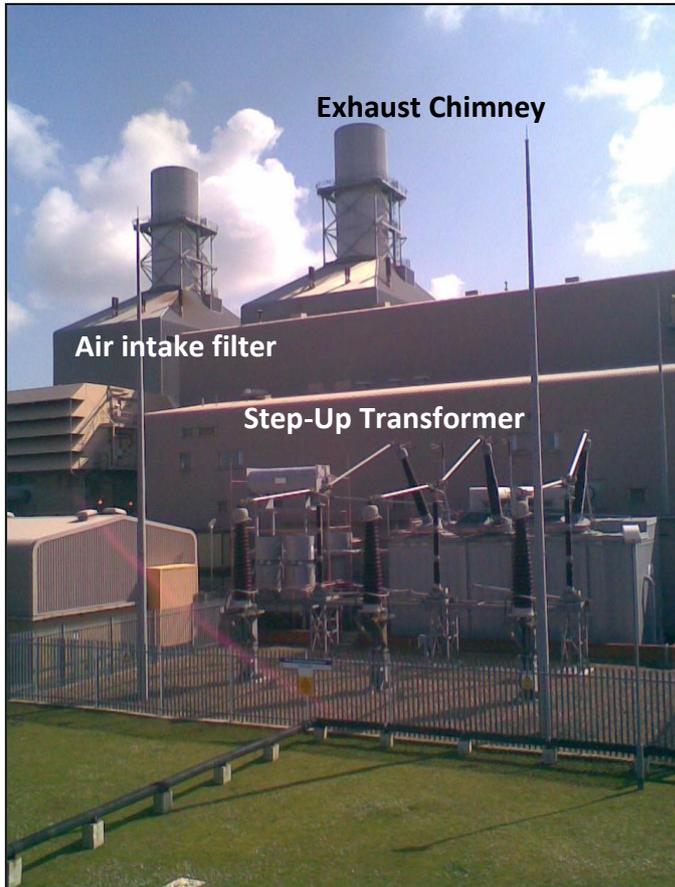


Little Barford Power Station Visit Report



By Stephen Lucas

Visit to Little Barford Power Station

The Physics Observed

In this report I will be discussing my visit to Little Barford Power Station, an approximately 54% efficient combined cycle gas turbine power station, built on the site of a pre-existing coal-powered power station, situated in Little Barford, St. Neots. The Power Station provides energy for over 700,000 people across Cambridgeshire and Bedfordshire and works on the basis of two gas turbines powering a generator, two heat recovery steam generators and a steam turbine linked to another generator. There were several aspects of physics observed on the visit, such as the cooling systems, the demineralisation of water, electromagnetic induction producing current (and thus electricity), the combustion of natural gas and the environmental impacts of the power station.

The two aspects of the power station I will be focussing on in this report are the transformers – stepping the voltage up from 15,500 volts (15.5kV) to 432,000 volts (432kV) and the actual generation of electrical energy from kinetic energy using an alternator – the driving of steam and gas turbines, rotating the electromagnet in the stator, producing a total of 684 Megawatts of electricity.

To aid my explanation of how Little Barford generates electricity, I will first look at the general process of how Little Barford Power Station produces kinetic energy and converts it into electrical energy.

The process of generating electricity at Little Barford Power Station is as follows:

