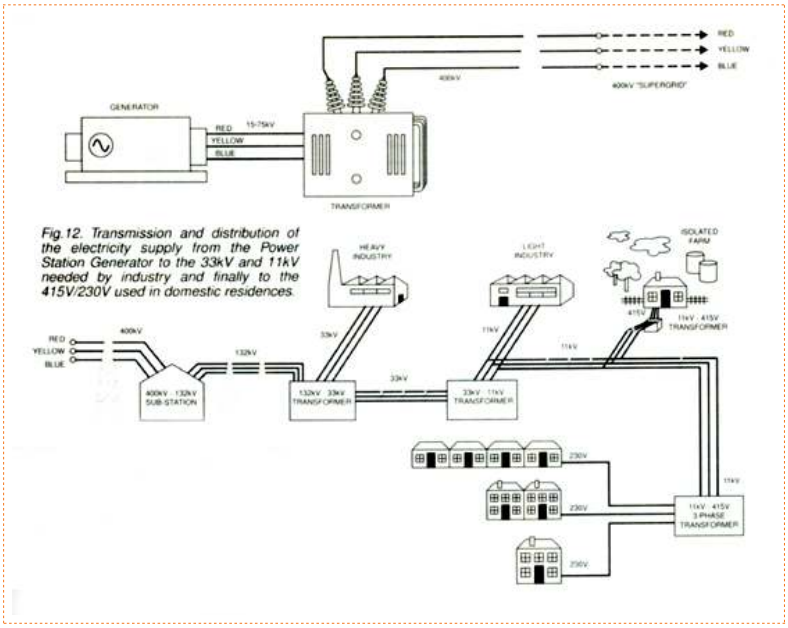


Fig.12. Transmission and distribution of the electricity supply from the Power Station Generator to the 33kV and 11kV needed by industry and finally to the 415V/230V used in domestic residences.

Fig. 12 The transmission and distribution of the electricity supply from the power station generator to the 33kV and 11kV needed by industry, and finally to the 415V / 230V used in domestic residences (UK).

| Click here to enlarge |

These extremely high voltages are transmitted over considerable distances to regional sub-stations, where they are progressively stepped down by transformers (auto transformers are usually used on the Super Grid). Figure 12 outlines the structure of the electricity distribution system. **| Click here to enlarge |**

In the UK, the Super Grid is first reduced to a 132kV grid system and then 33kV for use by industrial estates and heavy industries. Light industries may require an 11kV supply which is provided by a sub-station. The final reduction occurs in residential areas, where the 11kV is stepped down to three-phase 415V from which single phase 230V a.c. is produced, as we shall see later. (Officially, UK domestic supplies have been "harmonised" at 230V for reasons best understood by the European Union. In reality, UK supplies are 240V just as they always have been, evidenced by taking a quick measurement of 247V!).

In many cases, the customer (say, a farm in a remote location) will have his own 11kV-to-415V step-down transformer and these are a common site in the English countryside, perched on top of a wooden pole. Actually, the one in my photo had replaced one that had caught fire and set the pole and the field alight: firefighters refused to go anywhere near it until the power generation board isolated the entire circuit.

It is the job of the Regional Electricity Boards to distribute power to commercial and residential properties, and sub-stations with suitable step-down transformers will be used as appropriate: from Fig. 12 it can be seen how the Super Grid voltage is systematically stepped-down as the end users' locality is approached. **| Click here to enlarge |**

In Part 5 the use of star and delta conenctions are explained, the neutral and ground (earth) are explored and we show how electricity is distributed to the home.

On to Part 5

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The story of Electricity Generation from pipelines to pylons

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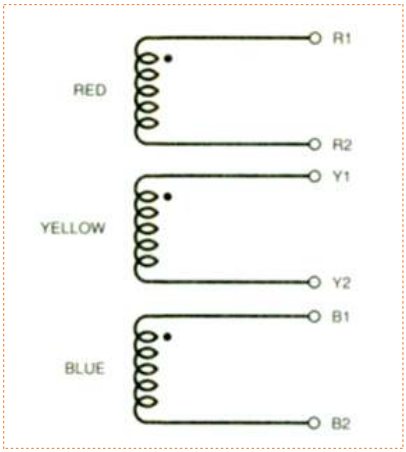
Part 5: Neutral and Ground; Delta and Star connections.

