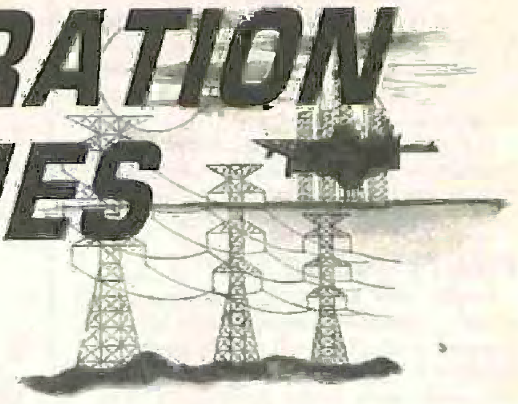
Special Feature

POWER GENERATION FROM PIPELINES TO PYLONS



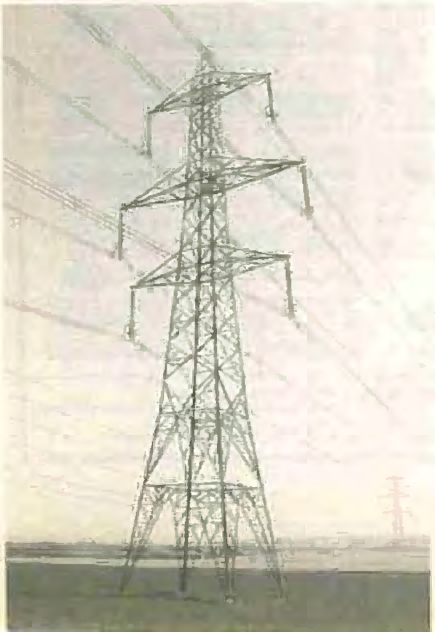
ALAN WINSTANLEY

Part One

In this two-part feature, supported by the expertise of the international power generation company National Power plc, *Alan describes some of 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 a.c. supply directly to our housing and industry.*

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 as well as the general public there is much mystique surrounding the way in which electrical power is created and delivered safely to our homes.

National Power generously granted the writer unlimited access to all parts of a modern gas-fired power station – Killingholme "A" near Grimsby – 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 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.



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 all this really means?

After reading these two 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 employed in your own country (some of which are undoubtedly British-built).

In The Beginning

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 1990s, 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.

On Demand

Over the many decades in which we have enjoyed virtually uninterrupted electrical supplies, the power providers have accrued much experience of the likely demands which will be placed upon them by their customers. This enables the power distribution companies to plan ahead and allocate, on a daily basis, the various power generation resources which are going to be available to meet the forecasted demands.

How, according to National Power, these various fuel types are available in "layers" to meet this demand, which in the UK totals nearly 70,000 Megawatts (MW), is shown in Fig.1. The graph also shows how the resources are divided amongst various fuel types.

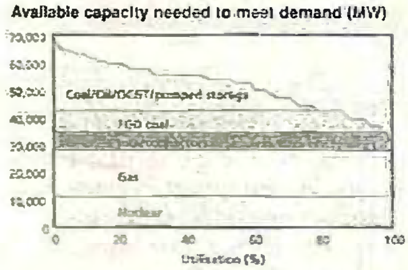


Fig.1. How the demand for electricity in the UK is fulfilled by different types of fuel. Nuclear, gas and "interconnectors" provide the base whilst coal, oil and hydro are only brought on-stream to top up the supply.

–Courtesy National Power

Underpinning the country's supply capability are both gas and nuclear fuel sources which produce a constant 30,000MW between them 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 45km long cables completed in 1986.

The rest of the UK's electrical capacity is provided by coal, oil 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 which are 100 per cent utilised.

The 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 people head for the electric kettle. These TV-related surges are known as "TV pick-ups". The average person 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, 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.

Price Matching

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 for American readers) 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 6·45 pence (10·6 cents), which equates to £64.50 or $106.42/MWH.

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.

In Fig.2, 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 6p.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. All power plants are identified in an "order of merit" table which highlights the individual cost of power generated by the various power plants.

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.