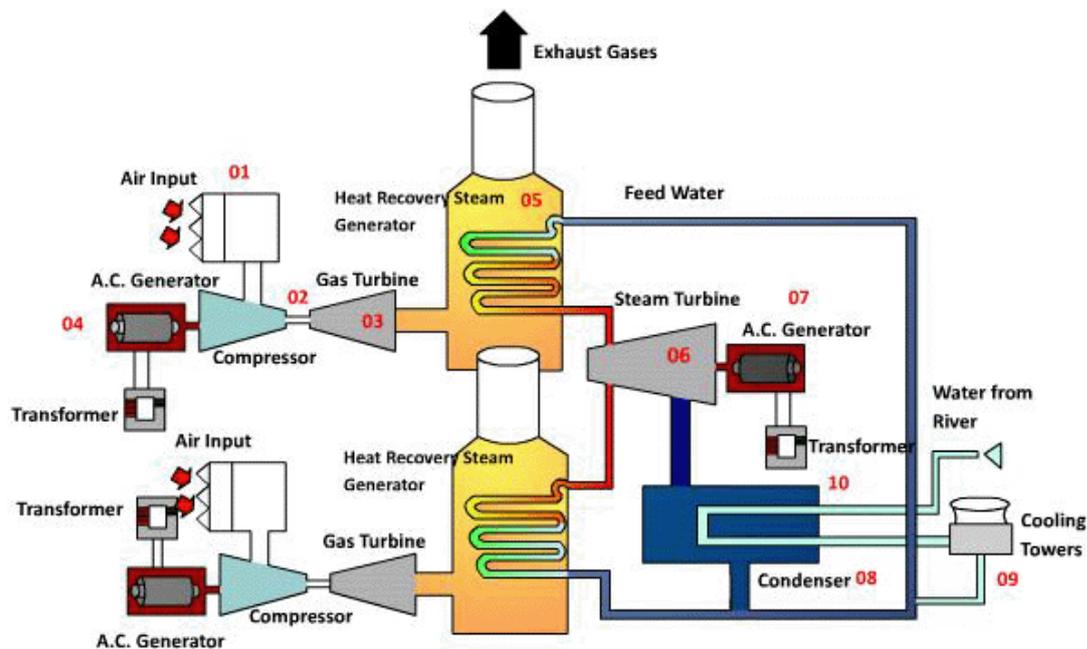


Image Source: 'n' power Little Barford Power Station visitor leaflet (Reconstruction)

Here the numbers represent the order and stages of representing electricity. I will be looking at stages 03,04,06,07 and 10 in close detail.

Purpose and Explanation of the generators at Little Barford Power Station

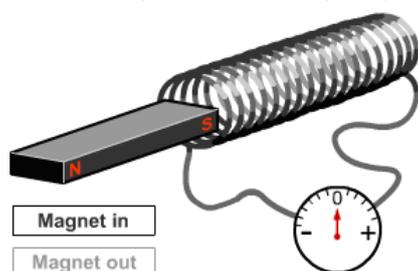
Before explaining how Little Barford Power Station generates its electricity I will first introduce Faraday's and Lenz's law and the basic principles of electromagnetic induction.

The conversion of kinetic energy into electrical energy

An electrical generator is a device used to convert mechanic energy into electrical energy, and at Little Barford Power Station, three generators are used to produce electrical energy from the kinetic energy of the turbines, all on the same principles of electromagnetic induction. In principle, generators consist of a coil, which is rotated between the poles of a magnet so that flux-linkage is continuously changing; however Little Barford Power Station works on the principle of an electromagnet rotating between the coils of a wire(s).

In an a.c. (alternating current) generator, the alternating electromotive force is applied to the external circuit via two spring loaded graphite blocks called 'brushes' which press against two copper slip-rings. These rotate with the axle, are insulated from one another and each is connected to one end of the coil. The general name for a generator that produces alternating current is an alternator.

Electric current can be generated in a wire if it is at right angles to a magnetic field, and the magnetic field is changing. As long as the magnetism changes by moving the wire past the magnet, or the magnet past the wire, an electrical current will be generated.



If we were to quickly move the magnet in and quickly remove it, the galvanometer would detect a current. If we were to swap the poles of the magnet, the flicker of the galvanometer would flick the opposite way and this is related to Lenz's and Faraday's Law.

Image Source: <http://www.bbc.co.uk/schools/gcsebitesize/physics/electricity/electromagneticinductionrev2.shtml>

Electromagnetic Induction

The generator is based on the principle of 'electromagnetic induction' discovered in 1831, by British Physicist Michael Faraday – the first person to create a dynamo.

Faraday's law states:

$$\mathcal{E} = -\frac{d\Phi_B}{dt}$$

The negative sign here is to show that the electromotive force is induced in a direction to oppose the change in flux. This is taken from Lenz's law that states: *the direction of the induced electromotive force is such that it will try and oppose the change in flux that is producing it.*

\mathcal{E} = The induced electromotive force (volts)

$\Delta\Phi_B$ = change in flux linkage (weber)

Δt = time taken (seconds)

N = number of turns in a coil

Note: 'd' in the equation refers to calculus and the first derivative of a change in a flux linkage time graph and is the same as writing 'change in' represented by Δ (delta).

Often the formula is written as: $\mathcal{E} = -N \frac{\Delta \Phi_B}{\Delta t}$

In this case, 'N', represents the number of turns in a coil. Since the electromotive force will be 'N' times greater if there are more turns in the coil of wire, since the electromotive force produced can be increased by increasing the number of turns in the coil of wire, as well as using stronger magnet, a coil with greater cross-sectional area (since Magnetic Flux, ' $\Delta \Phi$ ', equals number of turns in a coil, 'N', multiplied by magnetic flux density, 'B', multiplied by cross sectional area, 'A': $\Delta \Phi = N \times B \times A$) and moving the magnet faster. Unfortunately the change in flux linkage, time taken or the number of coils used at Barford was not noted, however, if I had the opportunity to visit again, this is an area I would investigate.