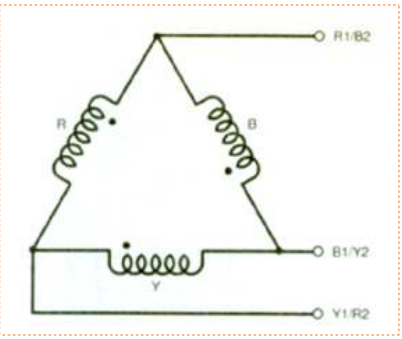
Let's now look at some three-phase basics. The red, yellow and blue colour code of the 3-phase system applies from the generator outputs of Killingholme "A" all the way through to the 415V transformers found near the end-user.



< Fig. 13a - Three separate windings need 6 wires to connect.

You might think that the use of three very large stator coils to generate three-phase power would demand *six* wires to conduct the current, as shown in Fig. 13a (left), noting the direction of each winding (or the start/ end of the coil) is denoted with a spot symbol.

After all, a single-phase load requires two supply wires to power it: normally known as live (or "hot) and neutral, though the live is more correctly called the *line* voltage.



< Fig. 13b A Delta connection uses three wires as shown.

However a three-phase system is able to transmit three times the power of a single phase design without the need for six wires, simply by arranging the windings as shown in Fig. 13b.

The start of one winding is connected to the end of another, and the three connections are brought out as shown. Because of its shape, this "triangular" configuration is known as a **delta** (or mesh) connection.

Three wires can be used to transmit a three phase supply in this way.

The alternative arrangement of windings shown in Fig. 14a below is called a **star** connection, (or Y connection) and the central connection is called the "star point" (or the neutral point). This is used universally by National Power on the output of all of its generators. The star point itself, to look at, is just an overhead box with three ducts entering:

By commoning the "starts" of each phase together as shown, a four wire-system (three "line" voltages or phases, and a neutral conductor) can be created. The net current flowing into or out of the star point is zero because each phase uses the other two for its return path. The net voltage is also zero at the star point.

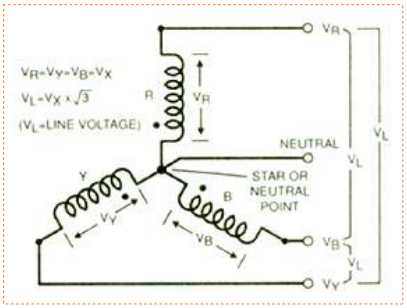


Fig. 14a. A star (or "Y") connection with the star being the neutral point. Compare with the Delta connection, Fig. 13b above.

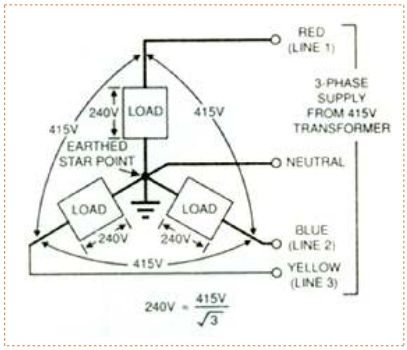


Fig. 14b A 3-phase system has 415V between phases, and produces 240V across each "load" connected to the star point,. Since the net voltage is zero in the 3-phase system, the star point is neutral or zero volts. It is connected to the ground.

The principles of delta and star circuits are relevant throughout the power transmission network, all the way down to the 230V supply delivered to a home. In the case of a three-phase 415V supply, Fig. 14b, a **step-down transformer** is used (not shown) which has a 11kV delta primary and a star-wired 415V secondary. Therefore 415V is supplied between any two lines as shown.

A voltage of 415V / √3 = 230V will be developed across a "load" placed between the star point and a single phase. This is precisely how a domestic 230V is derived - connected to the star/ neutral point and any of the 415V phases.