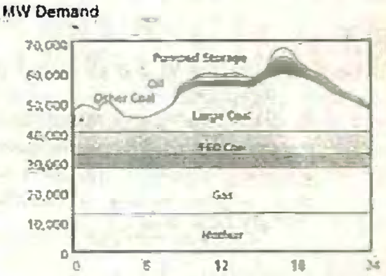


Fig.2. How a 24-hour demand, peaking at 17.30 hours, is met by the electricity industry.

Killingholme "A"

National Power's Killingholme "A" power station is situated near the ports of Immingham and Grimsby in North Lincolnshire, on the banks of the River Humber. It was their first gas turbine plant and was commissioned in 1993.

This 650MW plant runs as a "base load" operation, which means that it 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

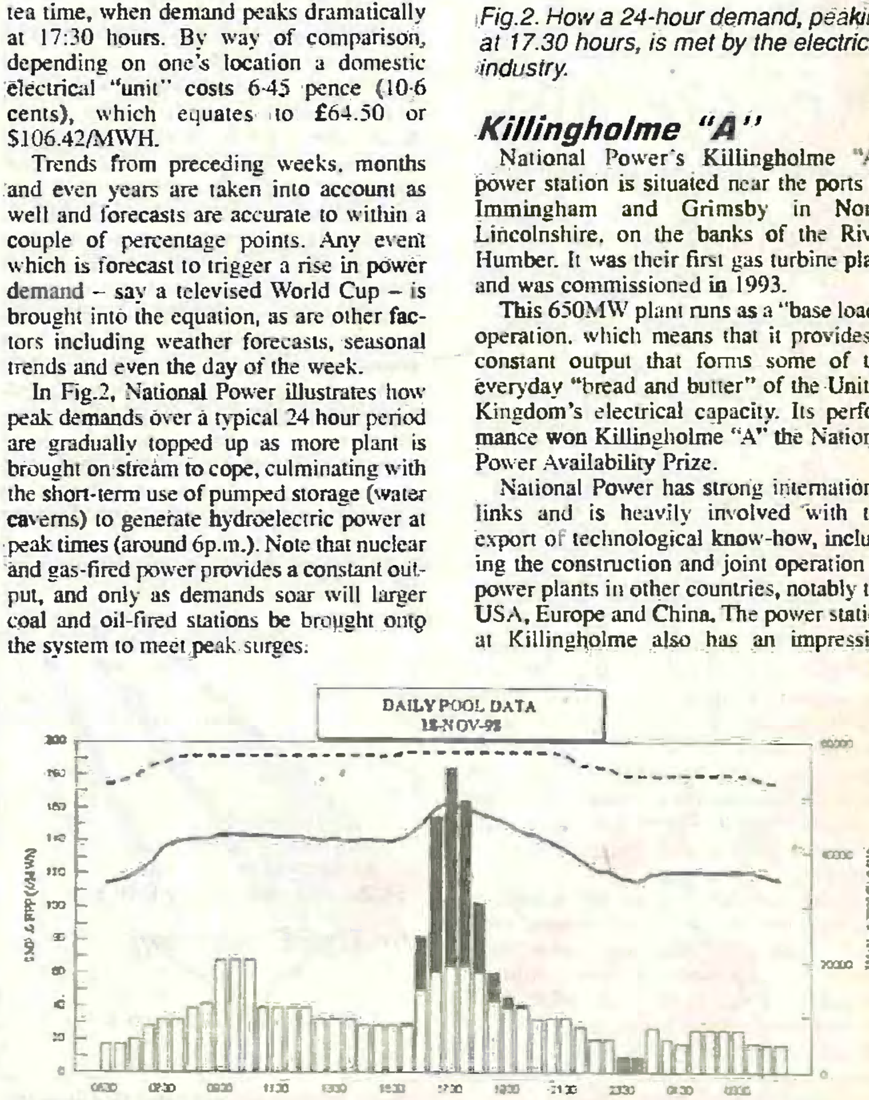


Fig.3. Daily demands are bought in half-hour blocks from electricity producers by the National Grid. The graph, produced daily, depicts several factors including the purchase price of electricity.

General view of the Killingholme "A" Gas-fired Power Station.

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.

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 that are proportional to the square of the current (I^2R).

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.

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). 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.