Faraday's model of electromagnetic induction shows that an e.m.f is induced whenever there is relative movement between a magnet and a coil of wires. For example: If you quickly move a magnet into and out of a coil of wires linked to a galvanometer, the needle of the galvanometer moves, indicating a current has been induced in the coil of wires. This only applies provided the wire is connected to an outside circuit, if it is not connected to an outside circuit, and then charge is separated, creating electromotive force (a terminal voltage), which drives current around the circuit.

In Faraday's model, the cutting of lines of magnetic flux causes an e.m.f to be induced across the conductor. In addition, when there is a change in flux linkage an e.m.f. is induced – e.g. pulling a search coil quickly out of a magnetic field.

Therefore if a permanent magnet, in the case of Little Barford Power Station: an electromagnet, moves through the space of a stationary conductor, the stator – which consists of coils of wire wound in uniformly spaced slots in a soft iron cylinder (the armature), an electromotive force will be induced in that conductor. The electromotive force induced will be due to the time rate of change of magnetic flux accompanying the magnetic field. If the wire is connected through an electrical load, current will flow and electrical energy is generated, converting the mechanical energy of the steam and gas turbines into electrical energy.

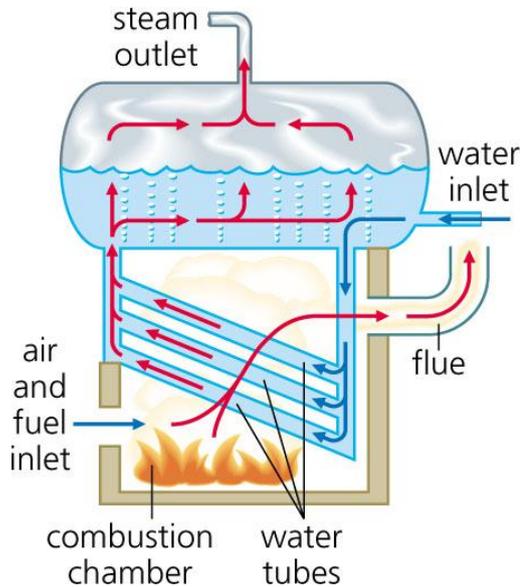
Electromagnetic Induction and its application to Little Barford Power Station

In Little Barford's case an electromagnet is rotated – *the rotor*, whilst the armature coils and their iron cores are stationary – *the stator*, in the alternator of the Power Station. In order to turn the rotar and therefore - make electricity, a turbine is used. Little Barford utilises two gas turbines and one steam turbine. In the gas turbines, natural gas and air compressed to almost 1MPa, are heated to a temperature of 1200°C in the combustion chamber and pass through the blades of the gas turbine. This turns the blades and turbine shaft at 3000 revolutions per minute and this shaft directly feeds into the generator. 3000 revolutions per minute equates to 50 cycles per second, and the high speed of the turbine, and thus electromagnet in the generator, means that the electromagnet is moved quickly, creating large currents and a frequency of alternating current at 50Hz.

The steam turbine works on the same principle but makes use of steam from the heat recovery steam generator, which turns 290 tonnes of water into steam every hour,

instead of natural gas. The turning of the turbine shaft, in turn, turns the electromagnet and induces an alternating e.m.f of the same frequency.

Simplified version of the boiler at Little Barford, producing steam to drive the steam turbine:



Flue refers to the gases (e.g. carbon dioxide, water vapour and nitrogen) that are formed when the fuel oil, natural gas, or propane is burned with the air.

The boiler at Little Barford will be far more complex than this diagram; however the principles are the same. The steam outlet pipe will return to the cooling towers, to be condensed and then the cycle will repeat itself. The fuel in Little Barford's case is Natural Gas.

