UNDERSTANDING ELECTRICAL TRANSMISSION

A Guide to the National Grid Transmission Model

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HEALTH AND SAFETY

The National Grid Transmission Model is intended for teacher demonstrations only, and no alterations should be made to the equipment. It is assumed that the demonstrations will be undertaken in suitable laboratories or work areas and that good laboratory practices will be observed. This booklet has tried to ensure that any recognised hazards have been indicated together with appropriate control measures (safety precautions). Teachers should consult their employers' risk assessments, and consider whether any modifications to the procedures are necessary for their own contexts. Further information about CLEAPSS guidance on the use of high-voltage equipment can be found on page 33 in the 'Notes for teachers'.

CONTENTS

INTRODUCTION

We all rely on having energy at our fingertips – from the light and warmth in our homes, and the power which keeps our factories and offices going, to the mobile communications and other technologies that are essential parts of our modern lifestyle.

National Grid owns and manages the grids which connect people to the energy they use. It 'joins everything up'. That puts National Grid at the heart of one of the greatest challenges facing society – creating new sustainable energy solutions for the future – and developing an energy system that can support economic prosperity throughout the 21st century.

The *National Grid Transmission Model* has been developed to provide teachers with a simple-to-use practical resource that illustrates key ideas about electricity. It addresses electricity generation, transmission and distribution, and provides a context for teaching about the basic principles of electromagnetism.

This booklet describes a range of teacher demonstrations that can be undertaken with the *National Grid Transmission Model.* These demonstrations are intended mainly for students aged 14-16, but the approaches can be adapted for younger or for older students. The classroom materials cover electromagnetic induction, the nature and generation of alternating currents, transformers, frequency and the effect of demand on generation.

It is hoped that these resources will support teachers in explaining to students the science underlying the electricity industry, and the challenges it presents for engineers now and in the future as society moves to a low-carbon economy.

CURRICULUM LINKS

The teacher demonstrations are this booklet is intended to support the science curriculum for 14-16 year old students, and are relevant to the areas indicated below.

Electric currents and magnetic fields

Production of a magnetic field when a current flows through a wire.

Motor effect and its applications.

Production of a current through an electrical conductor when it is part of an electrical circuit and it moves through a magnetic field.

Moving a magnet relative to a coil of wire induces a voltage across the coil.

Generation of electricity

Use of fossil fuels and nuclear fuels in power stations to heat water creating steam. This drives a turbine which is connected to a generator.

Use of a number of renewable energy resources (wind, hydroelectric, tidal, waves) to drive the generators directly.

Basic structure and operation of an electrical generator.

Effect of increasing the load on the generator and the fuel consumed.

Electric current and resistance

Factors that affect the resistance of a component and the current through it.

Heating effect of a current through a component.

Comparison of direct current (d.c.) and alternating current (a.c.).

Step-up and step-down transformers

Basic structure and operation of transformers.

Alternating current in primary coil produces a changing magnetic field which induces a changing voltage across the secondary coil.

Transformers can change an a.c. voltage but not d.c. voltage.

Electrical transmission and the National Grid

Key parts of the National Grid system.

Use of step-up and step-down transformers to change the voltage during transmission of electricity.

Reducing heat losses from transmission lines by using higher voltages (and thus lower currents).

Comparing relative merits of overhead power lines and underground cables.

The frequency and voltage of UK mains electricity supply.

Measurement and calculations

Using an ammeter in series with a component to measure the current through it.

Using a voltmeter in parallel with a component to measure the voltage across it.

Relationship between resistance, voltage and current.

Using displays of voltage against time for an alternating current to determine frequency.

For a transformer, relationship between voltage across primary and secondary coils and number of turns on primary and secondary coils.

Power as the rate of transfer of energy.

Relationship between power, voltage and current.

Measuring electrical power and calculating the efficiency of an electrical device.

USING THE NATIONAL GRID TRANSMISSION MODEL IN THE CLASSROOM

The *National Grid Transmission Model* was developed to support a series of teacher demonstrations to teach about the generation, transmission and distribution of electricity. These look first at how the model relates to the real-world system, before going on to explore the behaviour of each of the parts and the reasons for their design, and finally making quantitative measurements of the system as a whole.

This section gives an 'illustrated overview' of how the *National Grid Transmission Model* can be used in the classroom, along with some background information to set the scene. In the margin, references are given to the teacher demonstrations – the instruction sheets for these and the accompanying teachers' notes can be found later in the booklet.

Development of the National Grid

The first house in the world to be lit by electric light belonged to the British inventor, Joseph Swan, who patented a design for an incandescent light bulb in 1880. In the early days of electric lighting, the lamps were not far from the generators that powered them; today, power stations can be a long way from our homes. All are now connected across the whole country by complex distribution and transmission systems, even linked to Europe.

The National Grid lies at the heart of the system connecting the generation of electricity in power stations (left) to the supply in our homes (right).

The main stimulus for the development of the electricity industry was the drive for better lighting. In particular, lighthouses needed improvements to protect shipping, and the navy was very interested too. After this, came lighting in public spaces.

To power the lamps, electric generators were used. Batteries had been produced but their limitations had already started to hinder further developments. Electric generators were based on the work of Faraday earlier in the century, who had found that a current could be induced in an electrical conductor by a varying magnetic field. It is this same principle that underpins the operation of modern generators.

The world's first public electricity supply was provided in late 1881 in Godalming in the UK. This system used a water wheel which drove a Siemens alternator and powered 34 incandescent light bulbs. It was the pioneering work of Thomas Edison, Joseph Swan and Robert Hammond, in the cities of New York, London, and Brighton respectively, which contributed to the early development of what would become the electrical distribution systems. The limitation was that the generation had to be very close to the customers, and thus more and more coal had to be transported to meet the growing demand.

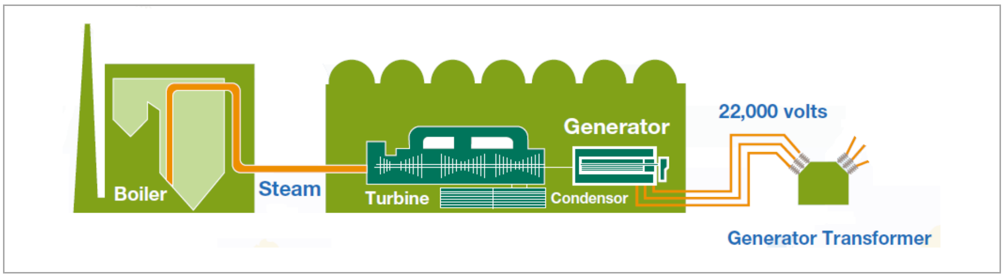
Edison's systems used *direct current* (d.c.) at a relatively low voltage; this leads to large power losses over long distances. Electricity could only be supplied to a small area around the generator. To avoid these problems, Nikola Tesla and George Westinghouse developed the use of high-voltage *alternating current* (a.c.) for electrical transmission, and despite Edison's vigorous opposition in the so-called 'War of the Currents', the technologically superior a.c. system emerged as dominant.

By the 1920s in the UK, around 6% of homes had electricity. It was supplied by many different local distribution systems working at different voltages. In 1926, an Act of Parliament established the Central Electricity Board responsible for creating a grid that would connect together about 120 of the most efficient power stations across the country. It was designed to operate at 132 000 V and 50 Hz. Underground cables were considered too costly and harder to maintain, and so overhead power lines were used suspended by 'pylons', technically known as transmission towers. This massive engineering project was completed in 1933. Because of increases in demand for electrical power, the grid was upgraded in 1947 using a higher voltage (275 000 V), with further links being upgraded with an even higher voltage (400 000 V) in the 1960s.

What the national transmission grid did was to enable the demand for electricity to be linked to the various sources of generation. This reduced the cost of electricity, increased energy security and enabled the growth of manufacturing. More recently, the transmission system is linking people to the renewable sources that can support a more sustainable society in the UK.

Today, electricity is generated from a variety of energy resources. Most electrical power is produced from fossil fuels (gas and coal) in thermal power stations. Water in a boiler is heated by burning fuels creating steam. This high-pressure steam passes over the turbine blades making the shaft rotate. This turns the generator, producing an electric current.

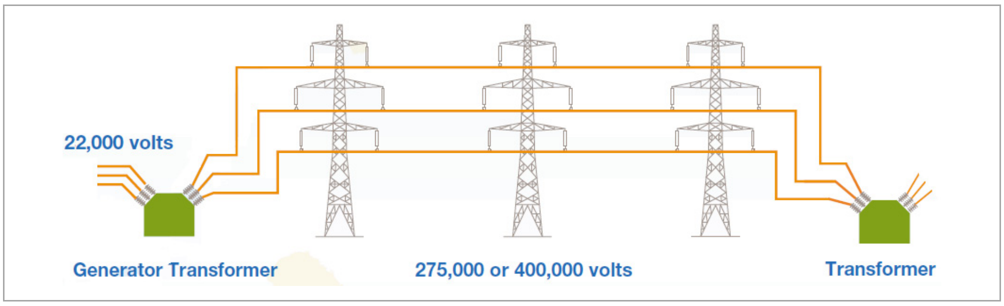
Generation of electricity: power stations are owned and operated by energy companies.



Nuclear fuels (and biofuels and geothermal energy) are used in a similar way, making water hot to generate steam. A number of renewable resources (wind, hydroelectric, tidal and wave power) are used to turn the generators directly. Photovoltaic cells (solar power) can generate an electric current directly.

A thermal power station generates electricity at around 22 000 V, though the exact voltage depends on the power station. This is stepped up at the generator transformer, before transmission via the National Grid at either 275 000 V or 400 000 V. The modern National Grid consists of 7000 kilometres of overhead lines, 22 000 transmission towers, over 1300 kilometres of transmission electrical underground cables and around 300 substations.

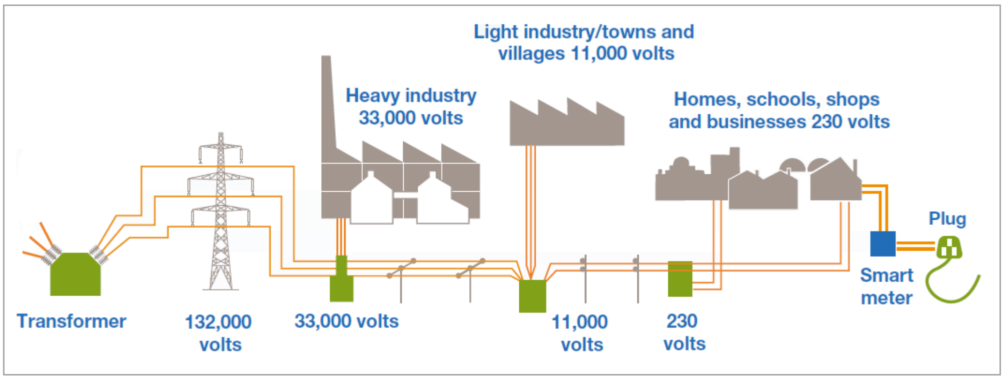
Transmission of electricity: the system of transformers and overhead transmission lines and underground cables is operated by National Grid.



The substations are the connecting points for the system, and include the transformers (for changing the voltage), and circuit breakers (for controlling the flow of electricity). The grid is now also connected overseas via underwater cables known as 'interconnectors' to Northern Ireland, France and the Netherlands.

The National Grid is connected to local distribution systems and the voltage is now stepped down using the grid supply transformers. The distribution system supplies customers with a wide range of needs, and for domestic use the voltage is successively stepped down until it reaches our homes at 230 V.

Distribution of electricity: factories and homes are connected to the National Grid via local systems operated by the energy companies.



Note that in these schematic diagrams, the electricity supply is represented by three lines, until this becomes two lines for domestic supply. This is because the generator actually contains three electrical circuits producing currents in sequence as a magnet rotates past them. This is known as 'three-phase' and makes better use of the available space inside the generator. Factories use all three phases for greater power, though in the home we only use one of these phases (the 'live' wire).

Introducing the system and its parts

The *National Grid Transmission Model* has been designed to help students to understand the principles of electricity supply, and to be able to relate these to the key parts of the real-world system as outlined in the previous section:

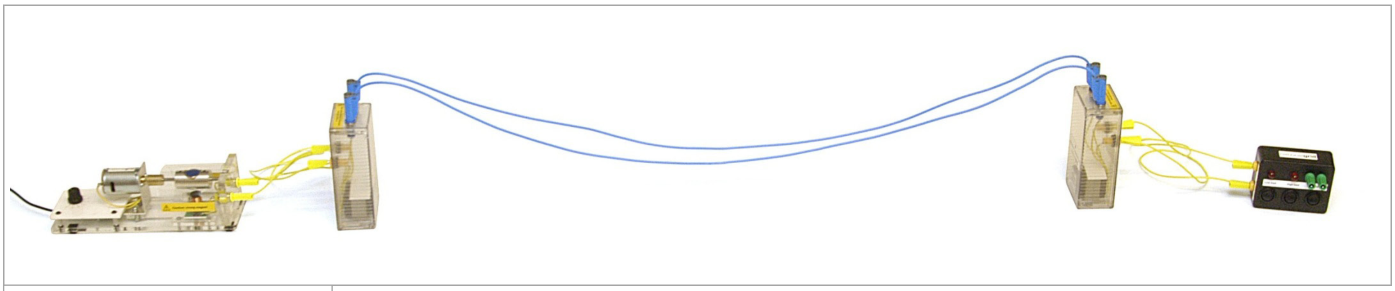
- boiler and turbine
- generator
- generator transformer
- overhead power lines
- transmission towers (pylons)
- underground cables
- substation
- grid supply transformer
- factories and homes.

CAUTION: The transmission model can produce voltages of up to 40 V a.c. and these demonstrations must only be undertaken by teachers. The equipment has been designed so that in normal use there are no exposed high-voltage contacts, and the generator must be switched off when connecting or disconnecting components. Further guidance about Health and Safety can be found on page 31 in the section 'Notes for teachers'.

In the classroom

See Demonstration A1
How is electricity generated and transmitted? (page 40)

The first thing to demonstrate to students is the operation of the *National Grid Transmission Model* as a whole, so that they can relate the parts of the model to the relevant parts of the real-world system. The model consists of a generator unit (with an integral mains power supply), a step-up transformer unit, a step-down transformer unit and a load unit, together with a set of connecting leads including a long pair of transmission leads. (For details of how to connect the units, see the section 'Setting up the equipment' on page 26.)



The National Grid Transmission Model set up and ready to use.

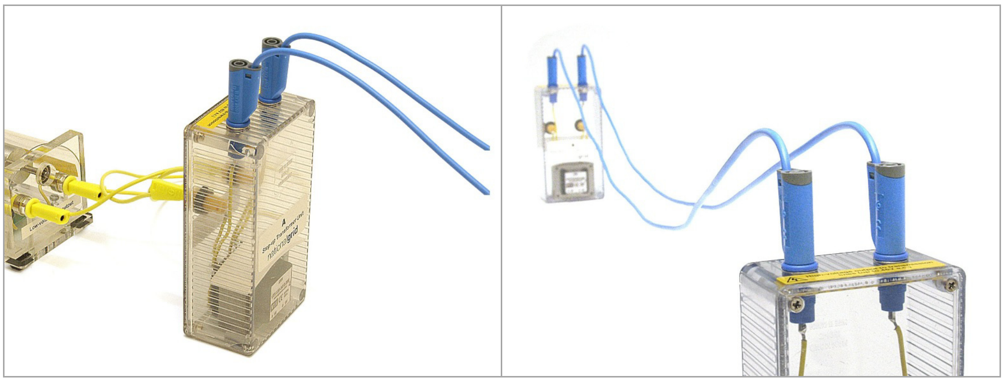
When the generator unit is turned on, students can see that the indicator LED on the load unit lights up. The basic function of each of the parts of the system can now be explained.

The generator unit consists of two parts. The drive motor (connected to the mains power supply) represents, for example in a gas-fired power station, the boiler and turbine. It is what turns the drive shaft that is connected to the generator.

The second part of the unit is a very simple generator consisting of just a magnet and coil – the magnet is attached to the drive shaft and rotates above an electrical coil which is connected to the output sockets. When the magnet moves over the coil it can generate a current in the external circuit.

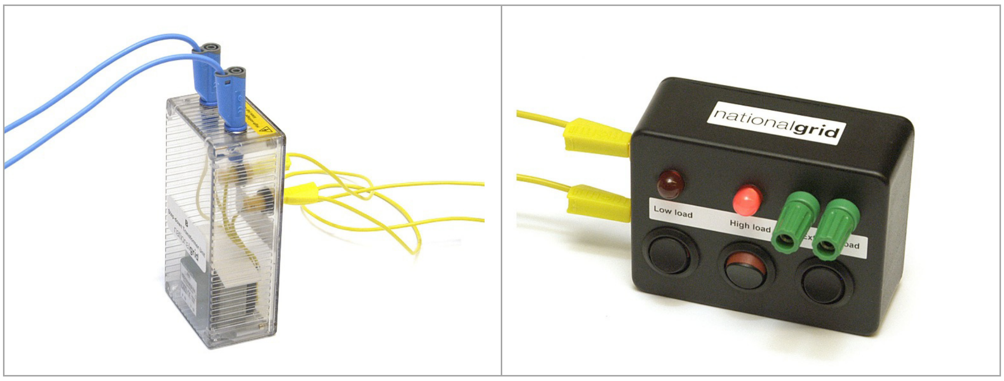
The two parts of the generator unit: the drive motor connected to a power supply (left) and the 'magnet and coil' generator (right).

The output from the generator unit is connected to a step-up transformer. This produces a higher voltage at the output sockets at the top of the unit. A long pair of transmission leads is connected to these sockets to represent the overhead lines that are part of the high-voltage grid.



The step-up transformer unit (left) and the transmission leads (right).

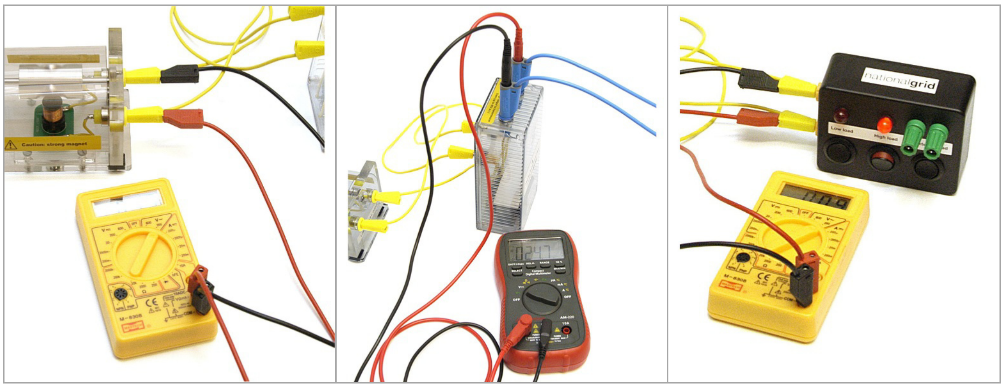
The other end of the transmission leads are connected to a step-down transformer, which reduces the voltage. The low-voltage output of this unit is then connected to the load unit. This has switches that represent low and high loads (and an even higher load when they are switched on together).



The step-down transformer unit (left) and the load unit (right).