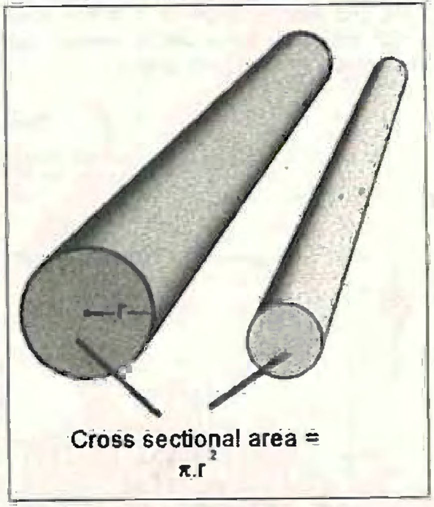


Fig.4. The resistance of a conductor is related to the cross-sectional area (CSA), the smaller the diameter, the higher the resistance.

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.

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

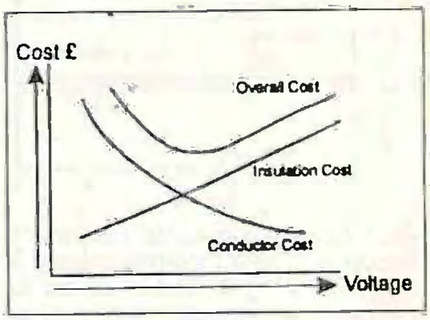


Fig.5. Illustrating the simple relationship between the cost of providing a supply versus the voltage and insulator costs.

Four 400kV transformers connected to the outputs of the four generators.

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 d.c. 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.)

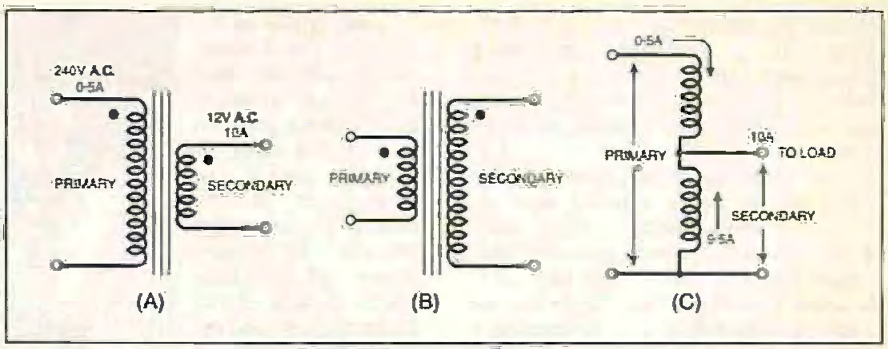


Fig.6a. Step-down transformer symbol. The "spot" indicates the direction of the windings. (b) Step-up transformer, and (c) auto-transformer.

The main function of a transformer is, of course, to step an alternating voltage up or down. Fig.6a 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 and 0V on the primary, and 12V and 0V on the secondary winding.