On Neutral Ground

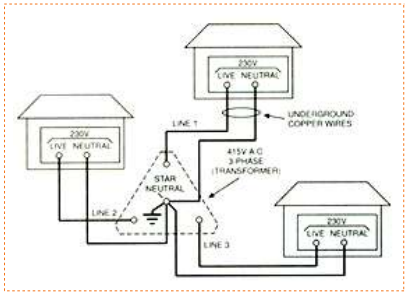
Having outlined the overall process of power generation, let's explore the need for a **neutral** wire, and also the requirement for **earthing**.

In order to provide a 230V domestic supply from a 415V three phase supply, the "live" 230V wire is taken from one of the transformer's 415V phases and the neutral is taken from the star point. The star or neutral point is also physically connected to the earth at the transformer, as depicted by the earth symbol in Fig. 14b, for safety reasons which will become apparent later.

In a typical residential installation, the three 230V supplies which are provided by a 415V three-phase transformer are evenly distributed to balance the load on the transformer. This is achieved by, say, connecting every third house to the same phase. A whole street of small 2-3 bedroom houses may have one phase whilst a small development of much larger houses - which will demand more power - might use a different phase to try to balance the loading, and so on.

A significant side effect of this arrangement is that neighbouring premises, whilst each enjoying a 230V supply, may have a potential of 415V between their respective live supplies: it can be seen in Fig. 14b how 415V exists between any two phases or lines.

The voltage between separate 'live' wires on different phases is 415V (UK). Therefore the 230V "live" of one residence should never be used in neighbouring installations because they might not share the same phase.



^ Fig. 15 How a 415V 3-phase system is utilised to distribute 230V to the end user. Each house uses one phase in order to balance the loading on the sub-station (refer to Fig. 14b)

Note especially each house has a Live and Neutral, and see how the Star point (neutral) is also grounded or earthed.

< A typical 3 phase transformer distributing the mains supply to residences nearby. This one had previously burned out, setting fire to the wooden pole and then the field below!

In Fig. 15 each "house" is connected to one of the 3-phase "lines", and the diagram shows how all three houses have their neutral wires commoned together to the star/ neutral point of the 415V supply transformer. That same star point is connected to the earth.

Quite how an individual house will be connected in practice depends on several factors, but if an underground supply is taken to the property, then usually a 230V supply is routed there through an armoured cable, see photo. The steel armour is wired as a "protective earth" and connects the house earth system to the earthed star / neutral point of the local 415V transformer.

^ Armoured cable with protective earth and cable gland termination

At the consumer's property, the steel wires in the armoured braid are inherently in contact with a brass cable gland/ strain relief. As the brass component is earthed, then anything it's bolted will be earthed as well. This completes a good quality metal earthing connection between the domestic earth system and the star/ neutral point of the 415V transformer. All exposed domestic copper water pipes and other metalwork which could become live through an insulation or wiring fault, are hardwired together by "**equipotential bonding**". This ensures that no single route to earth will be more electrically resistant to a fault current than any other.

Incidentally, the consumer's neutral may also be directly connected to an earth stake at their incoming supply, but usually this only occurs if the existing earth connection path is found to be inadequate, or if no earth has been provided at all by the electricity supply authority. Oother variations of house wiring are defined in the UK's IEE Regulations that a competent electrician will be familiar with. In the case of overhead domestic supplies, the earth terminal of the property might only be connected to earth but not to neutral.

In the last part, electrical safety considerations are described.

On to Part 6

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The story of Electricity Generation from pipelines to pylons

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Part 6: Getting down to Earth; Electrical Safety considerations.

We've now shown how a 230V a.c. supply is derived from a 3-phase 415V transformer, noting also that a consumer's neutral wire connects to the transformer's star/ neutral point further away. A separate "protective" earth (the steel armour of the underground cable) runs between the consumer's earth terminal and the (earthed) star point of the transformer as well.

In the final part of this feature, we examine the need for electrical "earthing" (or "grounding" in the USA/ Canada).

It's widely understood that the need for "earthing" is a safety measure designed to prevent electric shock from wiring faults or insulation breakdowns. More accurately, earthing is used to ensure that no open or exposed metalwork can accidentally become live should an internal insulation fault arise: instead a fuse will melt rapidly and disconnect the supply.

This principle is used in everything from a steel-cased electric heater right up to the infrastructure of an entire power station. This aspect is now examined in greater detail, and it's useful to start by seeing what happens in our adopted power station, Killingholme "A", before looking at a domestic situation.