The load unit also includes additional terminals to which external loads can be connected.

To demonstrate the change in voltage during transmission, multimeters can be connected at key points in the system: across the sockets of the generator, across the start of the transmission leads, and across the load. (Note that when making measurements at the high-voltage sockets on the top of the transformer units, a multimeter with shrouded leads must be used – see the section 'Setting up the equipment' on page 26.)



A multimeter can be connected at key points to show the change in voltage during transmission.

Typically, with a load connected, the output voltage (a.c.) of the generator is around 1.5 V. This is stepped up to around 25 V for transmission, while after being stepped down, the input voltage to the load unit is around 1 V.

An important part of the demonstration is to show students the effect of changing the load on the speed of the generator. If the load is switched off, you can hear the generator turn a bit faster; when the load is switched on again, the generator turns a bit slower. Increasing the load means that more power is needed from the generator, and this makes it turn more slowly.

This can seem counter-intuitive – the generator producing more power even though it is turning more slowly. An analogy can help students to understand this by thinking about what happens with a bicycle. If you are cycling on the level and then go uphill, you will tend to slow down. However, you will find it harder work because you need to produce more power.

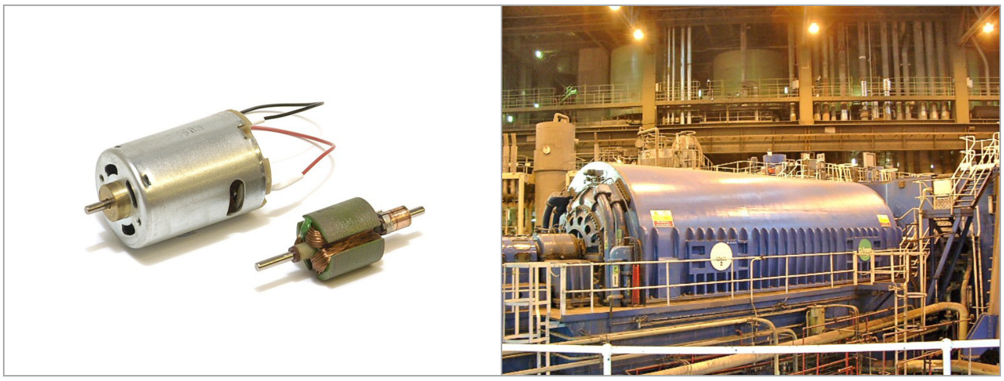
The National Grid needs to manage the energy flow into the system so that it is able to deal with changes in demand, and to keep the generators turning at a constant speed. This important idea is discussed in more detail in the following section on generators and on page 22 in 'Managing the demand for electricity'.

Having looked at the model as a whole, there is now a series of demonstrations that explore the key ideas in electromagnetism on which the electrical supply system is based. The following two sections look in more detail at the principles of the generator and of the transformer.

Key ideas in electromagnetism: the generator

When an electric current is passed through a wire, a magnetic field around the wire is produced. This effect is the basis of an *electromagnet*, in which an insulated wire is wound into a coil with a core of soft iron inside it in order to increase the strength of the magnetic field. If an electromagnet is placed near a permanent magnet, it will experience a force (attraction or repulsion depending on the orientation) when the current is switched on. This effect is the basis of a simple *electric motor*, in which the electromagnets are arranged on a shaft and the forces produced are used to create a rotation.

A simple electric motor, with the shaft and coils that are inside it shown alongside (left). One of the six generators (660 MW each) at Drax Power Station in Yorkshire (right).



Passing an electric current through a motor causes the shaft to turn around, but a simple electric motor like the one shown above can be also be used in reverse – if the shaft is rotated, an electric current is produced. This is because the coils experience a changing magnetic field as they rotate, and this induces an electric current in the wires. The motor is now acting as a generator. The huge generators found in power stations work on essentially the same principle. One difference, however, is that for the generator in a power station it is the *magnets* that are rotated by the shaft, with the *coils* being in fixed positions around the outside.

The generators in power stations produce an alternating current, the frequency of which is determined by the speed of rotation. Changing the load affects the speed of rotation, and an important role of the National Grid is to ensure that power generation matches demand, so that the generators do not slow down or speed up too much. Indeed they have a legal requirement that the frequency of our mains supply stays close to 50 Hz.

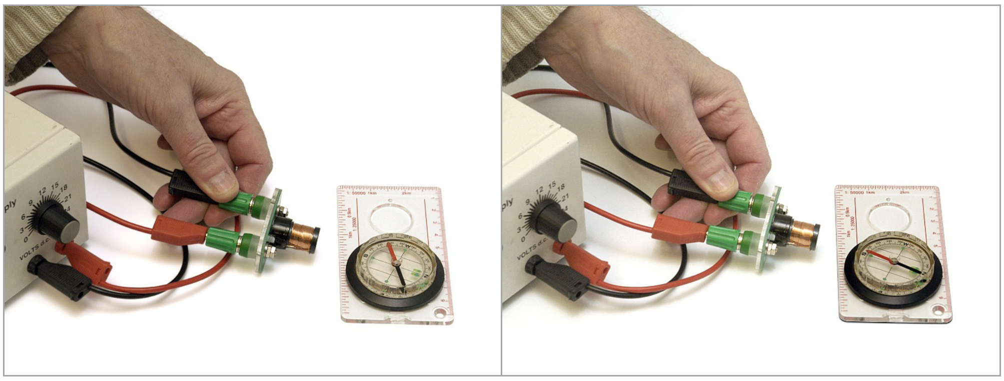
In an alternating current, the voltage constantly changes, oscillating from positive to negative values. When we say that the voltage of a domestic mains supply is 230 V, we are actually referring to an *average value*, and in fact the voltage would be oscillating between +325 V and –325 V. (The average is not a simple mean, which would give a value of zero, but the *root mean square* value, or *RMS* value.)

There are many 'classic' practical activities on electrical circuits and electromagnetism that could be done alongside the demonstrations discussed below. Complementary activities would include the nature of d.c. and a.c., the use of electrical meters, and electromagnetic induction. (For more details, see 'Additional practical work' on page 60 in the section 'References and further reading'.)

In the classroom

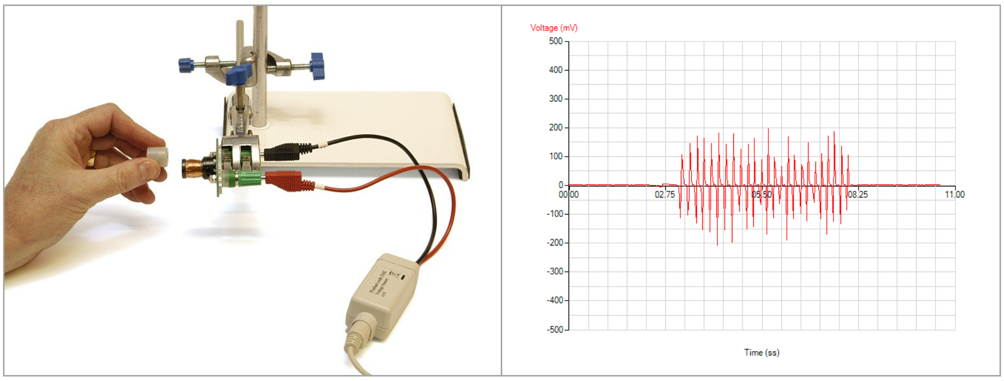
See Demonstration B1
How does the coil work?
(page 42)

At the heart of the model generator unit is a small electric coil. To demonstrate the coil's behaviour, it is convenient to use the separately mounted 'test coil' (identical to that used in the generator unit) included with the *National Grid Transmission Model*. If this is placed next to a magnetic compass, and then connected to a low-voltage supply, the compass needle is deflected. This shows that a magnetic field is produced when an electric current passes through the coil.



Test coil connected to a low-voltage power supply and placed next to a compass: before switching on current (left) and after (right).

The coil can also be used to *generate* an electric current. If it is connected to the voltage sensor of a datalogger, the effect of moving a strong magnet in front of it can be observed. While the magnet is moving towards or away from the coil, a voltage is detected, but when the magnet stops there is no voltage. The polarity of the voltage (+ or -) depends on the direction of movement. If the magnet is moved rapidly to and fro across the face of the coil, then an oscillating voltage is produced.



When a magnet is moved from side to side in front of the coil (left), the computer display shows that an oscillating voltage is produced (right).

So, in summary:

- When an *electric current* is passed through the coil it produces a magnetic *field* which causes the *movement* of the magnetic compass needle.
- The *movement* of a magnet next to the coil produces a changing *magnetic field* which induces an *electric current* in the coil.

See Demonstration B2
Generating electricity
(page 44)

Having explored the behaviour of the coil, students should now be able to understand how the generator in the *National Grid Transmission Model* works. They can observe that it has a magnet on a shaft which rotates above the coil and which induces a current in the coil – essentially the same effect as moving the magnet to and fro by hand.

To show how the voltage changes, the generator output can be connected to a voltage sensor as before, and the results displayed using a computer. The display shows an oscillating trace, as the voltage alternates between positive and negative values.

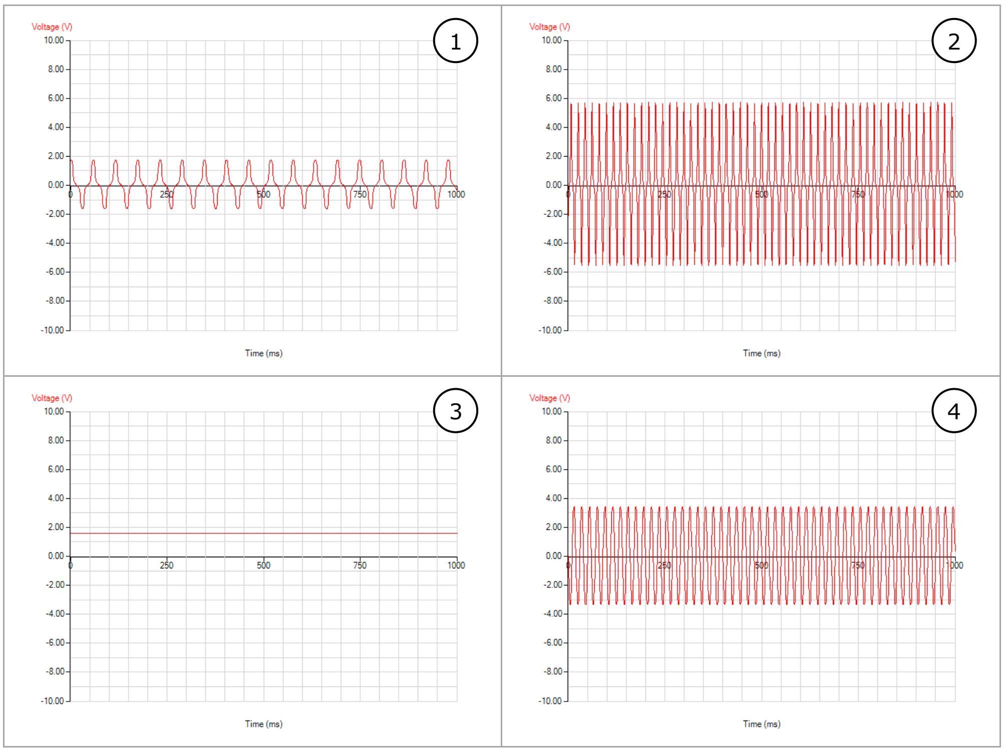
Computer displays showing the output of the following connected to the voltage sensor of a datalogger:

(1) generator unit (slow setting)

(2) generator unit (fast setting)

(3) 1.5 V battery

(4) a.c. power supply.



The frequency of this oscillation depends on the speed of rotation of the magnet which can be varied using the drive control in the generator unit. Students should be encouraged to listen to the sound of the motor and relate its pitch to the frequency shown on the datalogger display. The increase in maximum voltage and frequency can be observed as the generator turns faster.

If the datalogging duration is set to 1 second, then the frequency can simply be found by counting the numbers of oscillations shown on the display. For the generator on its maximum setting, the frequency is about 55 Hz.

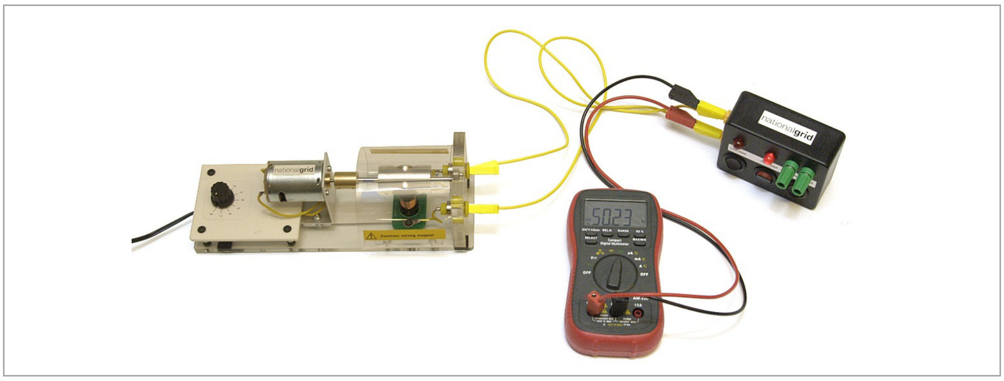
Students can be introduced to the idea that this is called an alternating current (a.c.). This can be compared to the 'flat line' output of a battery which is a direct current (d.c.).

The output from the generator unit can also be compared to the output of a low voltage a.c. power supply. Note that this produces a very regular oscillation (a sine wave), which contrasts with the less regular and more 'spiky' appearance of the output from the generator unit. The generators in power stations that provide our mains supply are carefully designed to ensure a 'clean' sine wave. The generator unit in this kit is a simple model, and the shapes of the magnetic field and of the coil are not optimised.

Using a voltage sensor and datalogger is a good way for students to get an understanding of the nature of the output, but making measurements of frequency and voltage is more conveniently done with multimeters. In subsequent activities, multimeters will be used, so it is useful at this point for students to compare the datalogger output with values measured using a multimeter. The value of the frequency shown on a multimeter should give a good agreement with that determined from the datalogger display. However, the value of the generator voltage measured with a multimeter is an *average* value, and will be less than the maximum voltage recorded by the datalogger.

See Demonstration B3
Connecting the generator to a load (page 46)

After seeing how the generator unit works, students can now be introduced to the idea of the effect of a *load*. If the load unit is connected to the generator unit, and the drive control turned up slowly, then students can see the LED on the load unit start to light. At first it appears to be flashing, but as the generator turns more rapidly, the LED appears steady. The point should be made that the LED is still flashing, but so fast that we are not able to perceive it due to persistence of vision.



The generator unit connected to the load unit, with a multimeter to measure the frequency.

The effect of the size of the load on the frequency can be show by turning the switches on the load unit to 'off', and adjusting the drive control until the multimeter reads about 50 Hz. If the 'High' load is now switched on, the frequency drops to about 47 Hz (and the pitch of the drive motor can be heard to lower). To maintain a constant frequency, the drive control is then turned up until the multimeter reads about 50 Hz again. Thus with an increased load, the power output of the generator needs to be increased in order to maintain the same frequency. This models the way in which the National Grid manages generation to match demand and keeps the frequency approximately constant.

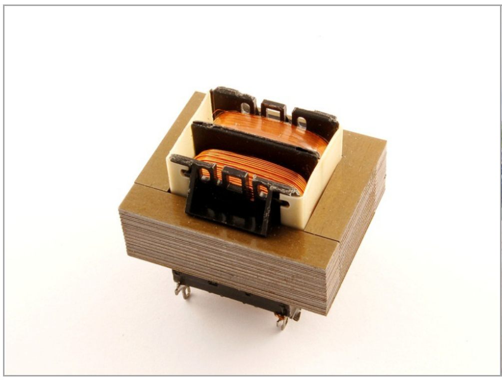
Note that this simple generator uses a spinning magnet and a single coil. Power stations have *three-phase generators* which also use a spinning magnet, but with three coils placed 120° apart around the outside, thus inducing a current in three circuits.

Key ideas in electromagnetism: the transformer

A *transformer* is a device that can change the voltage of an alternating current. In the generation, transmission, and distribution of electricity many different voltages are used. All these changes are achieved using transformers. Transformers that increase the voltage are called *step-up transformers*; transformers that decrease the voltage are called *step-down transformers*.

Many devices that we use in the home operate on lower voltages than mains electricity, and so transformers are used within the device or within a separate power supply. These small domestic transformers operate on the same principle as the large transformers that are used in the transmission of electricity. They consist of two sets of coils: the *input* or *primary coil* and the *output* or *secondary coil*.

A small transformer as used in domestic appliances (left). National Grid substation near Wrexham (right) showing transformer in foreground.



Passing an alternating current through the primary coil creates a changing magnetic field: this changing magnetic field induces an alternating current in the secondary coil. The voltage in the secondary coil depends on the relative number of turns in each coil:

$$\frac{\text{voltage across primary coil (V)}}{\text{voltage across secondary coil (V)}} = \frac{\text{number of turns on primary coil}}{\text{number of turns on secondary coil}}$$

So, for example, a step-up transformer that doubled the voltage would have twice as many turns on the secondary coil as on the primary coil.

The power output of a transformer cannot be greater than the power input – it does not give 'something for nothing'. An *increase* in voltage is accompanied by a *decrease* in the current. In an electrical circuit, the power is determined by the voltage across a component and the current through it:

$$\text{power (W)} = \text{voltage (V)} \times \text{current (A)}$$

Thus, for a transformer with 100% efficiency, if the voltage doubles then the current will be halved. For a real transformer with an efficiency of less than 100% (depending on size, transformers have efficiencies of around 90% - 99%), then the current in this case would be less than half.

To increase the strength of a magnetic field through the coil, the transformer contains an iron core. Making the core from a number of thin sheets of iron, rather than a single block, results in less heating and therefore greater efficiency. (The reason is that this reduces the 'eddy currents' induced in the core.) These laminated iron sheets can be seen in the photograph of the domestic transformer.

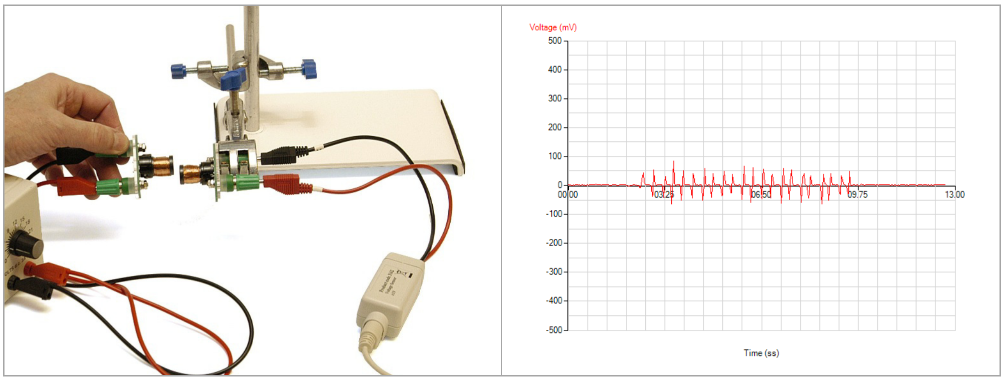
Even though the transformers used in electrical transmission are quite efficient, a significant amount of power is lost through the heating of the coils and the core, and the temperature needs to be controlled by dissipating this energy.