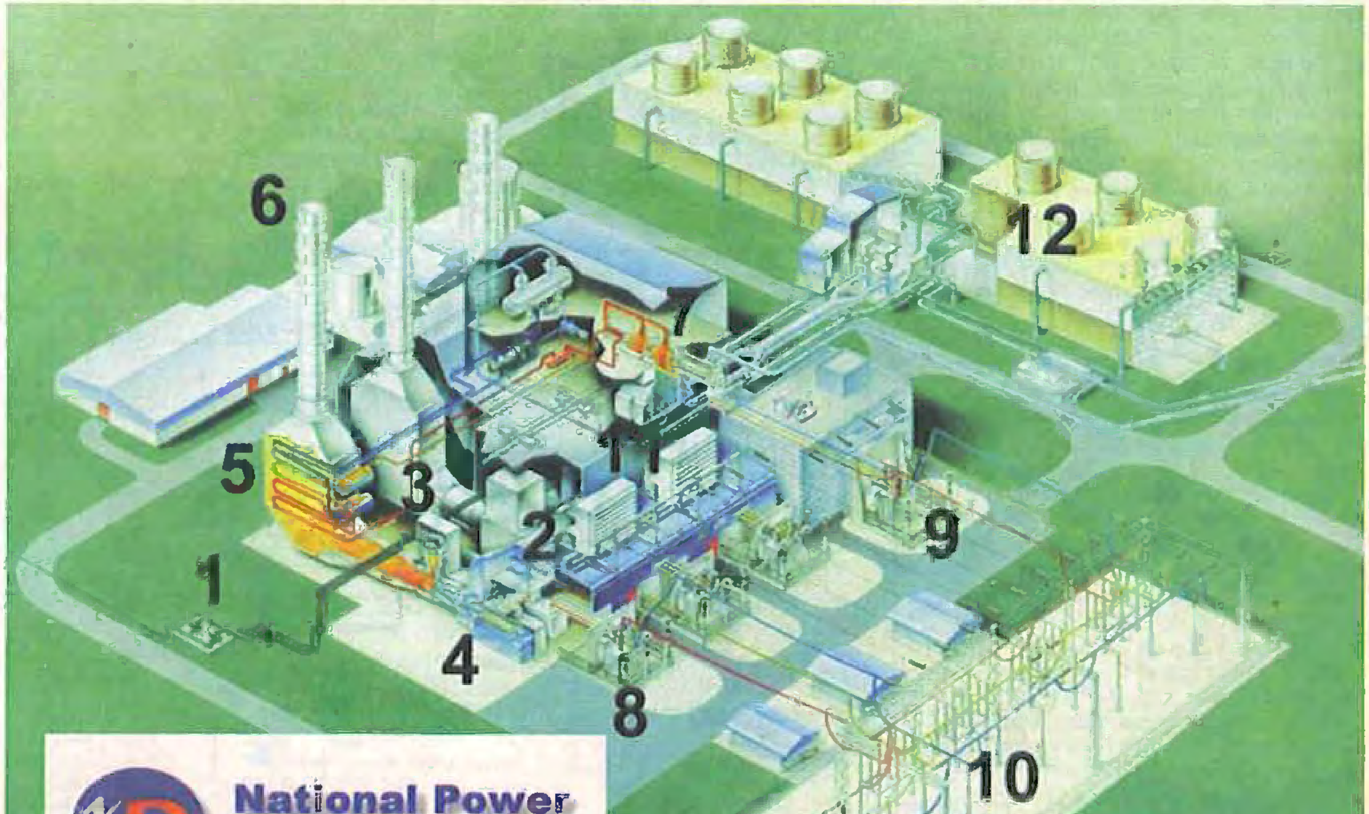
Whether the transformer will increase (step up) the alternating voltage applied to the primary, or reduce it (step down) depends on the ratio of the number of turns of both windings. Regardless of which type the transformer actually is, at a simple level it can be assumed that the power (V×I) across 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 240V 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 V_p and that across the secondary is V_s, then $V_p/V_s = N_p/N_s$, where N_p and N_s are the numbers of turns in the primary and secondary windings. As shown in Fig.6a, the primary power (240V×0·5A watts) is the same as the secondary (12V×10A) – ignoring losses.

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 × 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 used 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

National Power Killinghome "A" near Immingham in North Lincolnshire is a modern gas-fired CCGT power station which produces enough electricity to power a town the size of nearby Grimsby. It uses three gas and one steam turbine which operate non-stop for many months on end. 1: Natural gas is carried by underground pipelines, from offshore rigs in the North Sea. 2: Air is sucked in through large grilles on the front of the building, where it is filtered. 3: The gas/air mixture is swirled and burned in a combustion silo, which produces a force on the turbine blades below, making them rotate. 4: The generator is directly coupled to the rotating turbine shaft. 5: The turbine exhaust is used to heat water in the Heat Recovery Steam Generator, to produce "bonus" steam. 6: Exhaust then passes through the stacks, one per turbine. 7: A steam turbine produces further electricity from the steam created in the HRSG. 8: Each gas turbine outputs 3-phase 15·75kV to a large 400kV step-up transformer, outside the building. 9: The step-up transformer for the steam turbine, located by the main office block. 10: The Banking Compound contains the main isolators for the 400kV supply. 11: The exhaust steam from the steam turbine passes through a condenser, and produces high quality water which is recycled in the HRSG. 12: The cooling towers are used to reduce the temperature of the cooling water utilised in the condenser. 13: The underground 3-phase 40kV cable passes to a sub station, for onwards transmission by the National Grid.



terminal is therefore common to both the primary and the secondary (see Fig.6c). 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 Fig.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 measurements of current may be made. 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 to directly measure the output of each of the 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 substations 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.