Since the power station generator's output is a 15.75kV three phase supply, the first question to ask is, "15.75kV with respect to what?". Voltages exist between **two points** as a **potential difference**. Readers will know that electronic circuits contain signals and voltages which are almost always measured with respect to the 0V rail. When we say that something is "at +5V" or "-12V", it's implied that this is with respect to (w.r.t.) the **0V rail** unless otherwise stated. (See my feature How To Read Circuit Diagrams for more explanation.)

In the field of electricity generation, though, any voltages expressed are always understood to be **between phases** rather than with respect to earth or "ground". **A 415V three-phase supply has 415V between phases, not between a phase and ground (between which, 230V a.c. exists).** Recall how a 9.1kV generator coil produces 15.75kV **between phases**, and it is this latter voltage which everyone talks about.

However the ground or earth also plays a fundamental safety-related role in a power station. Remembering that the power generator's output takes the form of a star connection, the star point has a net voltage and current of zero.

^ A generator's star point - an overhead box with three phases entering. Nothing much exciting to look at here!

In practice, the generator's star point is connected to earth through a **"Neutral" Resistor.**

^ A Neutral Resistor housed in a metal cabinet is used on the power station's generators.

In the generators I saw at Killingholme "A", this resistor filled a large metal cabinet, but in older plants the resistor can actually be in liquid form, made from a tankful of potash and capable of handling kilo-amps of current. *However remember that the only currents which ever flow to earth through the neutral resistor are fault currents.* This aspect is explained below.

^ Every girder, metal platform and structure in the power station is heavily bonded with copper bus-bars and ground straps.

All exposed metal work, instrument racking, chassis, walkways, handrails, steel cabinets and even the metal girders of the buildings themselves are heavily interconnected with straps and bonding wires and also physically connected to the earth. This "ring of steel" ties all of the open metalwork together to form an escape route for fault currents to flow. It means also that all earthed parts are at the same potential - zero volts or very nearly so. It's the power station's equivalent to the equipotential bonding used in your home.

^ This temporary earth clamp was seen on an open cabinet during maintenance

If any fault develops in the generator - e.g. an insulation failure - then if any part of the exposed metal work becomes "live" there'll be an immediate short to earth, because the star point is connected to earth as well. The purpose of the Neutral Resistor is tol limit the fault current and prevent a serious failure. Although a fault current will now flow, this will be detected by earth fault relays, current transformers, circuit breakers or other devices. In the case of a major generator fault, the neutral resistor is capable of withstanding many tens of amperes for five seconds, at a potential of some 10kV or more.

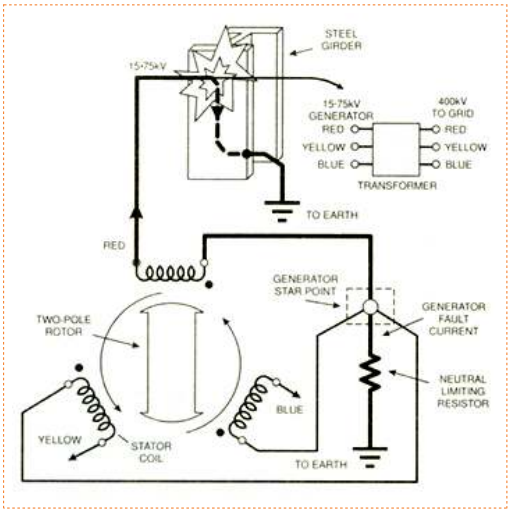

Fig. 17 How the generator's Neutral Resistor limits the current caused by a fault, until the power station's circuit breakers can trip.

In Fig. 17 above, a generator's Red phase has shorted to an imaginary steel girder, one end of which is connected to earth using copper bonding straps (photo above). The Neutral limiting resistor is now the load for the 'red' phase and a fault current will flow down to earth and through the resistor, which limits the current.

In my several days on-site at Killingholme "A", I saw countless examples of all kinds of earth straps, bus-bars and earth leads which ensure that high tension fault currents find their way directly to earth. It clearly makes sense to make it easy for fault currents to flow through a massive conductor - the ground - and trip a circuit breaker in the process to disconnect the supply. A similar form of protection is used in the home. (I discuss domestic electrical safety next.)