There are many 'classic' practical activities on electrical circuits and electromagnetism that could be done alongside the demonstrations discussed below. (For more details, see 'Additional practical work' on page 60 in the section 'References and further reading'.)

In the classroom

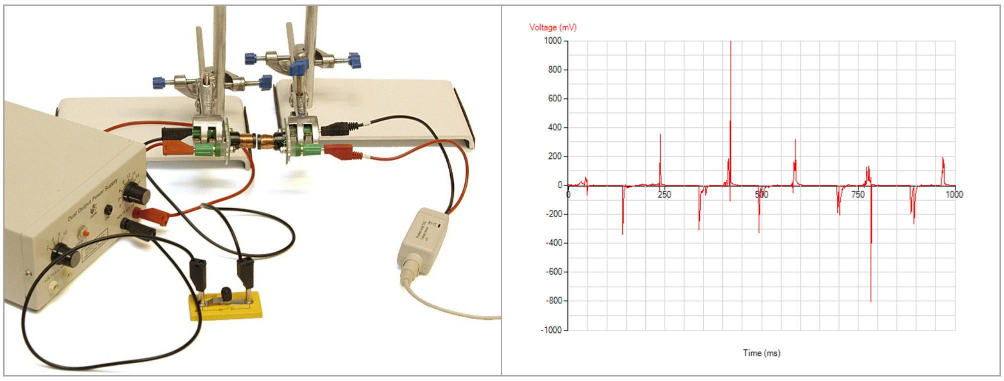
See Demonstration B4
How is the voltage changed? (page 47)

In the previous section, one of the 'test coils' included with the *National Grid Transmission Model* was used to demonstrate how a current could be induced in the coil by moving a magnet in front of it. However, there are other ways of creating a changing magnetic field than by moving a permanent magnet. It can also be done by using another 'test coil'. The first thing to do is essentially the same as before, but using a coil connected to a low-voltage d.c. supply instead of a permanent magnet. Moving the 'electromagnetic' coil in front of another coil, connected to the voltage sensor of a datalogger, produces an output voltage that can be displayed on a computer screen.



Moving a test coil connected to a d.c. supply across the face of a second test coil (left) will induce a current that can be displayed using a datalogger (right).

Another way of creating a changing magnetic field is to keep the first coil still, but to switch the current on and off. The two coils are clamped close to each other, and the push button switch is turned rapidly on and off. Note that it is better to leave a small gap between the faces of the coils as this emphasises that the current in the second coil is not produced 'by contact'.

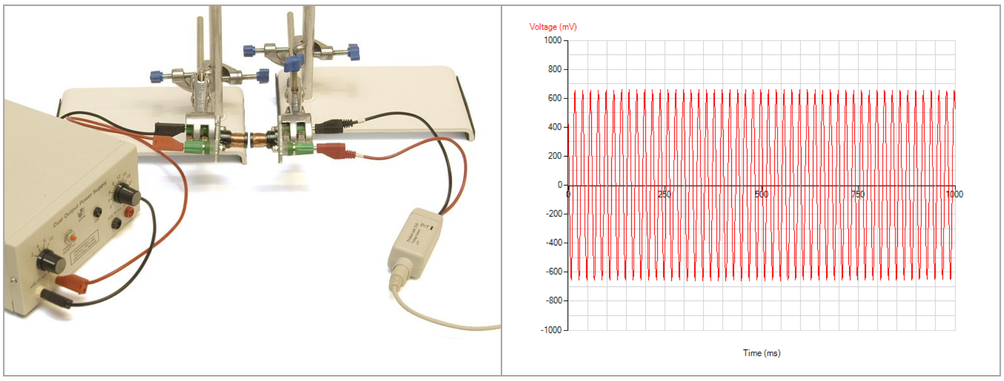


Switching a d.c. current on and off in the first coil (left) will also induce a current in the second coil that can be displayed using a datalogger (right).

A voltage peak is produced in the second coil each time the current in the first coil is switched on or off – note that switching the current on produces a peak of opposite polarity to switching the current off.

Finally the coil can then be connected to a low-voltage a.c. supply. An alternating current also produces a changing magnetic field, and the output consists of a series of 'up and down' peaks – similar, though more regular, to the effect of rapidly switching a d.c. supply on and off.

Passing an a.c. current through the first coil (left) will induce an alternating current in the second coil as shown on the display (right).



An important idea here is that the frequency of the a.c. input is *the same as* the frequency of the a.c. output. The changes of the current in the input coil are reflected in the changes of the magnetic field that it produces, which in turn are reflected in the changes of the induced current in the second coil.

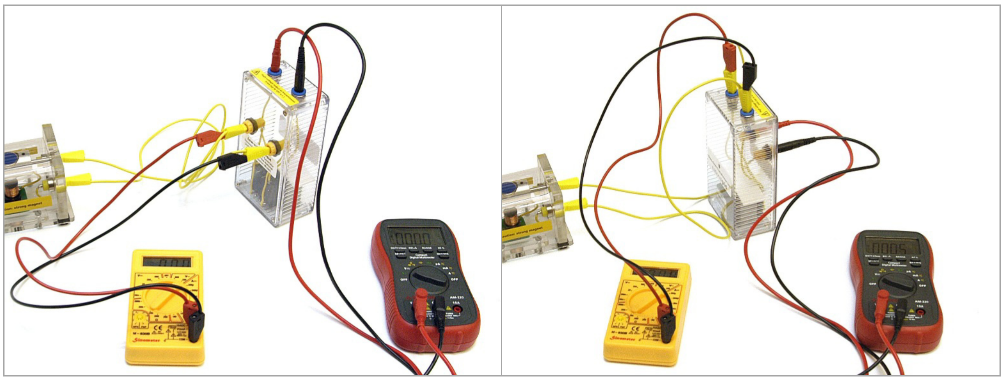
This can be shown by connecting a multimeter to the output from the power supply and the output from the second coil – the values will be the same (the mains frequency of 50 Hz).

See Demonstration B5
Step-up and step-down transformers (page 49)

The coils used in the previous demonstration are not very efficient, and a high proportion of energy is lost. The step-up and step-down transformer units used in the *National Grid Transmission Model* use commercial transformers specifically designed to be much more efficient at transferring energy. They still use the same principle of primary and secondary coils to change the voltage, and before carrying out the demonstrations with these units, students should observe the construction of the transformers within the transparent boxes. They should be able to see the laminated iron block and the connections to the primary and secondary coils.

The operation of each of the transformer units can be demonstrated separately. First, the step-up transformer is connected to the generator unit, and the input and output voltages of the transformer measured using multimeters. With the generator unit set on maximum, the input voltage is typically about 1.9 V and the output voltage about 35 V.

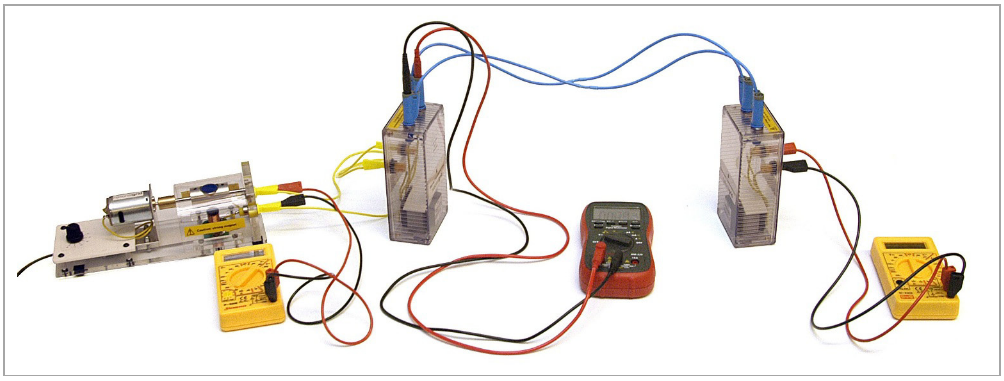
Measuring input and output voltages of the step-up transformer (left) and the step-down transformer (right).



A similar thing can now be done with the step-down transformer. Again with the generator on maximum, the input voltage is typically about 1.9 V and the output voltage about 0.15 V.

The two transformers can now be connected to each other to model the way that transformers are used in the National Grid. The output from the first transformer is connected (using the short blue connecting leads with shrouded plugs) to the input of the second transformer. Multimeters are connected to demonstrate how the voltage is first stepped up and then stepped down. For this arrangement, the output from the generator will be around 1.8 V which is changed to around 34 V by the step-up transformer, and back to around 1.8 V by the step-down transformer.

Using the step-up and step-down transformers together.



Finally, a multimeter with a frequency function can be used to measure the frequency at each of these three points of the system. As before, students can see that although a transformer changes the voltage, it does not change the frequency. This is also the case with the National Grid – the frequency at the generator is the same as the frequency in our home. Indeed, it is because frequency is the same everywhere that it can be used to monitor the system.

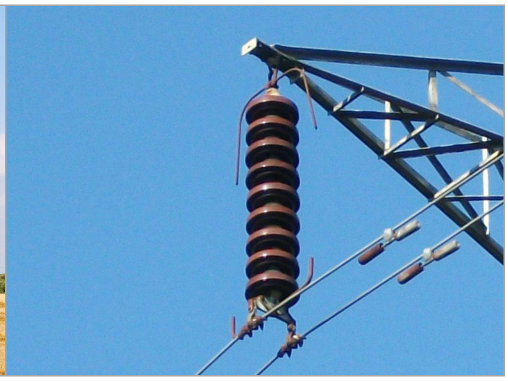
These demonstrations emphasise why a.c is used for electricity transmission. With a.c., the voltage can be changed relatively easily, but this would be more difficult if d.c. were used. Transformers only work with an alternating current, and not with a direct current, since only an alternating current produces a changing magnetic field.

Getting the energy where it is needed

Electricity in a power station is generated at around 22 000 V, but it is transmitted at much higher voltages. It requires expense to construct the transformers necessary to step up and step down the voltage, and in addition there are power losses during the operation of the transformers. So why not transmit the electricity at the same voltage as it is generated in the power station? The answer to this lies in the nature of the *transmission lines*.

In the laboratory, we generally think of connecting leads as having a 'zero resistance'. In fact, they do have a resistance, but it is so small that it can be neglected. However the National Grid needs to use 'connecting leads' over many hundreds of miles, and because of these large distances, the transmission lines do have a significant resistance. This means that they *warm up* with an electric current through them, and thus some *energy is lost*. By using a higher voltage the warming effect is reduced and less energy is lost.

The transmission of electricity over long distances leads to significant power losses (left). High voltages are used to minimise losses, but require careful insulation of the transmission lines (right).



The reason why higher voltages lead to lower power losses is because of the relationship:

power lost = current^2 x resistance (or $P = I^2R$)

Power losses can thus be minimized by keeping the current and the resistance as low as possible.

Resistance: The overhead power lines are about 3-4 cm in diameter, and consist of a number of strands of aluminium (a good conductor). The resistance of these lines is already very low – less that 0.1 ohm per kilometre. It would be possible to reduce the resistance by using thicker lines, or more lines, but this would be expensive and would require stronger towers.

Current: Using a step-up transformer increases the voltage and reduces the current. If the voltage is *doubled*, the current is *halved,* and thus the power lost through a transmission line would be reduced to *one quarter* (because it is proportional to the *square* of the current).

So, using higher voltages leads to dramatic reductions in power lost. This is why successive upgrades of the grid have gone from 132 000 V, to 275 000 V and to 4000 000 V.

The power losses could be reduced further if even higher voltages were used, but high voltages also have disadvantages. The higher levels of electrical insulation needed would be costly, and there would be problems with ionisation of the air, and so the existing voltage values represents a compromise.

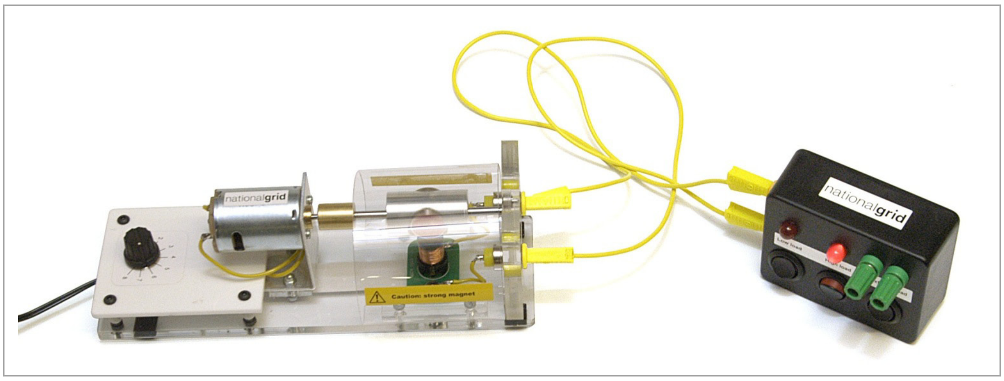
In the classroom

The first demonstration in this section shows that there are power losses when transformers are used. The second demonstration shows that the power lost is lower when electricity is transmitted at high voltages, and this outweighs the losses in the transformers.

See Demonstration C1
Transformers and power
(page 52)

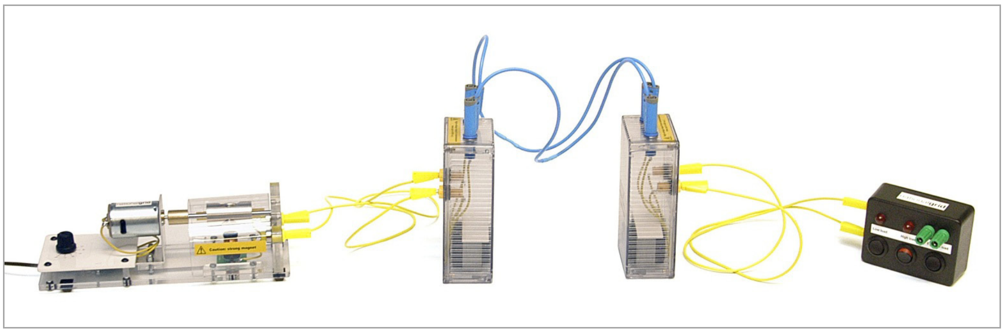
To show the effects of transformers on the power, firstly the generator and load unit are used on their own. With the load set on 'High', the drive control of the generator is turned up until the LED on the load unit *just* starts to light up.

The drive control of the generator set so that the LED just lights.



The generator is now switched off and the step-up and step-down transformer units are connected between the generator and the load. The transformer units are connected to each other using the short blue connecting leads: unlike the long blue transmission leads used in the initial demonstration, the short leads have a negligible resistance.

Using the same drive control setting, the LED does not light when the transformers are added.

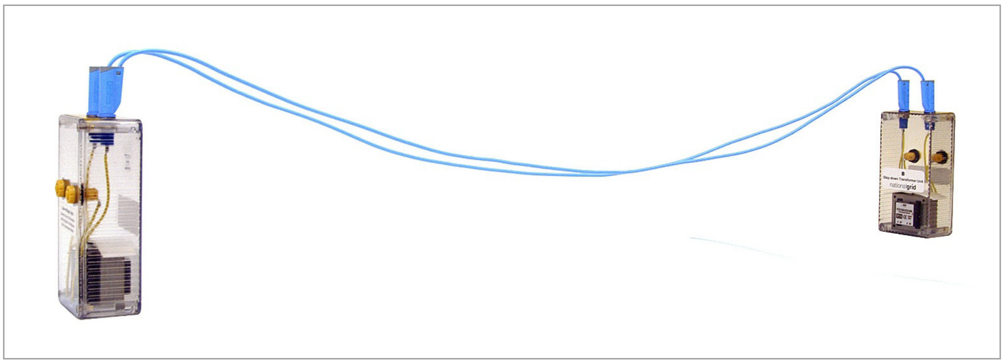


When the generator is switched back on again (with the same setting on the drive control) the LED does not light. This is because of the power losses in the transformers. When the drive control is turned up further the LED will light up again, making the point to students that the reason it did not light initially was due to a power loss, and not, for example, due to a faulty connection.

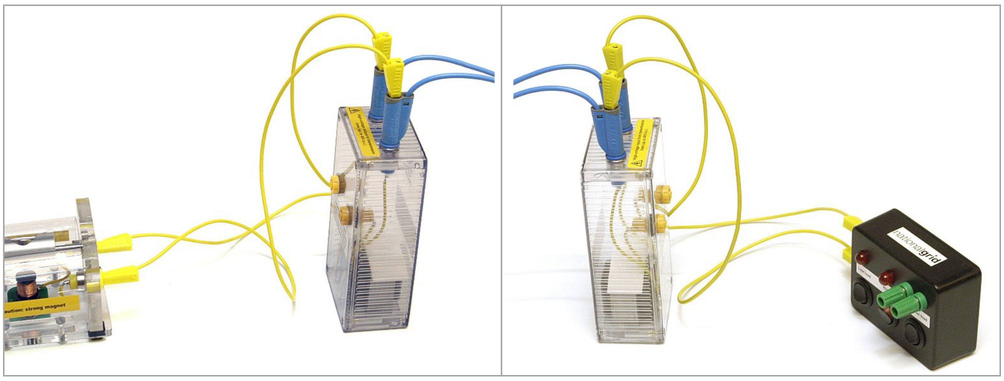
See Demonstration C2
Why are high voltages used for transmission? (page 53)

The short blue connecting leads are intended to represent the transmission of electricity over a short distance. To model long-distance transmission, the long blue transmission leads can now be used. Unlike the short leads, these have a significant resistance (note that for reasons of cost, these have been produced by including a resistor in a connecting lead, rather than by using insulated resistance wire). These leads are used to connect the step-up transformer to the step-down transformer.

Transformers connected using the long transmission leads.



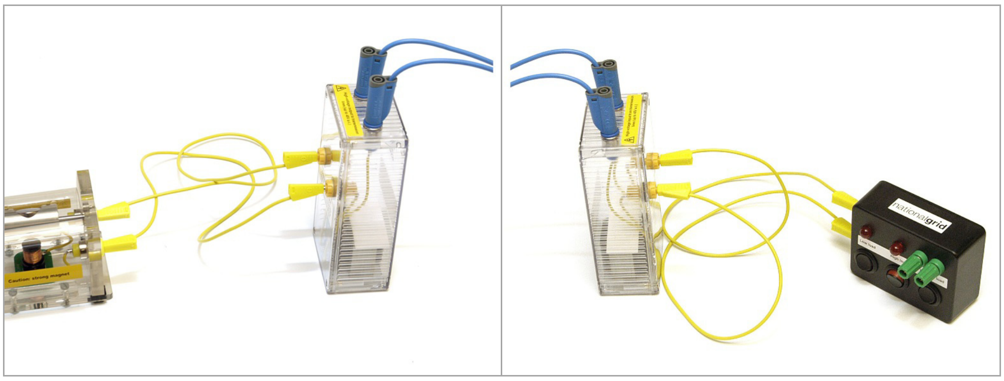
This arrangement can now be used to look at the difference between low-voltage and high-voltage transmission. For low-voltage transmission, the output from the generator is connected directly to the start of the transmission leads; the ends of the transmission leads are connected directly to the load unit.