Image Source: <http://www.lenntech.com/images/Boiler%20FE%20images/boiler-schema.jpg>

Diagram showing how steam from the Heat Recovery Steam generator, drives the steam turbine at Little Barford and how this is linked to the Power Station's alternator:

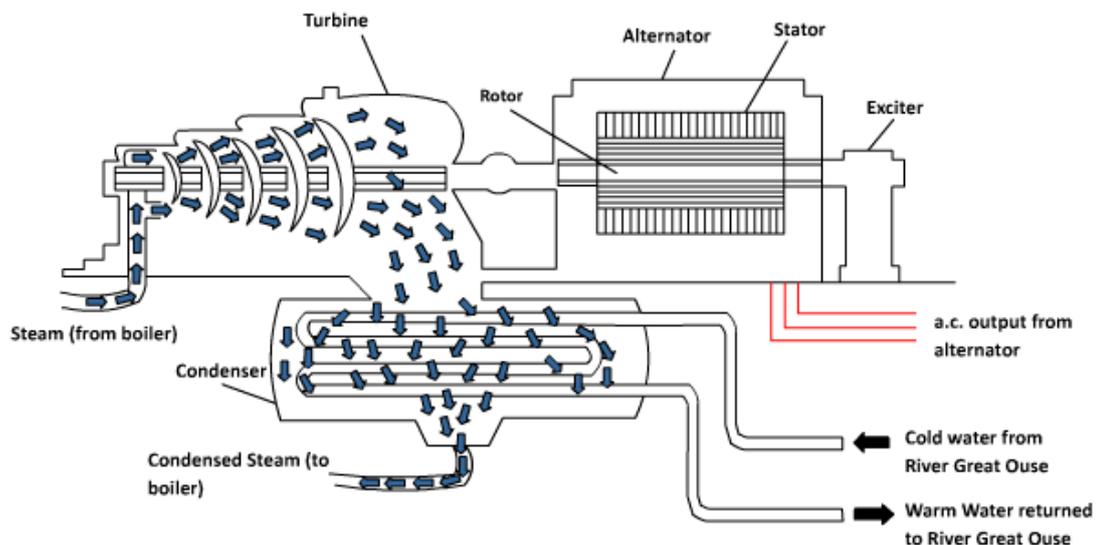


Image Source: Reconstruction of Figure 16.24 on page 256, Advanced Physics - Fifth Edition, Tom Duncan.

The diagram above shows that as high pressure steam from the Heat Recovery Steam Generator passes through the steam turbine, the blades and shaft are spun, causing the electromagnet to also spin.

As you can see from the diagram above, the blades of the turbine gradually increase in size, and this is to compensate for the steam losing pressure as it passes through the turbine, and increases the turbines ability to capture more steam and thus complete maximum revolutions.



Unfortunately it was not possible to photograph the steam turbine at Little Barford Power Station since it was insulated with about 1 metre of insulation surrounded by aluminium to reflect heat and getting close to it at such high temperatures would have been dangerous. The photograph on the left however is a similar representation of the steam turbine at Little Barford Power Station, showing the blades gradually increasing size.

Source: http://en.wikipedia.org/wiki/Image:Dampfturbine_Laeufer01.jpg

The steam, lower in pressure travels to the condenser, where it is turned back into liquid state by passing over tubes containing cold water drawn from the River Great Ouse. The warm water is returned to the Great Ouse, providing it abides the environmental agency's regulations and is below 30°C and of a neutral pH. The condensate is pumped to the de-aerator and then back to the heat recovery steam generator for re-use. The fact that Little Barford Power Station makes double use of the heat generated makes it more efficient than conventional Power Stations. Even the most efficient coal power stations today rarely exceed 30% efficiency.

The vessels containing steam are kept to a near vacuum to lower pressure, allowing more steam to be contained and reach the boiler faster, further improving efficiency. The water boiled to steam is also demineralised using Hydrazine and phosphate, to inhibit limescale, and allow constant flowing of steam.

The e.m.f. is similar in principle to a water pump, it does not create water, but it drives the water around, just like the e.m.f. drives a current around a circuit. Little Barford Power Station spins the electromagnet at 3000 revolutions per minute, and since the size of the e.m.f. induced increases when speed of which the magnet is moved increases, the power station has the ability to produce a total of 684 megawatts of electricity, 256 Megawatts from the steam turbine and 428 megawatts from the two gas turbines.