Remembering that the power station needs electricity itself for its own systems, then even if the worst happened and power was lost entirely, a Battery Room is installed that contains several very large banks of lead-acid accumulators which offer 48V, 110V and 220V d.c., sufficient to power auxiliary equipment for a considerable period. I had never seen so many Varta lead-acid batteries strapped together in one place but safety regulations (danger caused by sparks) prevented any photography in the Battery Room.

Welcome, Earth links: domestic electrical earthing and safety

Finally, we turn to the domestic need for earthing and look at what it offers the end-user.

As previously mentioned, the "neutral" wire of a 230V supply (UK) is provided by the star/ neutral point of the transformer and is therefore always close to zero volts with respect to the incoming "live". The star/ neutral point is also directly earthed as shown in Fig. 14b and Fig. 15 in Part 6. A separate good quality metal earth connection usually runs between the installation's earth circuit back to the transformer (e.g. to its metal body, which is also earthed).

The domestic arrangement is virtually identical to the one used by the power station generators to isolate failures in the insulation or other faults: if every piece of exposed non-live metal is earthed, then it will be very easy for "escaping" fault current to flow to earth as well: it will strive to complete the circuit back to the earthed star point of the 415V transformer. In so doing, a massive current will flow which will melt an in-line fuse or operate a circuit breaker. (A separate section "Fuses and the race to protect" gives a little more background to domestic circuit breakers and fuses.)

Let's take the example of an ordinary electric heater (see Fig. 18), its metal casing is connected to the earth terminal of the mains plug. Alternating current flows between the live and neutral wires when the heater functions normally.

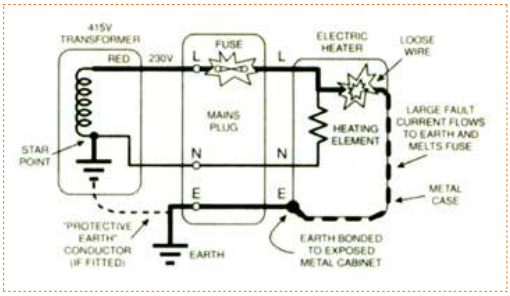

Fig. 18 How earthing (grounding) ensures that any insulation breakdowns will cause a fuse to melt, thereby disconnecting the supply. When e.g. a loose wire in an electric heater shorts the 230V live wire to earth via the metal case, a large fault current flows to earth. The fuse therefore melts, and/ or the supply's RCD will trip.

If a live wire comes adrift inside the heater and touches the metal cabinet, then a short circuit is formed with the 415V transformer's earthed star / neutral point and a heavy current flows to earth which melts the fuse in the mains plug, thereby disconnecting the supply. This prevents the user from being able to touch a "live" metal cabinet and acquire a mains potential, because otherwise he or she could be fatally injured by the fault current flowing from the live metalwork and through the human body en route to earth.

(These days, an RCD / ELCB (Residual Current Device/ Earth Leakage Circuit Breaker) provides life-saving protection against such potentially lethal faults. They detect the imbalance of input current and output, so when a fault current flows to earth, the device trips within milliseconds. RCDs are a life-saver and should be used on all outdoor electrical devices, gardening tools etc. ARW.)

There's a counter-argument which says that if **no** earth were installed, then even a human being *did* accidentally touch a live terminal, no ill effects could arise because there would be no reason for current to flow through the body to earth. The human body would merely be "floating" at the live voltage but because no potential difference existed across him or her, then no harm would be done.

However, standards of electrical insulation are sometimes poor, and leakage currents can easily occur. This means that the earth (or, say, the chassis of an apparatus) could still not be completely isolated from the supply — even if the supply has no apparent connection to earth and is supposed to be "floating". Poor insulation allows a leakage current to flow given a suitable opportunity.

There are more subtle ways in which the earth can form a return path for fault currents, even if the supply is supposed to be "floating", thereby causing a shock. As (UK) IEE guidelines state, electrical insulation can itself be thought of as a capacitor dielectric, with the live wiring forming one "plate" and the earth forming the other.