Low-voltage transmission: the transmission leads are connected *directly* to the generator unit (left) and the load unit (right).

With the generator on maximum, this arrangement provides sufficient power to light up the LED for the 'Low' load, but not for the 'High' load.

For high-voltage transmission, the output from the generator is now connected to the input of the step-up transformer; the output of the step-down transformer is connected to the load unit.



High-voltage transmission: the transmission leads are connected *via the transformer units* to the generator unit (left) and the load unit (right).

Now, this arrangement provides sufficient power to light up both 'Low' and 'High' loads together. This demonstrates how the use of transformers *decreases* the power losses overall by *reducing the power lost from the transmission leads*.

The effect of the power losses can be seen by measuring the voltage across each of the ends of the transmission leads. For low-voltage transmission using a 'Low' load, typical values are 1.8 V across the sockets at the start of the leads and 0.9 V across the sockets at the end. Corresponding values for high-voltage transmission might be about 26.3 V and 26.1 V. Relatively, there is therefore a very much higher drop for low-voltage transmission, and the effect is even more marked using higher loads.

This drop in voltage along the length of the transmission leads is a consequence of the power loss due to the resistance of the leads. If they had no resistance, there would be no power loss and no drop in voltage along their length.

Note that in other parts of these demonstrations, voltage measurements have only been taken at one end of a connecting lead, because it is assumed that for such a lead, the voltage will be the same at each end. The lead is a good conductor, and so the voltage drop along its length is hardly measurable (if it were a perfect conductor there would be no drop at all). However, this may not be obvious to all students, and so if this point arises, you could also make measurements at other points.

In an earlier section ('Key ideas in electromagnetism: the generator', the effect of the size of the load on the frequency was demonstrated by using a multimeter with a frequency function. This can also be done here, showing how a constant frequency of 50 Hz can be maintained as the load changes, although the effect of load on frequency with the transformers included is not as great as previously when the generator was connected directly to the load.

Measuring power and efficiency

Power losses are inevitable, but it is important to reduce them as much as is practicable. In the National Grid, power is mainly lost due to the heating effects of currents in electrical conductors (known as I^2R losses). This occurs in the generator transformers, in the overhead lines and underground cables of the network, and in the grid supply transformers that connect to the distribution system. There are also so-called 'fixed losses' due to such things as the ionisation of air around overhead lines and eddy currents in the cores of transformers.

Estimated power losses for the system at peak demand (2012/13).

Category	**Power loss (MW)**
Generator transformer heating losses	165
Transmission heating losses	1367
Grid supply transformer heating losses	145
Fixed losses	278
Total	**1995**

Thus, the estimate for total losses at peak demand is 1995 MW. That represents the output of three medium-sized power stations, which sounds a huge amount of energy until it is put in the context of total output. The estimate of peak demand including losses for 2012/13 is 63 765 MW, so the total loss as a percentage of demand is a rather modest 3.07%.

Thus overall losses in the National Grid are low, but because losses increase as the voltage decreases, there are significant losses in onward electricity distribution to the consumer. The losses on the distribution system can be up to 15%, causing a total distribution loss of around 7% to 8%.

In the classroom

See Demonstration D1
Power losses in transmission (page 56)

Previous demonstrations have used the brightness of the LEDs on the load unit to get an idea of the amount of power transmitted. It is also possible to make quantitative measurements of the power output of the generator and the input to the load in order to estimate the efficiency of transmission. Power can be found by measuring the *voltage across* a component and the *current through* it. The first step is to measure the power output of the generator connected directly to a load.

Finding the power output of the generator by measuring the values for voltage and current.

It is important here that students understand the differences in the ways that a voltmeter and an ammeter are connected, and the reasons for the differences. Here, the voltmeter is the yellow multimeter, and the ammeter is the red multimeter.

The *voltmeter* (yellow) is connected *across the sockets* of the generator; the *ammeter* (red) is connected as *part of a series circuit* with the generator and the load.

From these values, the power output from the generator to this load can be calculated:

power (W) = voltage (V) x current (A)

With the generator on its maximum setting and the load on ‘Low’, typical values are 1.8 V and 130 mA, giving a power output of 234 mW.

The power input to the load can now be determined using the three ‘transmission systems’ that were explored qualitatively in the previous section:

- high-voltage lines with negligible resistance (short leads with transformers)
- low-voltage lines with significant resistance (long leads with no transformers)
- high-voltage lines of significant resistance (long leads with transformers).

The ammeter is put in series with the load unit as before, and a voltmeter is connected across the sockets of the load unit. Typical values for the power input using the above three transmission systems are 126 mW, 45 mW and 119 mW respectively. With an output from the generator of 175 mW, this gives efficiencies of 54%, 19% and 51% respectively.

From these results, introducing the transformers but using connecting leads of negligible resistance causes the efficiency to drop considerably by almost a half to 54%. The power losses in the transformers for this kit are thus very high – proportionally much higher than for the National Grid.

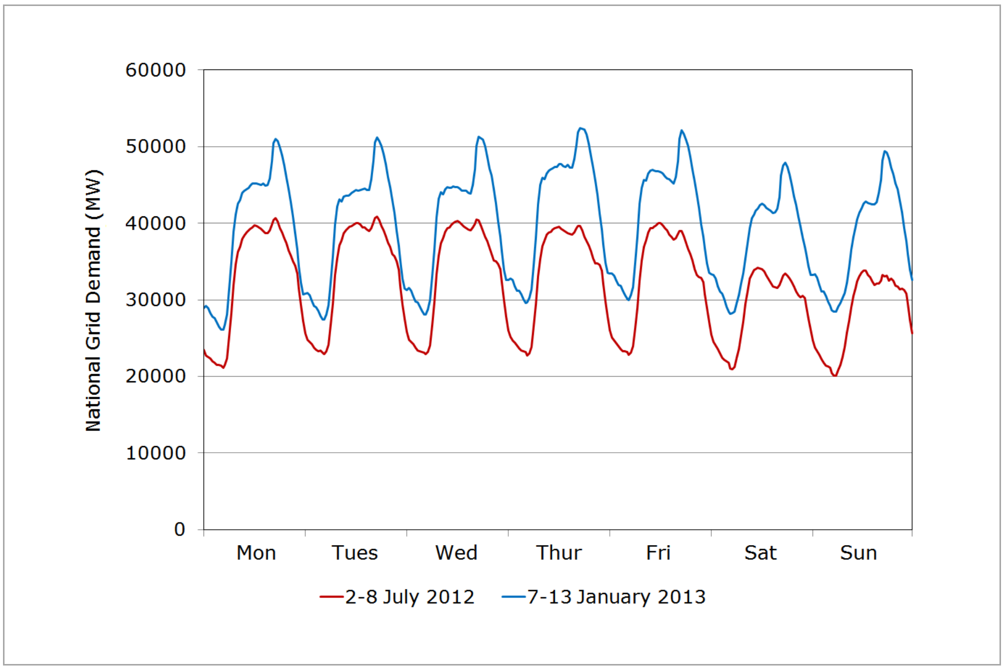
However, using this arrangement, the efficiency drops only a little further to 51% when the short connecting leads are replaced by the long leads with significant resistance. There is a relatively small power loss in the transmission leads.

This contrasts with the use of low-voltage with the long leads, where the efficiency is only 19%. No transformers are used in this arrangement, and all of this power is lost in the transmission leads. This result emphasises the importance of using transformers for high-voltage transmission in order to reduce power losses.

Managing the demand for electricity

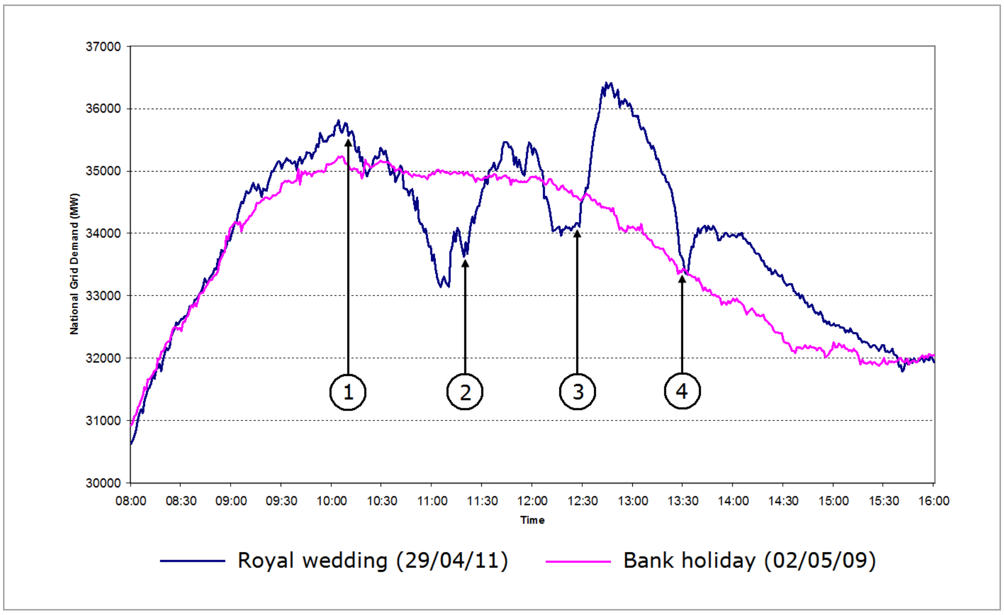
The demand for electricity is not constant. It changes over the year, with more power being needed in the colder months. It also changes over the course of a week, reflecting different patterns of behaviour during weekdays and weekends. And it varies over the course of a day – people generally require more electricity when they are awake than when they are asleep.

Variation in National Grid demand (in MW) over the course of a week (Monday to Sunday) – the graph contrasts the demand during a typical week in the summer and in the winter.



In particular, there are certain times of the day when the demand can change very dramatically over the course of seconds and minutes. As people put on kettles at the end of TV soaps, sports programmes or other popular events, there can be large surges in demand. This effect is known as 'television pickup'.

Electricity demand during the royal wedding of William and Kate shows marked differences from a typical bank holiday, with rapid rises and falls at key moments during the day.
1. William and Harry leave Clarence House.
2. Couple pronounced man and wife.
3. Bride and groom arrive at palace.
4. Balcony and kiss.

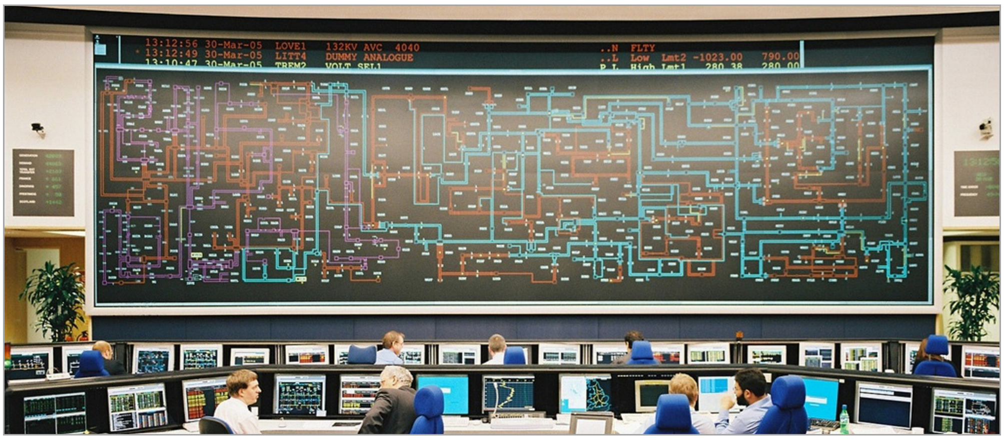


Electricity cannot be stored, and so the instantaneous generation must match the demand being taken from the system. If the instantaneous demand rises with no change in generation, then the system frequency will fall; conversely, if the demand falls below generation, then the frequency will rise.

It is the responsibility of the National Grid to ensure that generation matches demand as closely as possible. The normal system frequency is 50 Hz, but because of the continual changes in generation and demand this frequency varies. The National Grid has statutory obligations to maintain the frequency to within ±0.5 Hz of the target level of 50 Hz, though it normally operates within more stringent 'operational limits' which are set at ±0.2 Hz.

The system is monitored by the National Grid Control Centre. It uses computer models to predict changes in demand over long and short timescales, alongside information such as weather forecasts and TV schedules. As the demand varies, more generating capacity can be brought in or taken out.

It is easier to manage the more gradual changes over the day than the sudden surges of television pickup, because power stations need relatively long lead times to be brought online. However, pumped storage facilities, such as the 'Electric Mountain' at Dinorwig in North Wales, can be operational very quickly. During times of low demand, electrical power is used to pump water from a lower to a higher reservoir. When a large surge in power is needed, water from the upper reservoir is released to drive a turbine which can go from zero to maximum output in a matter of seconds.



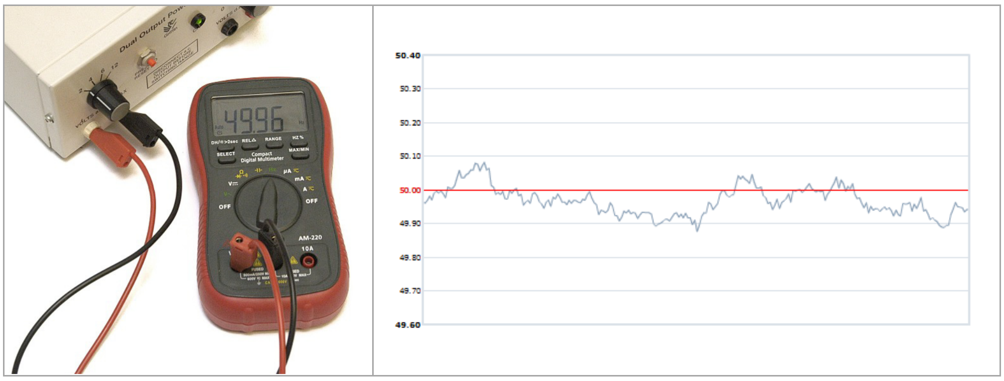
The National Grid Control Centre ensures that the frequency of the system is maintained.

The fluctuations in frequency are thus the result of a complex interaction of events involving demand and generation, and the pattern generated over any time interval is unique. It is this feature that has enabled forensic scientists to use the frequency of mains electricity as a kind of 'time fingerprint'. Any evidence involving audio recordings that have been made near an electrical power source will have this characteristic pattern of frequencies as a 'background hum'. This can be used to identify the exact time of recording, and whether a recording is genuine or includes edited sequences.

In the classroom

See Demonstration E1
Monitoring the National Grid frequency (page 58)

Using a multimeter with a frequency function, it is straightforward to monitor the changes in frequency of the National Grid. It just needs to be connected to a low-voltage a.c. supply and readings taken at regular intervals. There should be sufficient variation over the course of a lesson to show clearly how it rises and falls in an irregular pattern.



Measuring mains frequency using a multimeter (left). Real-time frequency data on the National Grid website (right).

The variation will be very small – very rarely is it greater than ±0.2 Hz – and so a multimeter displaying two decimal places will be needed. The readings taken from the multimeter can be compared to the real-time data on the National Grid website. There is a web page that displays the frequency data for the previous hour and updates automatically (note that there may be a delay, so the current value displayed on the graph may not be the same as the reading on the multimeter).

Students should be able to see the similarities between the values recorded on the multimeter and those displayed on the web, emphasising that these changes in frequency are *the same across the whole system*. Students should be encouraged to think beyond the set of digits displayed on the multimeter to the remarkable system that generates them – all of the generators in the power stations across the UK that are synchronized with this frequency and the way the changes in frequency are influenced by the decisions of millions of people across the country as they use electricity.

Future developments

Currently, electricity generation in the UK is heavily dependent on fossil fuels. Gas and coal account for around 75% of electricity produced, with most of the remainder being made up from nuclear and wind power. The UK is committed to a very significant reduction in greenhouse gas emissions over the coming decades, which will mean a move away from fossil fuels and the possibility of using 'carbon capture and storage' (CCS) to reduce the amount of carbon dioxide released from power stations. In addition, development of energy-efficient technologies, such as improvements in building insulation and heating, should lead to a decrease in emissions, but will lead to an increase in electricity usage. The biggest change will be the electrification of personnel transport.

This shift in the energy resources used for generation will have consequences for the National Grid. The original purpose of the grid was to connect power stations and consumers from all over the country, so that power no longer needed to be generated locally. There is at present a net flow of electricity in this country from north to south – about half of the demand is in the bottom quarter of the country geographically. As old gas-fired power stations are decommissioned, and renewable sources increase, this southwards flow will increase. Most wind power developments will be in coastal and northern regions, particularly in Scotland, and will tend to be more widely distributed than the old power stations. The high-voltage grid will need to be extended to adapt to these new circumstances.

Computer technology has touched every aspect of our lives, and electricity supply will be no exception. In the past, domestic electricity meters have required a visit by a meter reader for this information to be passed on to the energy company. Now, 'smart meters' are beginning to be installed and within the next few years most homes will have had their old meters replaced. These meters will send useful data regularly back to the company, as well as providing information to the consumer to help in managing their energy usage. This kind of technology will be used across the entire system, developing a 'smart grid' in which computer technology will play an increasingly prominent role in the collection of data and in the control of our electricity supply.

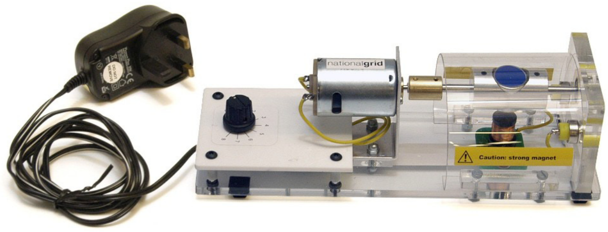
SETTING UP THE EQUIPMENT

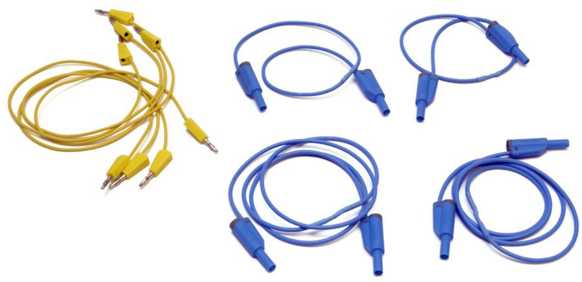
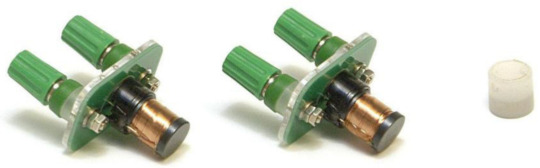
⚠ *The maximum recommended value for uninsulated electrical conductors is 28 V a.c. The National Grid Transmission Model can generate voltages of up to 40 V a.c. at the output sockets of the step-up transformer, but its design ensures that in normal use there are no exposed connections higher than the recommended value.*

The National Grid Transmission Model is designed to be used for demonstration by teachers. A number of demonstrations involve the generation of high voltages, *and these demonstrations must not be undertaken by students under any circumstances*. Other practical activities involving only low voltages may be suitable for student use. Further guidance on Health and Safety can be found on page 33 in the section 'Notes for teachers'.