Simplified Version of the Alternator at Little Barford Power Station

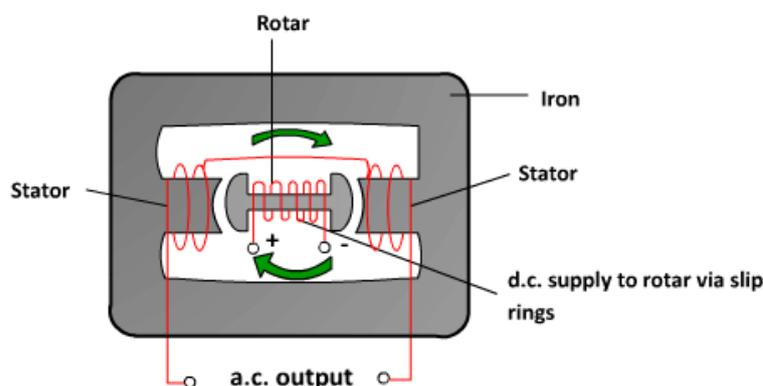
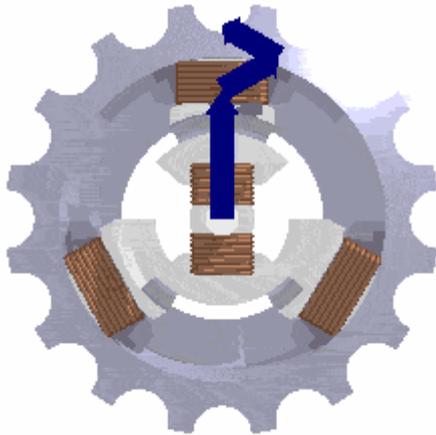


Image source: Reconstruction of figure 16.22 (a), page 256, Advanced Physics – Fifth Edition, Tom Duncan.

A relatively small direct current is needed for the field coils (the coils of wire around the electromagnet) and is fed through the rotating slip-rings. The large potential differences (15.5kV) and currents induced in the armature coils are then led away through fixed connections. The rotor is driven by steam or gas turbine which also powers a small dynamo called the exciter for supplying current to the field coils.

3- Phase Alternator



The output from the Power Station alternator is a 3-phase a.c. supply obtained by connecting the stator coils in three sets and having three rotor coils at 120° to each other. This gives three live wires (each current is 0 at a different time) with a common return or neutral wire and makes current flow possible most of the time in all the live wires. The benefit of this is that a steadier power supply is produced, more appropriate for powerful devices.

Image Source: <http://en.wikipedia.org/wiki/Image:3phase-rmf-60fv2-airopt.gif>

The current of the three live wires, alternating sinusoidally between '0' amperes at different times.

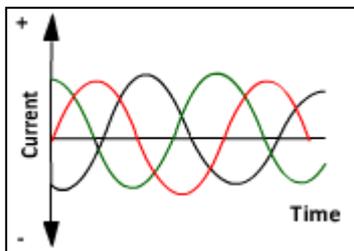


Image source: Reconstruction of figure 16.22 (c), Advanced Physics – Fifth Edition, Tom Duncan.

Strengths and Limitations of the Generator and electricity generating process at Barford Power Station

Advantages / Strengths

The method of inducing electromotive force produces a lot of power, more than enough to supply the county of Cambridgeshire and Bedfordshire. Having studied the unit – Technology in Space, I know that:

$$P = VI \text{ (Power = Potential Difference (V) x Current (A))}$$

Therefore if the three turbines combined produce 684 megawatts of electricity, and this is taken to the transformer at a voltage of 15.5kV, then it would appear that:

$$\frac{684,000,000}{15,500} = 44129.03 \text{ Amperes}$$

Although it is not as simple as that, since the process is not 100% efficient as energy is wasted as heat and sound – as experienced in the steam turbine room, and does not consist of one circuit, it is just an example of the scale of currents which Little Barford produces.

The alternator itself consists of an electromagnet spun in a stator, and the use of iron in the stator means that it is an excellent conductor of electricity as it has two delocalised electrons for every iron atom. Iron is also a ferromagnetic material and quickly demagnetises because the atomic magnets have enough vibrational energy to turn in random directions.

The fact that the generator is controlled by a computer system from the control room, allows the generator to be monitored and altered to meet supply and demand. For example, during Diana's funeral, the demand for electricity increased substantially, to power people's televisions and kettles during the advert breaks.

The use of a computer system also allows the output voltage to be monitored. If there is any sign of danger in an area of the power station, such as a build up of excess pressure in the turbine or hazardous temperatures, that area of the power station can be switched off, whilst the other areas continue to generate electricity, allowing the Power Station to continue operation.

Another obvious advantage of the whole electrical energy generation is the efficiency of the power station. Little Barford is 54% efficient in its energy production. Where $\text{efficiency} = \frac{\text{useful energy}}{\text{total energy}} \times 100$.