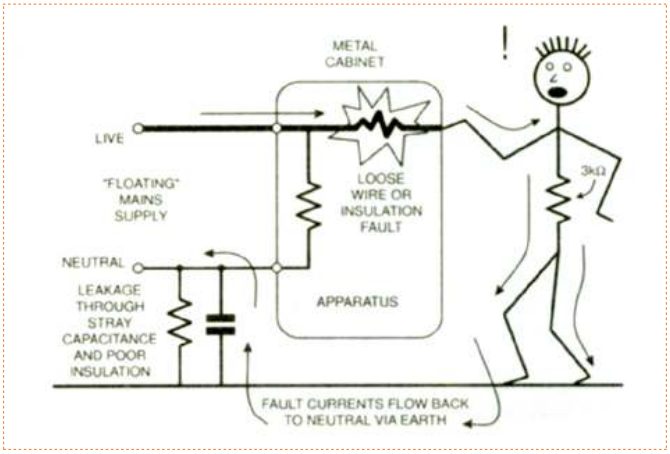

Fig. 19 How a "floating" (unearthed) a.c. supply can still cause electrocution due to stray capacitance or poor insulation completing a path back to neutral. Electrical insulation itself can act as a capacitor dielectric. (Adapted from Guide to IEE Wiring Regulations (15th Edition) - J.F. Whitfield)

This **stray capacitance** could form an adequate route for an a.c. fault current to pass, should a human body accidentally contact a live wire (see Fig. 19 above). There's thus the risk of receiving an electric shock from earth fault currents, even if it's thought that the mains supply is floating and supposedly "unearthed".

In Shock

Still on the subject of accidental electrocution, the human body, being full of water, is the walking equivalent of a 3 kilohm resistor as shown, and it only takes a current of 20mA to pass through a muscle to cause uncontrollable spasms and render the body unable to release a live wire. A separate section I entitled "Heartfelt Shock" explains some basic facts about the human body and its reaction to electric shock, and there is also some suggested First Aid advice to help with cases of suspected electrocution.

There are various earthing configurations permitted under the UK wiring regulations, but how earthing is achieved in an installation depends on whether the incoming supply is via underground cables or from an overhead supply. Due consideration is also paid by installers to the method by which earthing has been implemented in the locality by the supply authorities.

It should be again emphasised that the domestic electricity supply should never be interfered with except under expert guidance. It's worth pointing out that one should never totally rely for any reason on the neutral being at zero volts: the author has witnessed occasions where the electrical supply to a wall socket had been incorrectly wired by an electrician, with the result that the "neutral" pin was actually live at 230V with respect to earth. Various simple electrical testers are available which will reveal such faults, but in all cases a competent qualified electrician should be called if any doubts exist, and no form of measurement or interference with the mains supply should be undertaken except by experienced and knowledgeable persons.

Summary

That concludes this special feature. I described the entire UK power generation and distribution system starting with gas that fuels our adopted power station, all the way through to the sub-stations and transformers that ultimately deliver 230V safely to our homes. We looked at the principles of power generation and how a typical CCGT power station works. The UK distribution network was also outlined, showing three-phase electricity being delivered to industry and residential sites. Then the principles of safety-earthing and other safety-related aspects were described.

I found the whole project fascinating and I had great fun writing this article back in 1999. National Power (as it was then) was generous with their hospitality and their proof-reading. I examined every aspect of the entire power station and I can now admit that I did panic a bit (lots) when confronted with a vertical ladder to an overhead gantry (one of those open-mesh steel platforms - I'm afraid of heights!), but risking my life is how I got the overhead images of the gas burners and turbines under maintenance.

More resources:

- Electricity Pylons: an introduction

- Leaps & Volts: Safe Working Distances
- First Aid Guidance
- Fuses and Circuit Breakers

Acknowledgements

My thanks to all those who helped at the time, Station Manager Keith Ulyett who later went to the USA, staff at National Power and especially to Richard Power who facilitated my in-depth tour of Killingholme "A".

The power station subsequently changed hands and at the time of writing (Feb. 2011) is now operated by Centrica Energy.

Some diagrams adapted from ABB (Asea Brown Boveri) originals, IEE Regulations and National Power kindly provided some illustrations and training materials to support the article.

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