Contents of the kit

The National Grid Transmission Model consists of the following components:

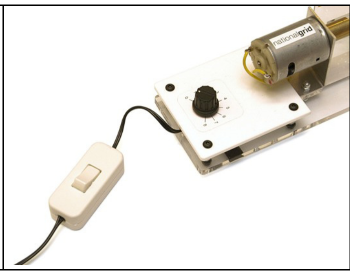
Generator unit The generator unit consists of an electric motor connected to a strong magnet which rotates above an electrical coil connected to the output sockets. The motor is attached to an integral mains power supply.	
Transformer units There are two transformer units – a step-up transformer unit (labeled 'A') and a step-down transformer unit (labeled 'B'). When put in the upright position, the high-voltage sockets that carry the transmission leads (colour-coded blue) are at the top.	 
Load unit The load unit contains two internal loads ('Low' and 'High') with LED indicators, each separately controlled with a switch. There is also a pair of terminals for connecting an external load.	

Connecting leads Low-voltage: 4 yellow plug-plug leads. High-voltage: 2 short blue connecting leads and 2 long blue transmission leads. (Note that the high-voltage leads have sheathed plugs.)	
Additional resources To demonstrate some key principles of electromagnetism, the kit also includes two test coils and a test magnet (a supermagnet in a 'holder').	

Most of the demonstrations described in this booklet require some additional standard laboratory apparatus. Further information about multimeters and dataloggers are given later in this section. Low-voltage d.c. and a.c power supplies are required for the demonstrations involving the test coils. Other power supplies should *not* be used in conjunction with the generator unit or the transformer units: these should only be used as described in the teacher instruction sheets.

The generator unit

⚠ *Caution should be taken to avoid magnets or metal objects getting close to the protective cover over the magnet on the generator unit. This is an extremely strong magnet, and its effects can be felt at some distance.*

The generator unit has an on-off switch and a drive control that adjusts the speed of the motor (left). The unit comes complete with its own mains power supply. Make sure that the switch is off before plugging the power supply into the mains (right).		

The generator can now be turned on using the on-off switch, and its speed changed using the drive control. Make sure that the generator is on a flat and stable surface. If there is any tendency for it to wobble, then this will create greater fluctuations in the measured frequency.

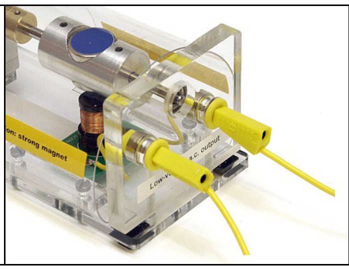
The mains power supply is attached permanently to the generator unit. The design of the unit and power supply ensures a safe limit on the output, and no other power supply should be used with the unit.

The generator unit can be connected directly to the load unit to show the effect of changing the load on the speed of the generator. To simulate the National Grid transmission system as a whole, the generator unit is used in conjunction with the step-up and step-down transformer units as well as the load unit.

Connecting the generator unit directly to the load unit

The generator unit can be connected directly to the load unit as shown below. This can be done to demonstrate how increasing the load makes the generator turn more slowly, i.e. the frequency decreases.

Make sure the generator unit is switched off before making the connections. Use a pair of yellow (low-voltage) connecting leads.

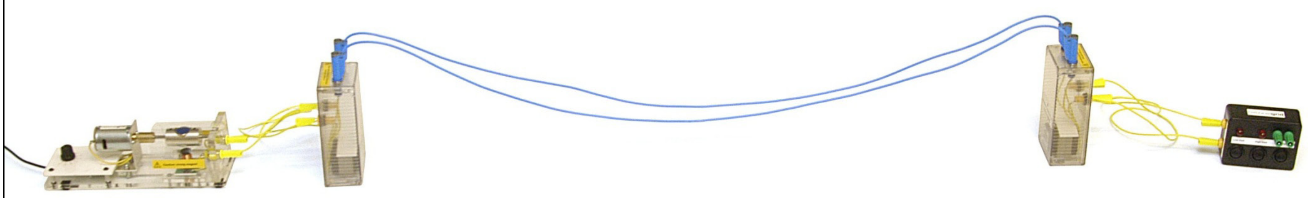
Connect the leads to the output sockets of the generator unit (left) and to the input sockets of the load unit (right).		

Switch on the generator unit and turn the drive control to its maximum value. Switch on the 'High' load on the load unit. You should be able to hear the speed of the generator drop.

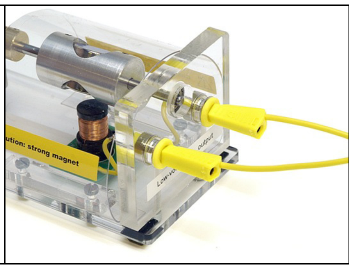
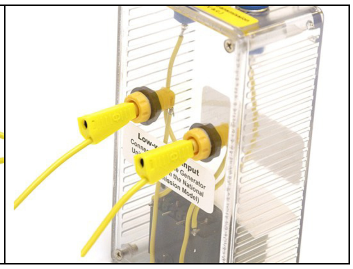
Connecting the whole system

⚠ *When using the step-up transformer, voltages of up to 40 V a.c. can be generated, and sheathed connecting leads must be used so that there are no exposed connections. Make sure that the generator unit is switched off when assembling or disassembling any of the equipment, or when adding or removing components, such as multimeters.*

The arrangement of the whole transmission system is shown below. This can be used to show the way in which the voltage is changed using step-up and step-down transformers.

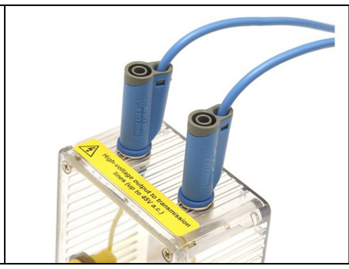
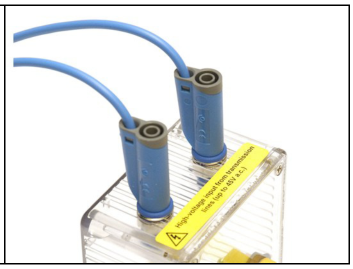


Make sure the generator unit is switched off before making the connections. Use the yellow leads for making low-voltage connections, and the blue leads for the high-voltage connections.

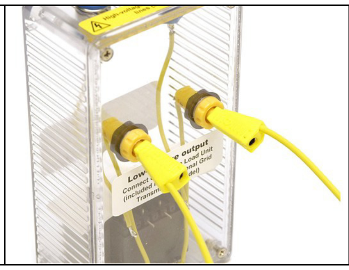
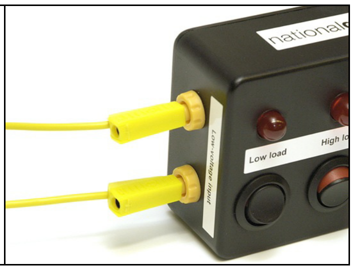
Connect a pair of yellow leads to the output sockets of the generator unit (left) and to the input sockets of the step-up transformer unit (right).		

To simulate the power losses during transmission, the long blue transmission leads include an in-built resistance. (Note that the kit also includes a pair of short blue connecting leads which have negligible resistance: these are needed for some of the demonstrations described elsewhere in the booklet.)

⚠ *Use only the transmission leads that are provided in the kit: do not use uninsulated resistance wire for the transmission lines.*

Connect the long blue transmission leads to the output sockets at the top of the step-up transformer unit (left). Connect the other ends of these leads to the input sockets at the top of the step-down transformer unit (right).		

Move the two transformer units apart until the transmission leads are 'suspended in the air'.

Finally, connect a pair yellow leads to the output sockets of the step-down transformer unit (left) and to the input sockets of the load unit (right).		

Switch on the generator unit and turn the drive control to its maximum value. Switch on the 'High' load on the load unit. You should be able to hear the speed of the generator drop.

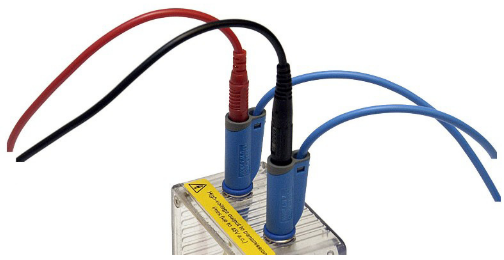
Multimeters

A number of demonstrations involve measuring a.c. frequency, and simple low-cost multimeters typically do not have this function. For these demonstrations it will be useful to have a multimeter with a frequency function. In addition, since the multimeter will be used to make measurements on equipment operating at more than 28 V a.c., it is essential that it is able to accept leads with sheathed plugs. Low-cost multimeters may not be designed to be used with sheathed plugs. A pair of connecting leads with sheathed plugs at each end will be needed for making high-voltage measurements.

Low-cost multimeters, such as the yellow one shown here which costs around £5, are useful for making low-voltage measurements at the generator and the load. The red multimeter shown costs around £25. It is suitable for making frequency measurements and accepts sheathed plugs. It could also be used in the demonstrations to measure a.c. voltage and a.c. current.

It is ideal to have two of the low-cost meters and one with a frequency function available: there are some demonstrations where these can then be left permanently connected in position, rather than having to move them each time a measurement is made.

The sheathed plugs on the blue leads supplied with the transmission model are *stackable*, so plugs can be inserted into these when using the multimeter to make frequency or voltage measurements at the high-voltage sockets at the top of the transformer units. The plugs on the leads connected to the multimeter must also be *sheathed* (though do not need to be stackable).



The following measurements are made in the demonstrations described in this booklet:

- Frequency (demonstrations B2, B3, B4, B5, and C2)
  It is useful have a multimeter that measures frequency to *two decimal places*, so it can detect the relatively small variations in mains frequency (mains power meters which plug directly into a mains socket may only read to 1 decimal place). With the larger variations in frequency using the generator unit, you may find it helpful to put a piece of tape to hide the second decimal place. The eye can follow the variation of a single decimal point, but the rapid variation in the last digit can be distracting.

- Voltage (demonstrations A1, B2, B5, C2, and D1)
  For most of the demonstrations, measuring a.c. voltage to one decimal place will be adequate, and indeed preferable due the fluctuations in the output voltage of the generator. In demonstrations B5 and D1 it will be better to be able to measure to two decimal places.

- Current (demonstration D1)
  Low-cost multimeters generally only measure d.c. current, but demonstration D1 requires a meter that can measure a low-voltage a.c. current.

Dataloggers

Being able to see a real-time graphical display of the voltage against time is particularly helpful in those demonstrations where the behaviour of the components is considered (Demonstrations B1, B2 and B4). The generator produces voltages of up to 6 V, so it will be useful to have a sensor with at least this range (e.g. ±20 V), but also may be useful to have one with a smaller range as well (e.g. ±1 V). A datalogger can display, for example, the effects of moving a magnet to and fro in front of the coil, or the rapid oscillations of an a.c. voltage allowing the frequency to be calculated. Particularly effective is to relate the datalogger display to the readings on a multimeter.

If no datalogger is available, these demonstrations could be adapted for use with a multimeter only, though the results would be less convincing, measuring voltage in demonstrations B1 and B4 and frequency in B2 and B5.

If two voltage sensors are available, then it is possible to compare voltage outputs on the same graph, for example, in demonstration C2, this can be used to show that the changes in voltage of the output of the generator and the input to the load occur in step with each other.

For some of the tasks, it is appropriate to set the datalogger to display continuously in real-time. However when following very rapid changes, it is recommended to set a recording time of 1 second with the maximum sampling rate, so that this is then displayed after recording. This makes it straightforward to find the frequency of alternating current simply by counting the number of peaks in the 1 second display.

On the teacher instruction sheets, there is guidance about suitable datalogging settings for each of the tasks. These are just given as general advice, and you will need to experiment to find the best settings for the particular equipment that you have.

Technical notes about the equipment

The transformer units contain identical transformers, but with the inputs and outputs labelled differently for the step-up and step-down transformer units: for the step-up transformer the ratio is about 1:19, and for the step-down it is about 19:1. When the step up-transformer unit is connected to the generator unit on its highest setting, the maximum voltage which can be produced at the output sockets of the transformer unit is about 40 V a.c. The transformer units should only be used in conjunction with the generator kit, and must not be connected to other power supplies.

The transmission leads consist of standard sheathed connecting leads into each of which has been inserted a 10 Ω resistor. This therefore shows the same behaviour as having lines made of insulated resistance wire (such wire is available but would be significantly more expensive). Because voltages of over 28 V a.c. are generated, uninsulated resistance wire must not be used.

The load unit consists of two loads in parallel with each other. The ‘low’ load consists of an LED in parallel with a 27 Ω resistor, and the ‘high’ load consists of an identical LED in parallel with a 10 Ω resistor. (Note that LEDs are normally used with direct current, but they will still work with alternating current, lighting up every half cycle). Other components (e.g. low-voltage light bulbs) can be attached to the ‘external load’ terminals. The resistances of the ‘low’ and ‘high’ loads have been chosen in order to enable the effects of varying loads on frequencies and voltages to be seen (light bulbs require more current than the LEDs to light up visibly, and it is harder to see these effects). It is best to treat the LEDs as ‘indicator lights’, rather than paying too much attention to their brightness.

NOTES FOR TEACHERS

The National Grid Transmission Model has been designed to support the teaching of electromagnetism and how it is applied in the generation and transmission of electricity. The demonstrations described here focus not just on the behaviour of these systems, but on the principles underlying their design. A particular focus that is unique to this kit is the emphasis placed on the measurement of frequency, and the way that this is used to monitor and control the system.

The materials are intended for teachers of 14-16 year old students, but by adapting the level of the discussion, the practical resources could be demonstrated to younger or older students.

The instruction sheets in this booklet are intended to provide guidance for teachers in carrying out the demonstrations and for questions that can be used with students in class discussion. As an alternative to using the hard copy materials in the classroom, there are PowerPoint presentations available that teachers can use alongside the demonstrations (see 'References and further reading' on page 59).

An overview of the teacher demonstrations

The teacher demonstrations are grouped into five sections:

A Introducing the system: generation and transmission

A1 How is electricity generated and transmitted?

B A closer look at the parts of the system

B1 How does the coil work?

B2 Generating electricity

B3 Connecting the generator to a load

B4 How is the voltage changed?

B5 Step-up and step-down transformers

C Maximising the efficiency of transmission

C1 Transformers and power

C2 Why are high voltages used for transmission?

D Making measurements of power

D1 Power losses in transmission

E Electricity demand

E1 Monitoring the National Grid frequency

Selecting the demonstrations

The map on the previous page indicates an appropriate sequence if all the activities are to be done, and suggests possible routes if a selection is made:

- *Sections A and C:* These are the core sections, using the National Grid Transmission Model to cover key ideas about electricity generation and transmission. This would be a suitable sequence if students already had a good understanding of electromagnetism.
- *Section B:* For those students with less of a background of electromagnetism, Section B looks at the ideas behind the operation of the key components. The demonstrations here form a natural sequence, but any of them could be done independently.
- *Section D:* This section uses the transmission model for quantitative work, with the calculation of power losses.
- *Section E:* This can be done after the core sections, and relates the work on the transmission model to real-time monitoring of National Grid frequency.

Student practical work

The instruction sheets provided in this booklet are designed for *teacher demonstrations*. In particular, demonstrations A1, B5, C1, C2 and D1 all involve the generation of high-voltages and *must not be undertaken by students under any circumstances*.

Other demonstrations (B1, B2, B3, B4 and E1) involve low-voltages and could be suitable for student use in appropriate contexts, following health and safety guidance where indicated.

In addition, there exist a very wide range of suitable practical activities that can be undertaken with standard laboratory apparatus, and which would effectively complement the demonstrations described in this booklet. Understanding the operation of the National Grid Transmission Model draws on a wide range of concepts that students need to study at this level. The generation and transmission of electricity therefore serves as a useful context for learning these ideas. For suitable sources of complementary practical activities, see 'Additional practical work' on page 60 in the section 'References and further reading'.

Health and safety

The National Grid Transmission Model can produce voltages of up to 40 V a.c., and it has been designed so that when used properly, in accordance with the instructions, there are no exposed high-voltage connections.

Further information about working in schools with high voltages can be found in the CLEAPSS Laboratory Handbook, section 6.1.1 'Shocks and burns' and section 12.9.6 'Power line (National Grid) simulation'. Two extracts are given below:

> The effects of an electric current on the body depend on the path taken but 5 mA is normally regarded as safe. Because the size of the current which flows depends on the resistance of the path, including the resistance of the skin, it is impossible to specify a maximum safe voltage. However, while lower voltages can be hazardous in exceptional circumstances, supplies greater than 28 V ac / 40 V dc are normally regarded as potentially dangerous in school science. Above these voltages, practical work must be designed to stop human contact with live conductors. [CLEAPSS Laboratory Handbook 6.1.1]

> A simulation of the efficient transmission of electricity along power lines, as used in the National Grid, is a popular and important demonstration in schools. Low-voltage ac from a power pack is sent along a pair of model power lines made from suitable resistance wire. Incidents have been reported where school staff received electric shocks by touching uninsulated model power lines during this demonstration. [CLEAPSS Laboratory Handbook 12.9.6]

CLEAPSS list a number of suitable control measures. The one adopted in the design of the National Grid Transmission Model is that all conductors and terminations operating above 28 V a.c. cannot be touched due to the use of insulated leads and shrouded plugs and sockets.

Teacher demonstration A1 How is electricity generated and transmitted?

This demonstration looks at the key features of the transmission model, and relates its structure and its behaviour to real-world electricity generation and transmission systems. (See also page 6 of this booklet, 'Introducing the system and its parts'.)

Objectives

Students should be able to:

- identify the main features of an electricity generation and transmission system
- describe the way in which the voltage changes along the system
- explain the effect of a change in demand on the generator.

Notes

CAUTION: Voltages up to 40 V a.c. can be produced at the output of the step-up transformer. Use leads with sheathed plugs to connect the sockets at the top of the transformer units (the yellow leads should only be used for the low-voltage connections). Make sure the generator is switched off each time you connect or disconnect components.

In Task 1, students need to relate the part of the transmission model to the real-world system. To help in making these links, there is a PowerPoint presentation that includes schematic diagrams (see 'References and further reading' on page 59).

In Task 2, with the load set to 'High', typical values for the measured voltages are:
- output sockets of the generator: 1.5 V
- output sockets of the step-up transformer: 25 V
- input sockets of the load unit: 1.0 V.

Switching the load on and off in Task 3 gives a noticeable change in frequency.

Resources needed

From the National Grid Transmission Model:

- generator unit, with mains power supply
- step-up transformer unit
- step-down transformer unit
- load unit
- 4 plug-plug leads (yellow)
- 2 long blue transmission leads (shrouded plugs).

Other resources:

- 3 multimeters to measure a.c. voltage (one of these needs to accept shrouded plugs)
- 4 plug-plug leads (2 red, 2 black)
- 2 insulated leads with shrouded plugs (1 red, 1 black).

Teacher demonstration B1 How does the coil work?

An important component in the transmission model is the coil. When a current is passed through the coil it becomes magnetic, and a moving magnet will induce a current in the coil. (See also page 8 of this booklet, 'Key ideas in electromagnetism: the generator'.)

Objectives

Students should be able to:

- describe the effect of passing a current through a coil
- explain how a current can be induced in a coil.