The largest source of energy loss is the intake of air through the compressors, as this accounts for about 60% of the 46% energy wasted. Nevertheless this is still a high percentage of efficiency in comparison to most power stations. The quality of Little Barford Power Station that makes it so efficient is its double use of the heat generated by the combustion of the natural gas, and sometimes oil. Once the gas has left the gas turbine, the gas at a temperature of 585°C is passed to the Heat recovery steam generator where it helps turn water into steam which is then used to drive another turbine, and power another generator. The exhaust gases such as carbon dioxide, are emitted through the exhaust chimney at a temperature of 90°C are discharged to the atmosphere through the chimney. Although the exhaust gases are pollutants, the emissions from Little Barford in comparison to a coal powered station of equal size is drastically less.

The fact that the generator at Little Barford relies on steam and natural gas, also means that the rotor can be continuously spun at a constant speed, synchronized to the electrical frequency of the power grid for non-destructive operation. Wind turbines on the other hand, are not operated at a constant speed, since they rely on the wind to turn the turbines, and the wind is not constant. The steam and gas turbines also produce considerably more electrical energy compared to the energy produced by a wind turbine.

Disadvantages / Limits

The most obvious disadvantage of the power producing process at Little Barford is the fact the turbines are driven by the combustion of natural gas and steam. The natural gas is obtained from reserves on the North Sea, and the amount of Natural gas is finite. Although the natural gas could be obtained from reserves beyond Britain, importing gas would be costly. The combustion of natural gas also involves burning hydrocarbons such as methane,

and these give off harmful emissions such as carbon dioxide – a contributor to global warming, carbon monoxide – a gas responsible for lowering the haemoglobins ability to carry oxygen around the blood stream and nitrogen dioxide – which can react with water vapour in the air to produce acid rain. Although Little Barford emits considerably less pollutants than a coal fired power station, and makes sure that the exhaust gases are at a relatively low temperature (90°C) so that the activation energy for dangerous reactions is less likely to be overcome, it still emits more pollution than that of a wind, solar or hydroelectric powered power station.

Other than the non-renewable source of energy, the fact that the energy cannot be stored (although a storing unit was attempted at Little Barford) is another limitation of the natural gas and steam powered turbine. In the event of a black start, where power needs to be restored if the main generators shut down, the Power Station would require service power of up to 10% of its capacity for boiler feedwater pumps, boiler forced-draft combustion air blowers and for fuel preparation. It would be uneconomic to provide Little Barford with such a large standby capacity at each station, so black start power must be provided over the electrical transmission network from other stations. Hydroelectric power plants are often designated as the black-start sources to restore network interconnections. This is one of the benefits of hydroelectric power stations in comparison to Little Barford, as although they are hard to find suitable locations, they require little power to open the intake gates, and create large quantities of power very quickly, since they can control the amount of water flowing through the pipes and turning the turbine. This makes them suitable to start-up fossil-fuelled or nuclear stations. The black start generator at Little Barford consists of a free-standing turbo-generator.

In terms of safety, the turbines at Little Barford generate a lot of heat, and need to be cooled with pure hydrogen. Hydrogen is only flammable if reacted with oxygen and is used for cooling the turbine since it has a high specific heat capacity and has the highest thermal conductivity of any gas. The Heat recovery steam generator also produces a lot of heat, and if the cool water was to stop reaching the steam generators, then this would result in increased steam pressure, and if the plant's release valve failed to open, the heat recovery system could overheat and the boiler would burst.

A downfall of the whole system is that since the turbines spin at such a high velocity, the slip rings and blades erode in time and need to be replaced. Likewise, if one of the blades of the turbine come loose, it can result in shearing through the others and damaging the whole system.

Future Developments

In terms of future developments, there are relatively few prospects for Little Barford Power Station. The actual process of how electricity is generated can only really deviate in the way in which the turbine is driven, for example, instead of coming from steam or natural gas, being driven by water or wind. Although the amount of power produced by Little Barford could be increased by using an electromagnet with more turns in the coil of wire, a coil of wire with greater cross-sectional area, or by moving the electromagnet faster, the Power Station already meets the needs of its network. Dismantling the electromagnet and generator would also cost the Power Station money since it would be unable to continue operation as effectively. The turbine also spins at a specific speed and so rotating the electromagnet faster could cause complications affecting the frequency of alternating current. The population of St. Neots, as well as Cambridgeshire and Bedfordshire, is however

growing with constant building of housing estates, and therefore the demand for energy is likely to increase with population, this will mean that the stock of Natural gas and oil will be further strained.