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!

The Killingholme station 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.

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 degrees Celsius.

Aerial view showing gas turbine blades (largest, front) and air compressor (rear) on the shaft, undergoing inspection.

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 145MW at 15·75kV. The Killingholme power plant has three such gas-turbine driven generators plus a steam turbine as well. We will be looking at what happens to the generator's output in greater detail later on.

To start the system, a "static starting device" (SSD) is utilised in which the generator is actually used in reverse, as a starter motor (consuming some 4MW of power in the process), see Fig.8. 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.

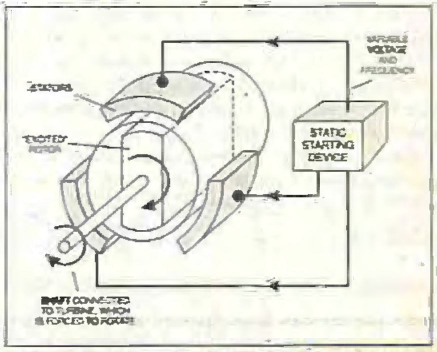


Fig.8. A static starting device (SSD) is utilised to convert a generator into a "starter motor" (consuming 4MW). This causes the rotor to spin, which in turn, turns over the turbine.

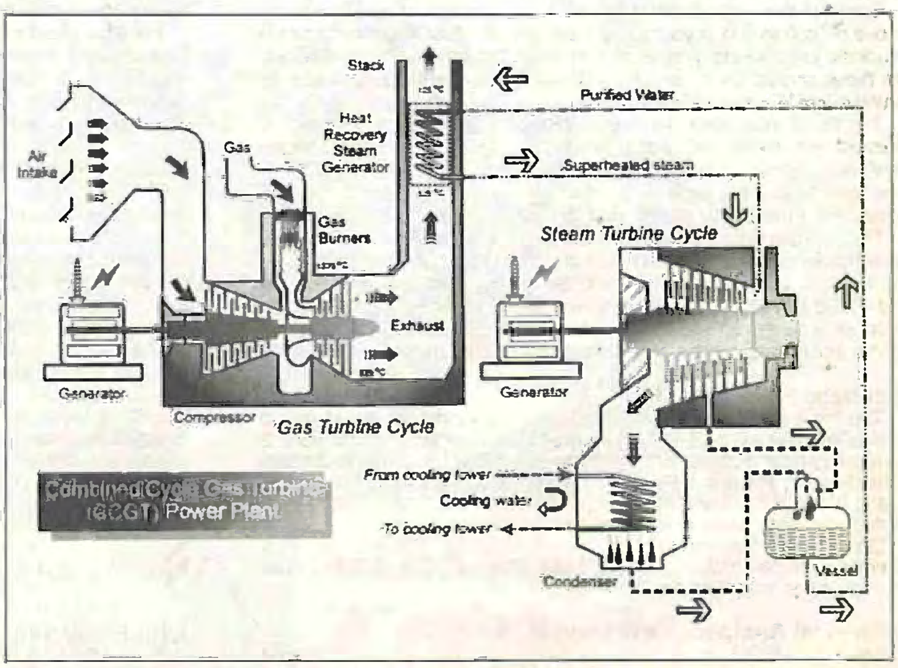


Fig.7. Schematic representation of the Killinghome "A" Combined Cycle Gas Turbine (CCGT) power plant.

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 or so 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, which can be seen from the author's window several miles away, actually vent exhaust from the gas turbines after it has passed through the heat exchanger.

The computer control room monitors and records the performance of the plant.

The "bonus" 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 227MW 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 warmed by the steam turbine's condenser, has to be cooled down and this is achieved in a cooling tower by 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 per cent to 50 per cent or so.

Next Month: In the next part, methods of power distribution and transmission are described, along with the means by which electricity is delivered to a typical home.