Notes

In Task 1, the compass needle will turn to point at the coil, which is acting as a magnet. To get the most noticeable effect for the deflection of the needle, position the coil so that it is facing East-West (i.e. at right angles to the compass needle).

When moving the magnet in front of the coil in Task 2, the changes in the induced current do not require a high resolution for display, and so the datalogger can be set to display continuously in real-time.

As an extension, you could try connecting the coil to a multimeter instead of the datalogger. By moving the magnet rapidly to and fro in front of the coil it is possible to get a reading on a multimeter set to measure frequency; the value is likely to be very variable, typically jumping around from between about 4 and 12 Hz. Also it is possible to get a voltage reading on a multimeter with a sensitive range (e.g. 200 mV a.c.); typically the value would be around 40 to 60 mV.

Resources needed

From the National Grid Transmission Model:

- test coil
- test magnet.

Other resources:

- datalogger with voltage sensor (e.g. ±1 V) connected to computer display
- low-voltage power supply (1 V d.c.)
- 2 plug-plug leads (1 red, 1 black)
- compass.

Teacher demonstration B2 Generating electricity

The generator unit is essentially a device for making a magnet move rapidly across the face of the coil. The output (alternating current) can be compared the output of a battery or a.c. and d.c. power supplies. (See also page 8 of this booklet, 'Key ideas in electromagnetism: the generator'.)

Objectives

Students should be able to:

- explain how a simple generator works
- interpret displays showing a change in voltage over time
- explain the difference between d.c. and a.c.
- recognise the difference between maximum and average a.c. voltage.

Notes

Before making measurements on the generator output, you should draw students' attention to the coil and the magnet, and note that the motor makes the magnet turn rapidly over the face of the coil. This is what induces a current in the coil.

In recording the output in Task 1, the datalogger is best run over a 1 second time period using the maximum sampling rate. A good resolution is important because of the rapidly changing current, and with a 1 second duration for the recording time, the frequency can be easily found by simply counting the number of peaks on the display.

The increase in voltage and frequency can be observed as the generator turns faster. Typically on drive setting '4', the maximum voltage (as shown by the peaks on the display) is about 2 V and the frequency is about 20 Hz, increasing to about 6 V and 55 Hz with the maximum setting of the drive control. You should also encourage students to relate the audible pitch of the motor to the observed frequency on the datalogger display.

In Task 2, the battery should produce a completely flat line. The a.c. power supply should produce a very regular oscillation (a sine curve) with a frequency of 50 Hz. This contrasts with the more 'spiky' appearance of the output from the generator unit. The output of the d.c. power supply will depend on the design of the supply itself (whether and to what extent it is smoothed) – the display may be very similar to the battery, or it might show a noticeable ripple.

From the datalogger display for the output from the a.c. power supply, it will be very clear to students that the frequency is about 50 Hz. This is the same as mains frequency, though it may not be so obvious to students that the frequencies are necessarily the same. The idea that transformers change the voltage but do not affect the frequency of a.c. is taken up in Demonstration B4.

A multimeter measuring a.c. voltage will give an *averaged* reading, and so will be less than the maximum voltage as displayed by datalogger. In Task 3, if the maximum voltage of the generator output is 6 V, the averaged reading on the multimeter might be 2.3 V. (Note that for the mains supply, the maximum voltage can be calculated from 'average voltage x $\sqrt{2}$', but this is for a sine curve and so does not apply for the 'spiky' generator output.)

In Task 4, the multimeter reading for the frequency should agree fairly closely with that obtained from the datalogger display.

As extension, you might want to try connecting a white LED to the output of the generator unit. This produces a stroboscopic effect, and when pointed at the generator it 'freezes' the position of the magnet. The two poles of the magnet are indicated by red and blue, and if the leads to the LED are swapped then you can see that the magnet is frozen in the 'opposite' orientation. The position of the magnet shown by the 'stroboscope' is the point at which the maximum current is being generated. You can verify this by switching off the generator unit and connecting the output to a multimeter (d.c. voltage setting) or datalogger - turning the drive shaft by hand will show the position at which the maximum effect is achieved.

Resources needed

From the National Grid Transmission Model:

- generator unit, with mains power supply.

Other resources:

- datalogger with voltage sensor (e.g. ±20 V) connected to computer display
- multimeter(s) to measure:
  - a.c. voltage
  - frequency
- low-voltage power supply (2 V d.c. and 2 V a.c.)
- battery in holder (1.5 V, D size)
- 2 plug-plug leads (1 red, 1 black).

Teacher demonstration B3 Connecting the generator to a load

Adding a load to the generator makes it turn more slowly. This demonstration models the way in which the National Grid is able to maintain a constant frequency as the demand varies. (See also page 8 of this booklet, 'Key ideas in electromagnetism: the generator'.)

Objectives

Students should be able to:

- describe the behaviour of a generator connected to a load
- explain how the system can be adjusted to maintain an approximately constant frequency.

Notes

In Task 1, it is clear to see that the LED on the load unit is flickering when generator is operating at 20 Hz; when the frequency reaches 40 Hz, the LED appears steady.

In Task 2, switching the load unit from 'off' to the 'High' setting causes a frequency drop of about 3 Hz, which should be easily detectable by the human ear.

The way in which the drive control is changed to maintain a constant frequency while the load is changed reflects the operation of the National Grid. You may wish to make this point by making one student represent consumers (operating the load unit) and another student represent the control centre (operating the generator unit and monitoring the frequency of a multimeter).

The load unit provides a 'step change' in the load. If you wish to simulate a continuously varying load, you could connect a variable resistor or potentiometer (controllable over the range 1 – 50 Ω) to the external load terminals.

Resources needed

From the National Grid Transmission Model:

- generator unit, with mains power supply
- load unit
- 2 plug-plug leads (yellow).

Other resources:

- multimeter to measure frequency
- 2 plug-plug leads (1 red, 1 black).

Teacher demonstration B4 How is the voltage changed?

There is more than one way of creating a changing magnetic field. An alternating current (a.c.) in a coil also produces a changing magnetic field, and induces a current in a second coil. (See also page 12 of this booklet, 'Key ideas in electromagnetism: the transformer'.)

Objectives

Students should be able to:

- describe how moving a magnet creates a changing magnetic field which can induce a current in a coil
- explain how a changing d.c. current and an a.c. current can induce a current in a coil
- explain why the frequency of an induced a.c. current is the same as the original.

Notes

CAUTION: The coil connected to the 3 V d.c. power supply produces a smaller magnetic field than the test magnet, and thus produces a smaller induced voltage in the second coil. Do not be tempted to increase the voltage beyond 3 V d.c. or the coil will overheat. Even when using at the recommended voltage, make sure that you hold the coil arrangement by the terminals and not by the coil itself.

In Task 1, it is best to use a fairly small range for the vertical voltage scale, e.g. 500 mV. The test magnet will produce a voltage of around 200 mV in the second coil, and the coil connected to the 3 V d.c. supply will produce a voltage of around 50 mV. The datalogger can be set to display continuously in real-time.

In Tasks 2 and 3, the changes in output voltage are rapid: set the datalogger for a 1 second duration for the recording time with the maximum sampling rate. Because of the short recording time, in Task 2, you need to be rapidly pressing the push button switch on and off before starting to record.

The a.c. frequency can be found from the datalogging display by counting the number of peaks in the 1 second recording period. It should agree closely with the value found using a multimeter.

Resources needed

From the National Grid Transmission Model:

- 2 test coils
- test magnet.

Other resources:

- datalogger with voltage sensor (e.g. ± 1 V) connected to computer display
- multimeter to measure frequency
- low-voltage power supply (3 V d.c. and 2 V a.c.)
- push button switch
- 4 plug-plug leads (2 red, 2 black)
- 2 clamp stands, bossheads and clamps.

Teacher demonstration B5 Step-up and step-down transformers

This demonstration looks at commercial transformers specifically designed to be much more efficient at transferring energy, but which still use the same principle of input and output coils. (See also page 12 of this booklet, 'Key ideas in electromagnetism: the transformer'.)

Objectives

Students should be able to:

- identify the key features of a transformer and how it can change an a.c. voltage
- explain how the change in voltage depends on the number of turns on the input and output coils
- describe the behaviour of a step-up / step-down transformer arrangement
- explain why the frequency of the output is the same as the frequency of the input.

Notes

CAUTION: Voltages up to 40 V a.c. can be produced at the output of the step-up transformer. Use leads with sheathed plugs to connect the sockets at the top of the transformer units. Make sure the generator is switched off each time you connect or disconnect components.

Tasks 2 and 3 measure the input and output voltages for the step-up and step down transformers when connected to the generator unit. Typical values are:

Step-up transformer:
Input 1.9 V. Output 35 V.

Step-down transformer:
Input 1.9 V. Output 0.15 V.

Note that while a voltmeter with a 200 V a.c. range (reading to one decimal place) is generally sufficient, it is possible that the output from the step-down transformer may be too small to measure (i.e. the reading may be zero). If so, a multimeter with a 20 V a.c. range (reading to 2 decimal places) will be needed.

The calculated ratios of the voltages for the step-up and step-down transformers are similar but reversed (1:17.0 and 16.2:1). In fact, the transformers used in these units are identical, with the inputs and outputs being reversed.

In Task 4, when both transformer units are used together, typical values are:
- output of the generator: 1.8 V
- output of the step-up transformer: 34 V
- output of the step-down transformer: 1.8 V.

Resources needed

From the National Grid Transmission Model:

- generator unit, with mains power supply
- step-up transformer unit
- step-down transformer unit
- 2 plug-plug leads (yellow)
- 2 short blue connecting leads (shrouded plugs).

Other resources:

- 3 multimeters to measure a.c. voltage (one of these needs to accept shrouded plugs, with a frequency function and if possible able to measure a.c. voltage to 2 decimal places)
- 4 plug-plug leads (2 red, 2 black)
- 2 insulated leads with shrouded plugs (1 red, 1 black).

Teacher demonstration C1 Transformers and power

This demonstration shows that when the voltage is stepped up and then stepped down, there are power losses in the transformers. It raises the question of why transformers are used and why the voltage is changed which is addressed in the next demonstration. (See also page 16 of this booklet, 'Getting the energy where it is needed'.)

Objectives

Students should be able to:

- recognise that the use of transformers in a system increases the power losses.

Notes

CAUTION: Voltages up to 40 V a.c. can be produced at the output of the step-up transformer. Use leads with sheathed plugs to connect the sockets at the top of the transformer units. Make sure the generator is switched off each time you connect or disconnect components.

When using the generator unit connected directly to the load unit, you should turn up the drive control so that the 'High' load LED is lit up reasonably brightly (i.e. it can be a good deal brighter than the point where it just becomes visible). This makes the effect on the load of adding the transformers more noticeable.

As extension, you could also use a multimeter to measure the frequency and how it changes as an indication of the increased load on the transformers are added.

Resources needed

From the National Grid Transmission Model:

- generator unit, with mains power supply
- step-up transformer unit
- step-down transformer unit
- load unit
- 4 plug-plug leads (yellow)
- 2 short blue connecting leads (shrouded plugs).

Teacher demonstration C2 Why are high voltages used for transmission?

Even though there are power losses in transformers, this demonstration shows how the use of high-voltage transmission decreases power losses overall by reducing the power lost from the transmission lines. (See also page 16 of this booklet, 'Getting the energy where it is needed'.)

Objectives

Students should be able to:

- recognise that there are power losses in transmission lines because they have a significant resistance
- describe the change in voltage along a low-voltage and a high-voltage transmission system
- explain how the system can be adjusted to maintain an approximately constant frequency.

Notes

CAUTION: Voltages up to 40 V a.c. can be produced at the output of the step-up transformer. Use leads with sheathed plugs to connect the sockets at the top of the transformer units. Make sure the generator is switched off each time you connect or disconnect components.

In Task 1, only the 'Low' load LED lights up – if the 'High' load is switched on, the output from the transmission lines is not sufficient to light the LED.

In Task 2, when the load unit has both 'Low' and 'High' switches on, both LEDs light up. The output from the transmission lines is sufficient to meet this higher demand.

Task 3 is similar to B3 Task 2 (in which the generator was connected directly to the load). If students have already seen the previous demonstration, then less time needs to be spent on it here. If not, it is worth looking back at this demonstration and the accompanying notes for further information.

Resources needed

From the National Grid Transmission Model:

- generator unit, with mains power supply
- step-up transformer unit
- step-down transformer unit
- load unit
- 4 plug-plug leads (yellow)
- 2 long blue transmission leads (shrouded plugs).

Other resources:

- multimeter to measure a.c. voltage (needs to accept shrouded plugs, and with a frequency function)
- 2 plug-plug leads (1 red, 1 black)
- 2 insulated leads with shrouded plugs (1 red, 1 black).

Teacher demonstration D1 Power losses in transmission

This builds on the ideas in the previous two demonstrations, by making measurements of voltage and current to determine the power input to the load. It compares the power losses in different 'transmission systems'. (See also page 20 of this booklet, 'Measuring power and efficiency'.)

Objectives

Students should be able to:

- calculate values for power from readings of voltage and current
- recognise how to connect a voltmeter and an ammeter in a circuit to obtain suitable readings
- explain the differences in the power input to a load using different transmission systems.

Notes

CAUTION: Voltages up to 40 V a.c. can be produced at the output of the step-up transformer unit. Avoid touching the terminals at the top of the transformer units. Make sure the generator is switched off each time you connect or disconnect components.

In Task 1, the power output from the generator is measured when it is connected directly to the load (set on 'Low'). Typical values are:
V = 1.8 V, I = 130 mA, P= 234 mW.

In Task 2, the power input to the load (set on 'Low') is measured when it is connected via different 'transmission systems'.

Typical values are:

Via transformers with short blue connecting leads:
V = 1.4 V, I = 90 mA, P= 126 mW

Directly via long blue transmission leads:
V = 0.9 V, I = 50 mA, P= 45 mW

Via transformers with long blue transmission leads:
V = 1.4 V, I = 85 mA, P= 119 mW.

Resources needed

From the National Grid Transmission Model:

- generator unit, with mains power supply
- step-up transformer unit
- step-down transformer unit
- load unit
- 4 plug-plug leads (yellow)
- 2 short blue connecting leads (shrouded plugs)
- 2 long blue transmission leads (shrouded plugs).

Other resources:

- multimeter to measure a.c. voltage
- multimeter to measure a.c. current
- 4 plug-plug leads (2 red, 2 black).

Teacher demonstration E1 Monitoring the National Grid frequency

In order to match the output from power stations to demand, the frequency is monitored to keep as close to 50 Hz as possible. In this demonstration, the variation in mains frequency is measured over a period of time and compared to the National Grid's own real-time data. (See also page 22 of this booklet, 'Managing the demand for electricity'.)

Objectives

Students should be able to:

- compare variation in measured values with upper and lower operating limits
- suggest possible reasons that cause the frequency to increase and decrease.

Notes

Task A can be done co-operatively with students, by splitting the class into a number of small groups who are responsible for recording the data for part of the lesson. By entering values directly into a spreadsheet, the graph could be drawn immediately on completing the data collection.

The upper and lower legal limits for the frequency are 50.5 Hz and 49.5 Hz, while the operating limits are 50.2 Hz and 49.8 Hz. Students should see that the maximum and minimum measured values lie between these limits.

For Task B, the web address for the frequency data is shown on page 59 in 'References and further reading'. The web page should refresh automatically, though if this does not happen with your browser, then refresh the page manually. It should be possible to see an exact correspondence between the graph of measured values and the graph on the web page.

Students should be able to explain how an increase in frequency could be caused by an increase in generation or a decrease in demand; similarly, a decrease in frequency could be caused by a decrease in generation or an increase in demand.

Resources needed

- low-voltage power supply (2 V a.c.)
- multimeter to measure frequency
- 2 plug-plug leads (1 red, 1 black)
- computer with internet connection.

How is electricity generated and transmitted?

The National Grid Transmission Model is a simple model of the way that electricity is generated and transmitted in the UK. This demonstration looks at some of the key components of the kit and how they relate to the real-world electricity system – from the power station to our homes.

> **Teacher instruction sheet**
> This demonstration uses the National Grid Transmission Model, and *involves high voltages*. Questions for students are shown in the boxes.

Task 1 A simplified model

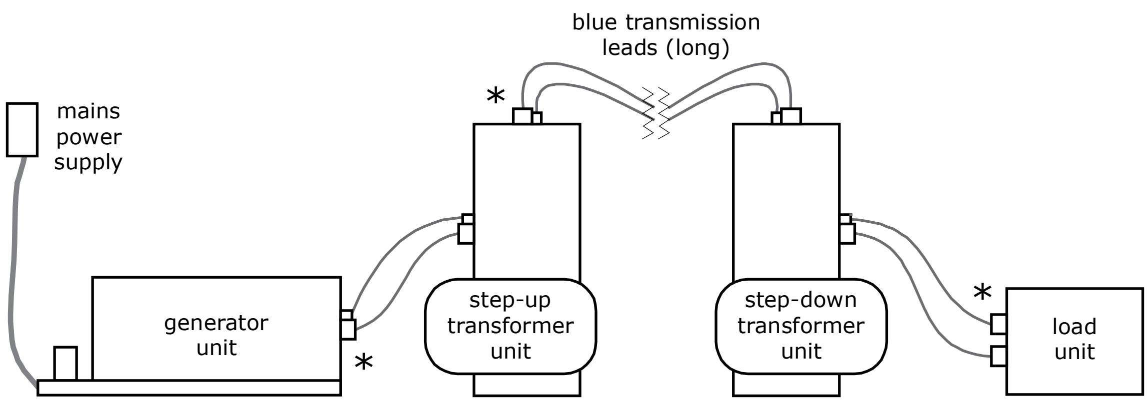
Make sure the generator is switched off each time you connect or disconnect components. Use leads with sheathed plugs to connect the transformers to each other.

Connect the four parts of the system as shown (using the long blue transmission leads between the two transformer units). With the generator unit switched off, plug in its mains power supply.

Set the drive control on the generator unit to '8' and set the load unit to 'High'.

Switch the generator unit on. The LED on the load unit should light.

Note the key parts of the system that can be related to the real-world system – the drive motor, the magnet and coil, the step-up transformer, the transmission leads, the step-down transformer, the load unit.



1. Below is a list of key elements related to electricity transmission. What do they correspond to in the transmission model?

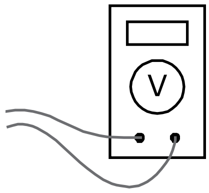
- boiler and turbine
- generator
- generator transformer
- overhead power lines
- transmission towers (pylons)
- underground cables
- substation
- grid supply transformer
- factories and homes.

How is electricity generated and transmitted? (continued)

Task 2 Measuring the voltage

Make sure the generator is switched off each time you connect or disconnect the multimeters.

You will need three multimeters (a.c. voltage setting): one of these needs to accept shrouded plugs.



Switch off the generator. Connect the multimeters in the following three positions, as indicated on the previous diagram (marked *):

- across the output sockets of the generator
- across the output sockets at the top of the step-up transformer (using leads with shrouded plugs)
- across the input sockets of the load unit.

Switch on the generator and note the three voltage readings.

Switch off the generator and disconnect the multimeters.

2. For the transmission model, what are the voltages of the following?

- generator output
- transmission leads
- load input.