The future in terms of power generation seems to point towards renewable energy sources and nuclear energy. The world's stock of natural gas and oil is limited and will eventually run out. The world's supply of radioactive substances is far more abundant and the environmental impact of nuclear power stations is considered less, since it does not directly emit any greenhouse gases or gases associated with acid rain. Little Barford Power Station emits approximately 1.6 million tonnes of sulphur dioxide as well as 4 million tonnes of nitrogen dioxide, although this is comparably less than a coal powered power station of equivalent size, this still contributes to the formation of acid rain, which forms when the oxides are reacted with water vapour in the air. In terms of global warming, Little Barford emits 17.5% of the carbon dioxide released by a coal powered station. Perhaps a catalytic converter could be fitted to the exhaust chimneys to reduce these risks? Assuming it hasn't already been installed.

Nuclear power stations turn a turbine in the same way as Little Barford, but the heat for creating steam is generated from the splitting of radioactive atoms in a process known as Nuclear Fission. Nuclear power stations are considered more cost efficient than combined cycle gas turbine power stations, however this does not take the dismantling costs, and cost of storing radioactive waste into consideration.

Renewable energy resources seem to be the main future for the power industry. The threat of global warming is forever dawning on us, and energy sources which emit no carbon dioxide are most favourable. Hydroelectric, solar and wind power seem the best sources of non-renewable energy, although they have issues, as the sun does not always shine to power a solar panel, and the wind does not always blow, or at high enough speeds, there is also the issue of suitable locations which make them undesirable.

A future development that 'n power' is pursuing at Little Barford is finding a way to store the electrical energy.

Other uses and applications of the generator at Little Barford

The electricity generated at Little Barford has endless uses, such as powering people's personal computers, keeping streetlight lamps on and generally supplying electricity to any appliance that needs it and is connected to the mains.

In terms of the principle of rotating a magnet in a coil of wires to induce a current, there are several other instruments that use this concept. The Seismometer, an earth-quake detecting instrument, works on the basis of an electromagnet being displaced in a coil of wires by the tectonic movement of the earth's crust. When there is movement or vibration in the ground, the magnet is moved, and induces an electromotive force proportional to the amount of displacement in the earth. The induced electromotive force is amplified and causes a trace on the piece of a paper with the recorder pen.

A simple generator that many people will have encountered is the dynamo on a bicycle, and again works on the same principle. As the magnet is turned directly from the wheel rim, the kinetic energy is converted into electrical energy and used to power the lights.

The gas turbine at Little Barford is more than powerful enough to drive a jet plane or the M-1 tank since it has the ability to produce a speed of over 1,500 horsepower. The turbine of a large jetliner plane is simply a gas turbine with a fan at the front.

Although the gas turbines at Little Barford are probably too large to operate a jetliner, the velocity of the spinning turbines could power a jet plane or a tank.

The Transformers at Little Barford Power Station

Before the electrical energy produced at Little Barford is transmitted to the National Grid, it is first stepped up from 15,500 volts to 432,000 volts. The process stepping up the voltage involves a step-up transformer. A transformer changes the value of alternating voltage (and hence only works with alternating current) through a similar principle to the generator.

The Transformer at Little Barford:

A transformer consists of two coils wound around a soft-iron core. As an alternating potential difference flows in the primary coil, the resulting current produces a large alternating magnetic flux in the soft iron core which links the secondary coil and induces an electromotive force in it. This means that the flux linkage of the secondary coil is constantly changing and so, as Faraday's law tells us, an alternating voltage is induced across it.

The transformer at Little Barford is a step up transformer since it needs to produce bigger voltages in order to sufficiently supply its counties with power.

The fact that Little Barford Power Station uses a step up transformer means that the secondary coil has a greater number of turns than the primary coil. This is because the secondary electromotive force will be larger than the primary electromotive force since:

$$\mathcal{E} = - N \frac{\Delta\Phi_B}{\Delta t}$$

And therefore an increased value of 'N', the number of coils means a greater induced secondary voltage. The ratio of the input voltage to the output voltage is the same as the ratio of the number of turns on the primary coil to the number of turns on the secondary coil. This is given by the formula:

$$\frac{V_s}{V_p} = \frac{N_s}{N_p}$$

V_s = Secondary Voltage
 V_p = Primary Voltage
 N_s = Number of turns on the secondary coil
 N_p = Number of turns on the primary coil

As Little Barford uses step-up transformers, the value for N_s is larger than N_p . The above equation only applies to an ideal transformer with 100% efficiency, whereas the transformer at Little Barford is likely to be approximately 97% efficient. However, assuming Little Barford was 100% efficient in stepping up its a.c. voltage, the formula would give:

$$\frac{432,000 \text{ V}}{15,500 \text{ V}} = 27.87$$

Therefore, simplistically, the transformer would look something like this (not drawn to scale):