3. For the real-world system, what are the voltages of the following?

- generator output
- overhead power lines
- home electricity supply.

Task 3 Changing the load

Switch on the generator (with the load unit set to 'High').

Listen carefully while you switch the load off. Listen again while you switch it back on.

4. What can you hear when the load is switched on and off?

5. What is the effect of the load on the speed of the generator?

6. Why do you think this happens?

How does the coil work?

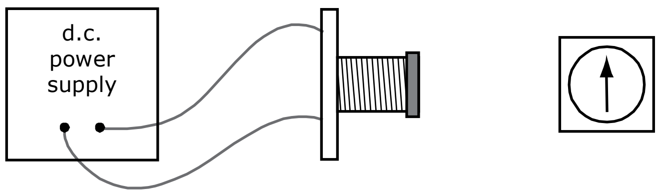
Teacher instruction sheet
This demonstration uses the National Grid Transmission Model. Questions for students are shown in the boxes.

An essential part of the generator unit is a small coil of copper wire. This demonstration looks at the way that this coil behaves, and at the way that magnetic fields and electrical currents are related. These principles are applied in a wide variety of devices including motors, loudspeakers, dynamos and generators.

Task 1 Passing a current through the coil

Connect the test coil to a power supply (1 V d.c.), and switch on the power.

Hold the coil in your hand and move it closer to the needle of a compass. Move the coil away.



1. What happens to the compass needle? What does this show about the coil?

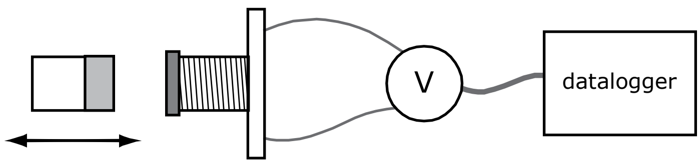
Switch off the power and hold the coil close to the compass. Switch the power on and off several times.

2. What happens to the compass needle? Why do you think this happens?

3. This effect is sometimes called the 'motor effect'. Why do you think it is given this name?

Task 2 The effect of a magnet on the coil

Remove the coil from the power supply and connect it to the voltage sensor (e.g. ±1 V) of a datalogger connected to a computer.



Select suitable settings for the datalogger (e.g. scale: ±500 mV, duration: continuous, sample interval: 30 ms).

Start the datalogger to show a real-time graph.

Hold the test magnet in your hand with its face pointing at the end of the coil. Bring it up slowly to the coil, and hold it there. Then move it away.

Repeat, trying the effects of moving the magnet at different speeds.

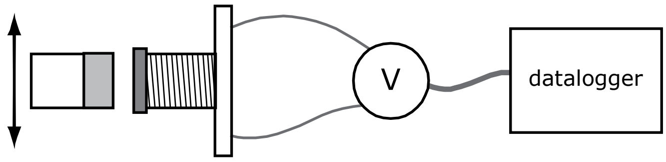
Behaviour of the coil (continued)

4. What happens to the voltage across the coil when the magnet moves towards the coil?

5. What happens to the voltage when the magnet moves away from the coil?

Hold the face of the magnet close to the end of the coil. Then move it from side to side in front of the coil.

Repeat, doing it a little closer to the coil.



6. What happens to the voltage across the coil when the magnet oscillates in front of it?

Ask a student to move the magnet across the face of the coil. What do they feel?

7. Which of the following is true?

- A voltage is produced across the coil when the magnet is held near it.
- A voltage is produced across the coil when the magnet is moved near it.

8. What factors affect the size of the voltage?

Task 3 Summarising these ideas

The previous two tasks both explore the relationship between the following:

- electric current
- magnetic field
- movement.

9. Use these three terms in a sentence to summarise:

- the key idea in Task 1
- the key idea in Task 2.

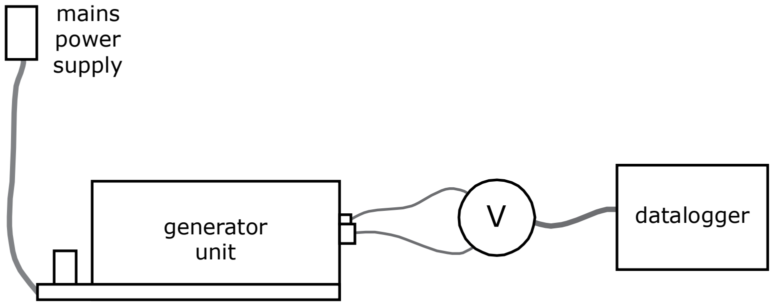
Generating electricity

The generator used in the transmission model is simply a device for making a magnet move rapidly across the face of the coil – just doing what could be done by hand but faster. The output is an alternating current (a.c.) in contrast to the direct current (d.c.) output of a battery.

Teacher instruction sheet
This demonstration uses the National Grid Transmission Model. Questions for students are shown in the boxes.

Task 1 How does the generator work?

Connect the output of the generator unit to the voltage sensor (e.g. ±20 V) of a datalogger connected to a computer. With the generator unit switched off, plug in its mains power supply.



Select suitable settings for the datalogger (e.g. scale: ±10 V, duration: 1 second, sample interval: 1 ms).

Set the drive control to ‘6’ and then start the datalogger.

1. How does the generator work? What effect does the magnet have on the coil?

2. What pattern can you see on the datalogger? What does this show?

3. What is the highest value of the output voltage?

4. How can you work out the frequency from this display?

Repeat this procedure, with the drive control set at a lower speed (‘4’). Repeat with a higher speed (’8’).

5. How does slowing down or speeding up the generator affect the pattern on the datalogger display?

6. What effect does the generator speed have on the output voltage?

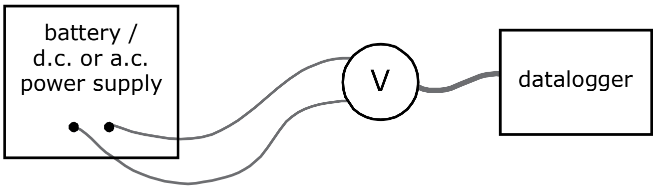
7. What effect does the generator speed have on the output frequency?

Generating electricity (continued)

Task 2 Looking at the output from other sources

Repeat the procedure looking at the output voltage from the following:

- 1.5 V battery
- power supply set at 2 V a.c.
- power supply set at 2 V d.c.



8. In what way is the output from a battery different from that of the generator?

9. Does the output from the a.c. power supply look similar to the output from the generator? What is its frequency?

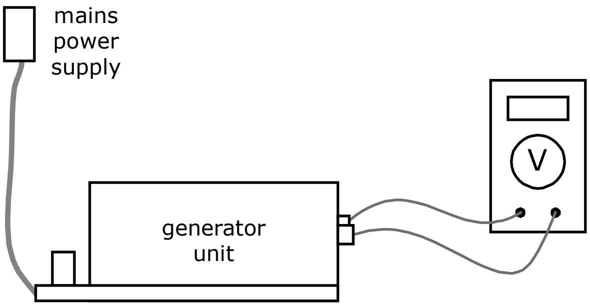
10. How does the output from the d.c. power supply compare to the battery?

Task 3 Making voltage measurements

Run the generator unit on setting '6' and display the output on the datalogger.

11. What is the maximum output voltage as shown on the datalogger?

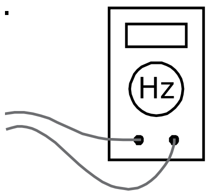
Now connect the output from the generator unit to a multimeter (a.c. voltage setting) to measure the voltage.



12. What is the output voltage as recorded by the multimeter? Is this the same or different from the maximum voltage shown on the datalogger display? Why is this?

Task 4 Making frequency measurements

Connect the output from the generator unit to a multimeter (frequency setting).



13. What is the reading on the multimeter? How does this compare to the value you worked out from the datalogger?

Connecting the generator to a load

A 'load' refers to whatever is connected to an electrical power supply – in our homes this could be lighting, televisions, washing machines or fridges. This demonstration looks at the importance of having a power supply that is sufficient to meet the demands of the load.

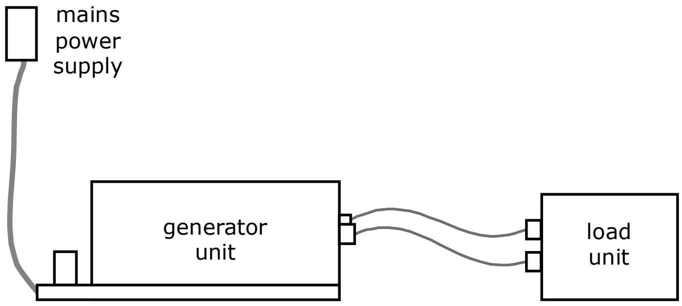
> **Teacher instruction sheet**
> This demonstration uses the National Grid Transmission Model. Questions for students are shown in the boxes.

Task 1 Changing the speed of the generator

Connect the generator unit to the load unit. With the generator unit switched off, plug in its mains power supply.

Set the drive control on the generator unit to '0' and the load unit to 'Low'.

Switch the generator unit on, and turn up the drive control until the LED just lights. Then slowly increase the drive control and observe the LED.



1. Does the LED produce a steady light or does it flash?

2. Why do you think this is?

Task 2 Changing the size of the load

Connect a multimeter (frequency setting) to the load unit.

Set all the switches on the load unit to 'off', and adjust the drive control until the multimeter reads about 50 Hz.

Now switch the load to 'High'. Listen to the change in pitch of the drive motor and note the frequency reading on the multimeter.

Adjust the drive control so that the multimeter reads about 50 Hz again.

Try different loads on the load unit, adjusting the drive control each time to try to maintain a frequency of about 50 Hz.

3. What effect does increasing the load have on the frequency?

4. How can a constant frequency be maintained even if the size of the load varies?

5. If a constant frequency is maintained, does this mean that the power output of the generator stays the same? Explain why.

How is the voltage changed?

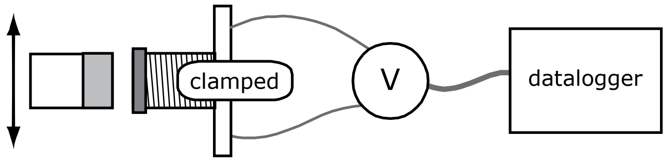
The National Grid transmits electricity at 400 000 V – this is much higher than the voltage at which it is generated. Voltages can be changed by using transformers. This demonstration uses two coils of wire to look at the principle that underpins the way that transformers work.

Teacher instruction sheet
This demonstration uses the National Grid Transmission Model. Questions for students are shown in the boxes.

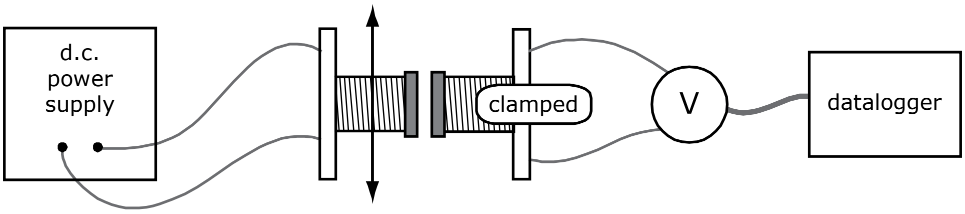
Task 1 A moving magnet

Put a test coil into a clamp stand. Connect the coil to the voltage sensor (e.g. ±1 V) of a datalogger connected to a computer. Select suitable settings for the datalogger (e.g. scale: ±500 mV, duration: continuous, sample interval: 30 ms).

Move the face of the test magnet in front of the clamped coil. The changing magnetic field creates a changing voltage across the coil which can be observed on the datalogger display.



Now connect a second test coil to a low-voltage power supply (set at 3 V d.c.). *Note that the coil will get quite warm.* Hold the coil using the terminals (*avoid touching the coil itself*), and move it in front of the clamped coil.

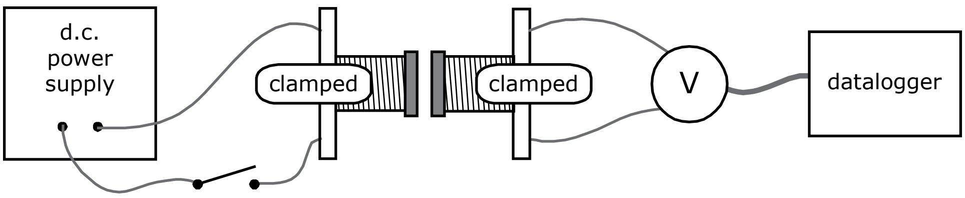


1. What can you see on the datalogger? In what way is it similar to the magnet? What does this show?

Task 2 Switching a d.c. current on and off

Put the second test coil into a clamp stand. Position it next to the other coil so that they are facing each other.

Add a push button switch into the circuit with the power supply and coil.



Changing the voltage (continued)

Select suitable settings for the datalogger (e.g. scale: ±1 V, duration: 1 second, sample interval: 1 ms).

Press the push button switch rapidly to turn the current through the coil on and off many times a second. While doing this start the datalogger.

2. What happens when the push button switch is turned on and off rapidly? Why?

3. Which of the following is true?

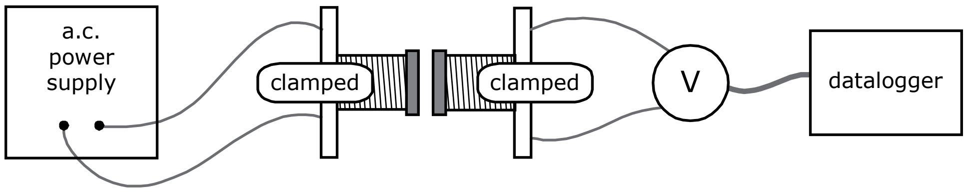
- A voltage is produced across the coil connected to the sensor when a current flows through the other coil.
- A voltage is produced across the coil connected to the sensor when the current through the other coil changes.

Task 3 Using an a.c. current

Switch off the power supply, and remove the push button switch from the circuit.

Select suitable settings for the datalogger (e.g. scale: ±1 V, duration: 1 second, sample interval: 1 ms).

Set the power supply to 2 V a.c. and switch on the power supply.



4. What can you see on the pattern on the datalogger? Why does this happen?

5. How is this pattern different from the previous one in which a d.c. supply was switched on and off rapidly?

Connect a multimeter (frequency setting) to the a.c. power supply, and measure the frequency. Connect it to the output of the second coil and measure the frequency.

6. What is the frequency of the output from the power supply?

7. What is the frequency of the output from the second coil?

8. How do the frequencies compare? Why?

Step-up and step-down transformers

Transformers can increase the voltage (step-up) or decrease it (step-down). This depends on the relative numbers of turns in the input and output coils. This demonstration looks at the commercial transformers used in the transmission model, which are much more efficient at transferring energy than simple wire coils.

Teacher instruction sheet
This demonstration uses the National Grid Transmission Model, and *involves high voltages*. Questions for students are shown in the boxes.

Task 1 What is inside the transformer units?

The step-up transformer unit has a transparent box so that you can see what is inside it. The transformer has a block of laminated iron sheets (which can be seen) and an input coil and output coil with different numbers of turns (which cannot be seen).

1. What is the purpose of having different numbers of turns on the input and output coils?

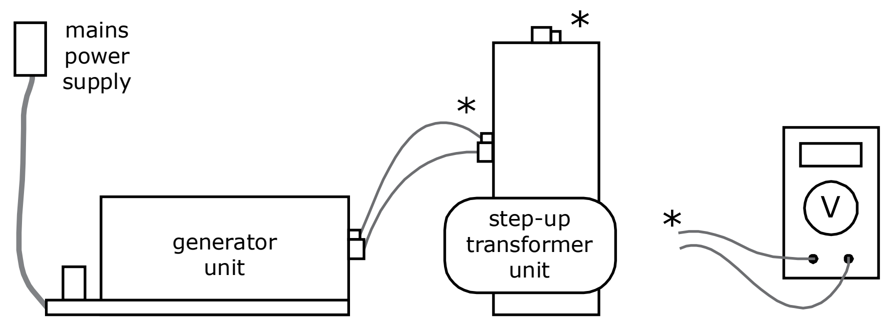
2. What is the purpose of the block of iron sheets?

Task 2 Step-up transformer

Make sure the generator is switched off each time you connect or disconnect components. Use leads with sheathed plugs to connect to the output of the transformer unit.

Connect the generator unit to the input of the step-up transformer unit (lower sockets). With the generator unit switched off, plug in its mains power supply.

Set the drive control to '8'.



You will need two multimeters (a.c. voltage setting): one of these needs to accept shrouded plugs. Connect the multimeters as follows:

- across the input sockets (i.e. lower sockets) of the step-up transformer.
- across the output (upper) sockets of the step-up transformer (using leads with shrouded plugs).

Switch on the generator unit and note the two voltage readings. Switch the generator unit off.

3. How did the input voltage of the step-up transformer compare with the output voltage?

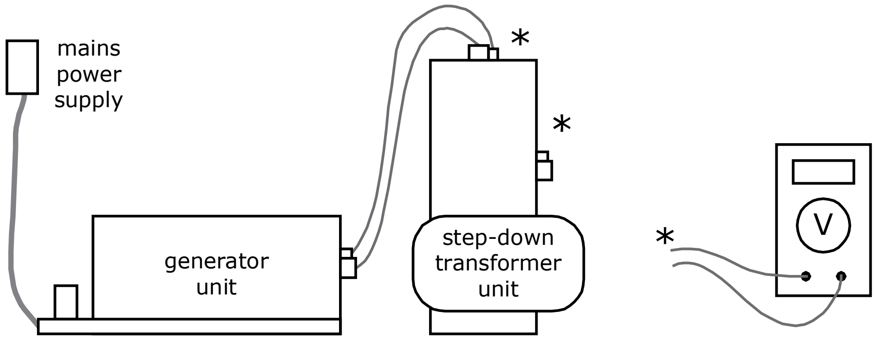
4. What does this tell you about the number of turns on the input and output coils?

Step-up and step-down transformers (continued)

Task 3 Step-down transformer

With the generator unit switched off, disconnect the step-up transformer unit. Connect the generator unit to the input of the step-down transformer unit (*upper sockets*).

Connect the multimeters as follows:



- across the input sockets (i.e. upper sockets) of the step-down transformer
- across the output (lower) sockets of the step-down transformer (using leads with shrouded plugs).

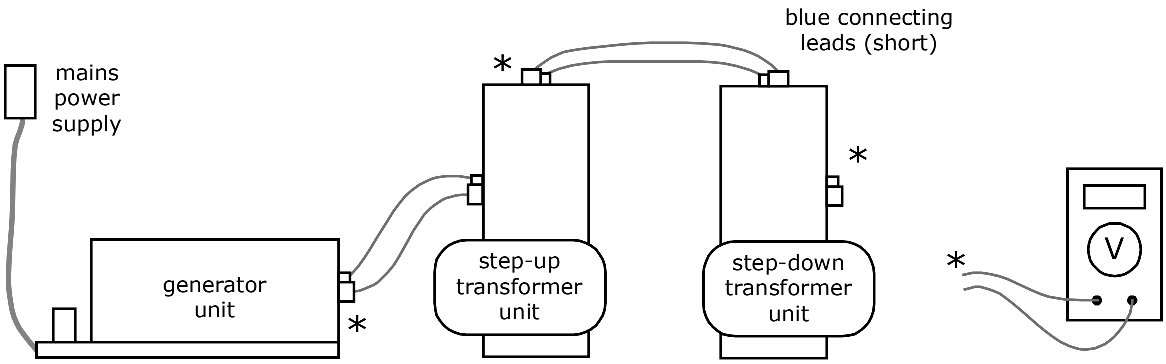
Switch on the generator unit and note the two voltage readings (the output value is quite low, so you may need to use a smaller range on the multimeter). Switch the generator unit off.