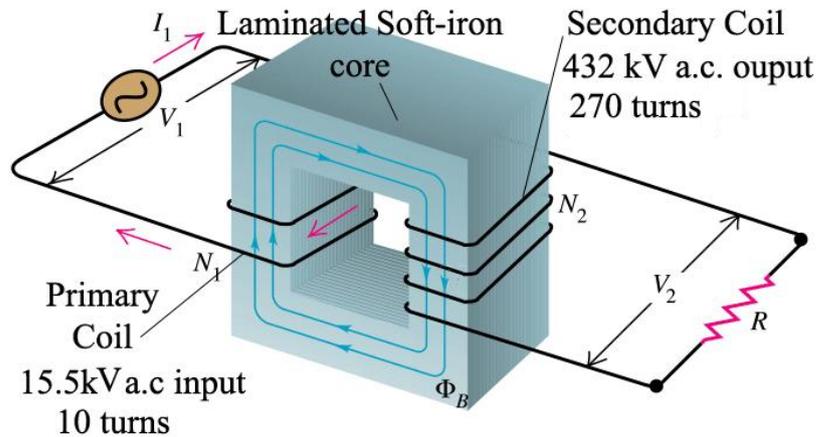


Image source: Edited version of: http://www.physics.sisu.edu/becker/physics51/images/32_16_Step-up_transformer.JPG

There are probably not 10 turns or 270 turns on the transformer at Barford, but again, the equation gives an estimate ratio, given the transformer was 100% efficient.

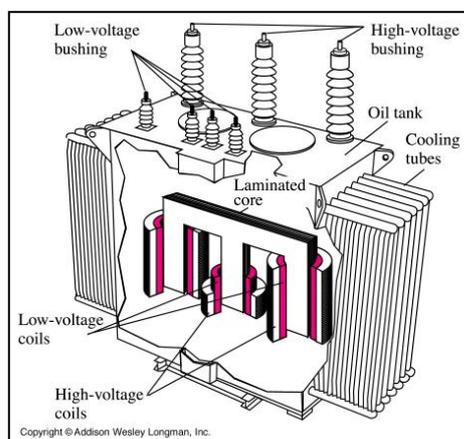
Strengths and Limitations of the Transformer at Little Barford

Although the transformer is highly efficient, there are still small energy losses. The copper wire used for windings has resistance and so ordinary (I^2R) heat losses occur. The alternating magnetic flux induces eddy currents (currents induced in the direction to oppose the motion or the change in flux producing them) in the iron core and causes heating.

The magnetization of the core is repeatedly reversed by the alternating magnetic field in a process known as Hysteresis, and results in the expenditure of energy in the core dissipated as heat. Flux leakage can also occur if the core is badly designed and has air gaps in it. The induced e.m.f can also be dangerous, since it is so large, arcing can occur, where electrical charge is discharged, often forming a spark to a power of lower charge or earth.

There are however modifications that can be made to the transformer to limit these causes in loss of energy and dangerous situations.

In high-current, low potential difference windings, thick wires are used to reduce the resistance of the copper wire. In addition, the core is made from thin sheets of iron called laminations, separated by insulating material; this makes eddy currents harder to flow and reduces their effects of heating the soft-iron core.



The heating of the core as a result of Hysteresis is kept to a minimum by using a magnetic material like iron, which demagnetises quickly. The general effects of increasing temperatures of the transformer are also reduced as the core is cooled with oil. This obviously has a disadvantage since the world's reserves are finite, however not a great deal of oil is needed. As a result of the measures taken to reduce wasted energy, the transformer only loses about 3% of its total energy.

Image Source: http://www.physics.sisu.edu/becker/physics51/images/32_18_Large_transformer_at_power_station.JPG

The arcing possibilities occurring from the transformer are reduced by using arcing rings, which provide an alternative path of lower resistance for the current to flow through in the event of arcing. It has been recorded that charge can jump over 4 metres, and so arcing rings are necessary to make Barford Power Station a safe working environment.



Arcing Rings

Image Source: My Photos

In conclusion I found the visit to Little Barford extremely informative and has definitely inspired me to consider a Physics career, as well as enlightened me to how Physics is applied to the real world. Little Barford only employs about 54 people and is one of the most efficient power stations in the country.

However with the limited stock of natural gas, and onset of nuclear power stations, power stations like Little Barford might be overtaken by the nuclear industry. If I had been given the opportunity to visit the power station again, I would have investigated the number of coils around the primary and secondary coil of the transformer, and obtained actual quantities to show how the formulas I used actually work. I could have also looked at the cooling system in more detail.

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