5.	How did the input and output voltages compare?
6.	What does this tell you about the number of turns on the input and output coils?

Task 4 Using the transformers together

Make sure the generator is switched off each time you connect or disconnect components. Use leads with sheathed plugs to connect the transformers to each other.

With the generator unit switched off, connect the generator unit, step-up transformer unit and step-down transformer unit as shown (using short blue connecting leads between the two transformer units).



Step-up and step-down transformers (continued)

You will need three multimeters (a.c. voltage setting): one of these needs to accept shrouded plugs. Connect the multimeters as follows:

- across the output sockets of the generator
- across the output (upper) sockets of the step-up transformer (using leads with shrouded plugs)
- across the output (lower) sockets of the step-down transformer.

Switch on the generator and note the three voltage readings. Switch off the generator unit.

7. What happens to the voltage in using the step-up / step-down arrangement?

8. Why is this?

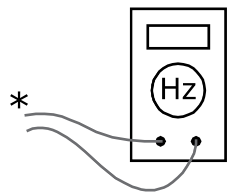
9. Why is it important that the generator gives an a.c. output?

10. What would happen if a d.c. output was used?

Task 5 Measuring the frequency

⚠ *Make sure the generator is switched off each time you connect or disconnect the multimeter.*

Use a multimeter set to measure frequency.



With the generator switched off, connect the multimeter to the output of the generator. Switch the generator on, and note the frequency reading.

Switch the generator off, and connect the multimeter to the output of the step-down transformer. Switch the generator on, and note the frequency reading.

11. What happens to the frequency in using the step-up / step-down arrangement?

12. Why is this?

Transformers and power

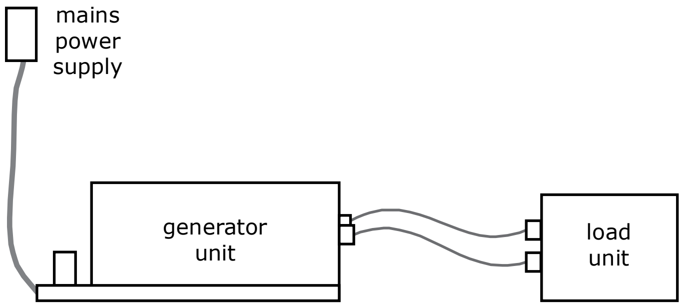
It is costly to construct the huge transformers and to build the tall pylons across the country necessary to safely transmit electricity at 400 000 V. Why not just transmit at the voltage generated in the power station? This demonstration takes a first look at the behaviour of the transformers in the system.

Teacher instruction sheet
This demonstration uses the National Grid Transmission Model, and *involves high voltages*. Questions for students are shown in the boxes.

Connect the generator unit to the load unit. With the generator unit switched off, plug in its mains power supply.

Set the drive control to '0' and the load unit to 'High'.

Switch on the generator unit, and turn up the drive control until the LED on the load unit starts to light up.

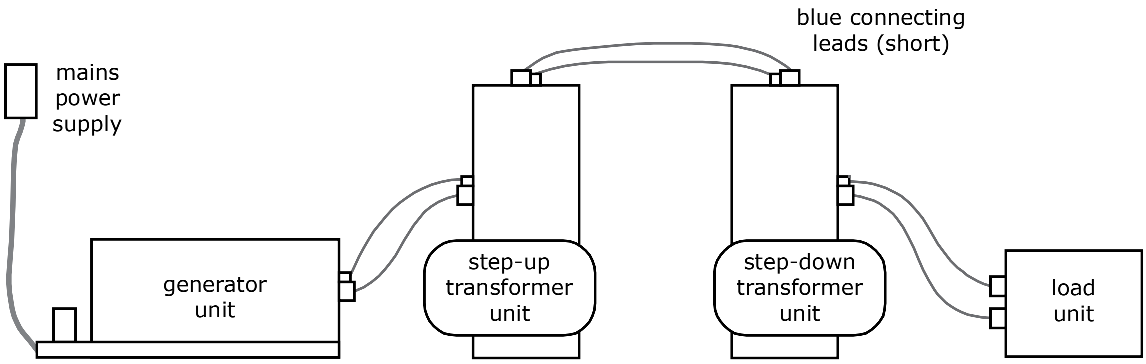


1. What do you think might happen to the brightness of the LED if the step-up and step-down transformers are connected between the generator and the load unit?

Make sure the generator is switched off each time you connect or disconnect components. Use leads with sheathed plugs to connect the transformers to each other.

Switch off the generator (keeping the drive control setting the same).

Add the step-up transformer unit and step-down transformer unit as shown (using short blue connecting leads between the two transformer units).



Switch on the generator and observe the LED on the load unit.

2. What has happened to the brightness of the LED? Why do you think this has happened?

3. Does this explain why transformers are used in the electricity transmission system?

Why are high voltages used for transmission?

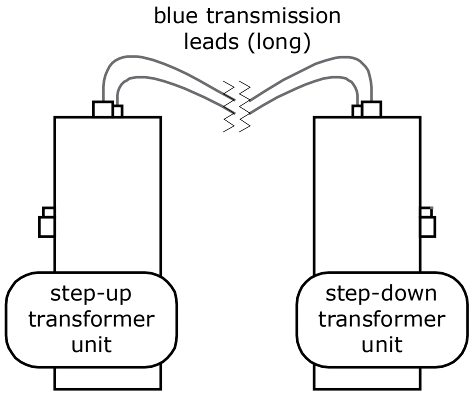
There are power losses in transformers, but there are power losses too in the transmission lines – since they are many miles long they have a significant resistance. This demonstration compares the different power losses involved in using low-voltage and high-voltage transmission.

Teacher instruction sheet
This demonstration uses the National Grid Transmission Model, and *involves high voltages*. Questions for students are shown in the boxes.

Task 1 Low-voltage transmission

You will need the two long blue transmission leads, which have a higher resistance than the short blue connecting leads.

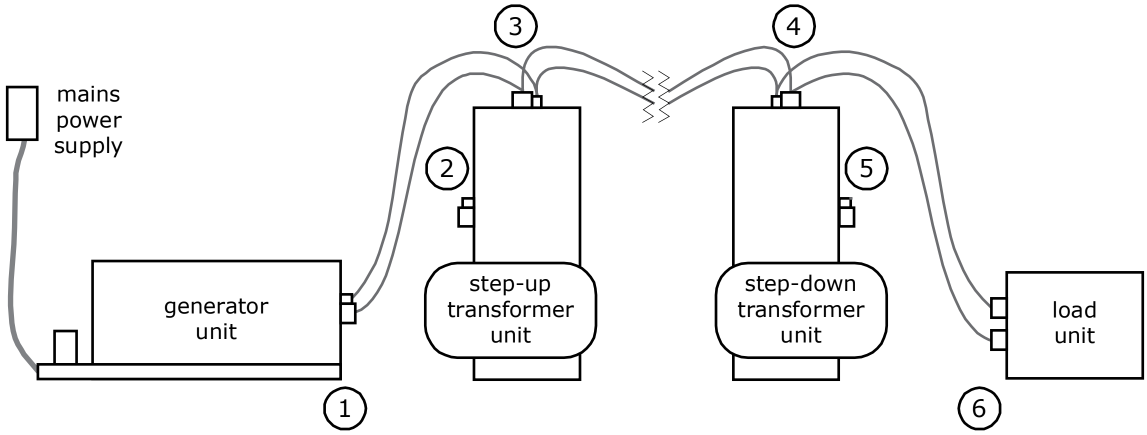
Connect the transmission leads from the upper sockets of the step-up transformer unit to the upper sockets of step-down transformer unit. Move the units apart (about 1 metre) until the transmission leads hang between them.



Initially, you will be connecting the generator unit to the load unit directly via the transmission leads (i.e. without using the transformers).

Use the yellow plug-plug leads to connect:

- the generator unit (1) to the *upper sockets* of the step-up transformer (3)
- the *upper sockets* of the step-down transformer (4) to the load unit (6).



With the generator unit switched off, plug in its mains power supply.

Set the drive control to '8' and switch on the generator. Observe the LED indicators as you increase the load as follows:

- 'Low' only
- 'High' only
- 'Low' and 'High'.

Why are high voltages used for transmission? (continued)

1. Can the generator provide enough power for the maximum load on the load unit?

You will now measure the voltage across the start and across the end of the transmission leads.

Set the load unit to 'Low'.

Switch off the generator and connect a multimeter (a.c. voltage setting) across the sockets at position (3). Switch on the generator and note the voltage.

Switch off the generator and connect the multimeter across the sockets at position (4). Switch on the generator and note the voltage.

2. What is the voltage across the transmission leads at the start? What is the voltage across the transmission leads at the end?

3. What causes this difference?

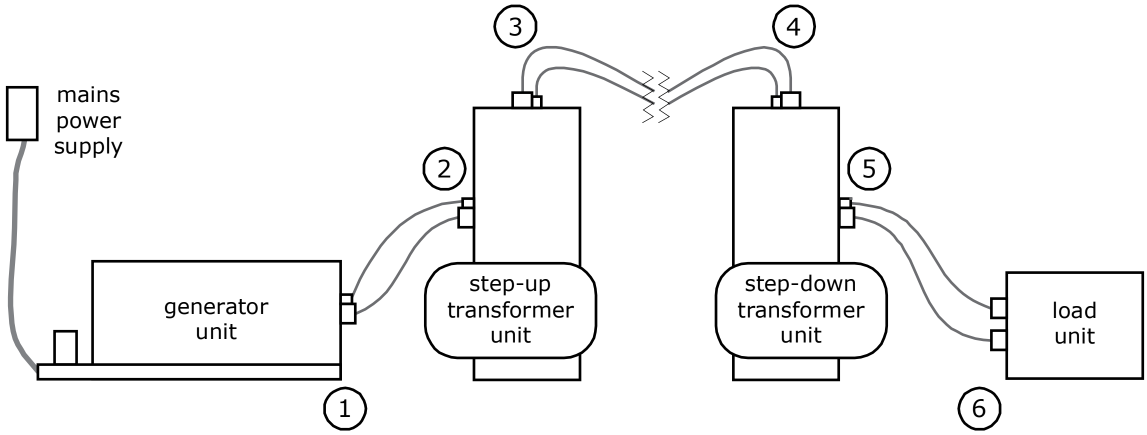
Task 2 High-voltage transmission

Now, you will connect the generator unit to the load unit using transmission leads at a higher voltage (i.e. by using the transformers).

Make sure the generator is switched off each time you connect or disconnect components.

Switch off the generator. Use the yellow plug-plug leads to connect:

- the generator unit (1) to the *lower sockets* of the step-up transformer (2)
- the *lower sockets* of the step-down transformer (5) to the load unit (6).



Keeping the drive control on '8', switch on the generator unit. Observe the LED indicators as you increase the load as before:

- 'Low' only
- 'High' only
- 'Low' and 'High'.

Why are high voltages used for transmission? (continued)

4. Can the generator provide enough power for the maximum load on the load unit?

5. What effect does using a higher voltage for the transmission leads have? Why is this?

You will now measure the voltage across the start and across the end of the transmission leads.

⚠ *Make sure the generator is switched off each time you connect or disconnect the multimeter. Use leads with shrouded plugs to connect the multimeter to the high-voltage transmission leads.*

Set the load unit to 'Low'. Switch off the generator and connect a multimeter across the sockets at position (3). Switch on the generator and note the voltage.

Switch off the generator and connect the multimeter across the sockets at position (4). Switch on the generator and note the voltage. Switch off the generator.

6. What is the voltage across the transmission leads at the start? What is the voltage across the transmission leads at the end?

7. How does the voltage drop for high-voltage transmission compared to that for low-voltage transmission? Why is this?

Task 3 Measuring frequency

Connect a multimeter (frequency setting) to the generator output, and switch on the generator. Note the frequency.

Connect the multimeter to the input of the load unit. Measure the frequency.

8. How does the frequency at the generator compare to the frequency at the load?

Set all the switches on the load unit to 'off', and adjust the drive control until the multimeter reads about 50 Hz.

Now switch the load to 'High'. Listen to the change in pitch of the drive motor and note the frequency reading on the multimeter.

Adjust the drive control so that the multimeter reads about 50 Hz again.

9. What effect does increasing the load have on the frequency?

10. How can a constant frequency be maintained even if the size of the load varies?

Power losses in transmission

The power input to a load can be found by using a voltmeter and an ammeter to measure voltage and current. The calculated values for power can be used to look at the power losses involved in using transformers and transmission lines, and of low-voltage and high-voltage transmission.

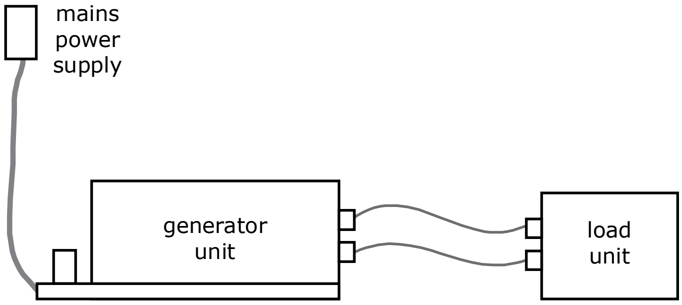
Teacher instruction sheet
This demonstration uses the National Grid Transmission Model, and *involves high voltages*. Questions for students are shown in the boxes.

Task 1 Power output from the generator

Connect the generator unit to the load unit. With the generator unit switched off, plug in its mains power supply.

Set the drive control on the generator unit to ‘8’ and the load unit to ‘Low’.

Switch the generator unit on. The LED on the load unit lights, indicating that energy is being transferred from the generator unit to the load.



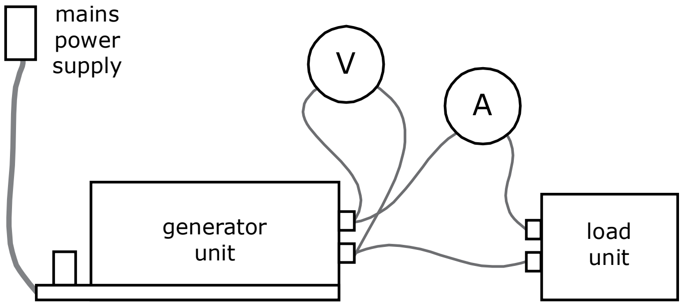
1. What quantities do you need to measure to calculate the power output of the generator?

2. What instruments would you need to use?

3. How would you connect them in the circuit?

When connecting the voltmeter and ammeter it is better to start with the ammeter.

Switch off the generator and insert an ammeter (multimeter on a.c. current setting) into the circuit as shown. Switch on the generator to show that the circuit is still working.



Switch off the generator, and add a voltmeter (multimeter on a.c. voltage setting) across the input sockets of the load unit as shown.

Switch on the generator, and note the readings on the voltmeter and ammeter.

4. What is the value of the voltage across the output sockets of the generator unit?

5. What is the value of the current in the circuit?

6. What is the power output of the generator unit?

Power losses in transmission (continued)

Task 2 Power input to the load after transmission

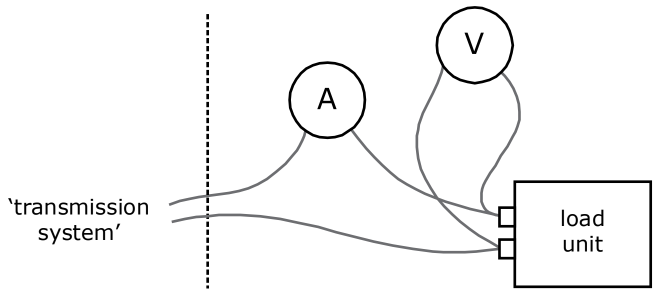
Having measured the power output to the load when connected directly, the next step is to compare with the power inputs using various 'transmission systems':

- high-voltage power lines of negligible resistance
- low-voltage power lines with significant resistance
- high-voltage power lines of significant resistance.

⚠ *Make sure the generator is switched off each time you connect or disconnect components. Use leads with sheathed plugs to connect the transformers to each other.*

Disconnect the voltmeter from the generator and connect across the load.

Disconnect the generator unit, leaving the ammeter in the same position. This arrangement will now be connected to the three different 'transmission systems'.



High-voltage power lines of negligible resistance: Connect the generator unit to the step-up and step-down transformer units, and connect the transformers together using the short blue connecting leads (see second diagram in Demonstration C1).

Use the same settings as in the previous task (drive control on '8' and load set to 'Low'). Note the readings on the voltmeter and ammeter.

7. What is the power input to the load?
8. How does this compare to the power output from the generator?

Low-voltage power lines with significant resistance: Connect the generator unit to the load unit using the two long blue transmission leads (see diagram in Demonstration C2 Task 2).

Switch on the generator and note the readings on the voltmeter and ammeter.

High-voltage power lines with significant resistance: Connect the generator unit to the step-up and step-down transformer units, and connect the transformers together using the two long blue transmission leads (see diagram in Demonstration C2 Task 3).

Switch on the generator and note the readings on the voltmeter and ammeter.

9. What is the power input to the load in each of these two systems?
10. How do these two systems compare to the first one?

Monitoring the National Grid frequency

In order to match electricity generation to demand, the National Grid monitors the frequency and adjusts generation to keep as close to 50 Hz as possible. It has a legal requirement to keep the frequency within ±0.5 Hz of this value, though its normal operating limits are set at ±0.2 Hz.

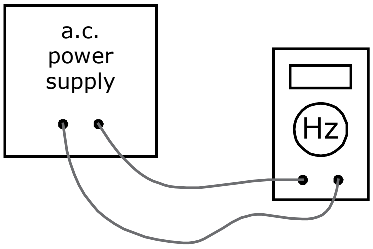
Teacher instruction sheet
This demonstration can be set up by the teacher, with students reading the values. Questions for students are shown in the boxes.

Task 1 Measuring the mains frequency

Connect a multimeter with a frequency function to a low-voltage power supply (set at about 2 V a.c.).

Take measurements of the frequency every 15 seconds over the course of a lesson.

Use a spreadsheet to draw a graph showing how the frequency changes over the measurement period.



1. What is the value of the highest frequency over the measurement period? What is the value of the lowest frequency?

2. What are the upper and lower limits of the frequency that the National Grid must maintain by law?

3. What are the values of the upper and lower operating limits?

4. Look at the graph of the data collected. Does the frequency lie between these limits?

Task 2 Comparison with data from the National Grid

Go to the page on the National Grid website that shows real-time frequency data for the last 60 minutes. (The page should automatically refresh every 15 seconds, but note that there may be a delay in the data shown.)

5. Compare the current value of frequency on the multimeter with that shown on the website. Are they the same?

6. Compare the real-time website graph with the graph of the data collected in the previous task. Do the patterns match?

7. What are the possible reasons that the frequency might increase?

8. What are the possible reasons that the frequency might decrease?

REFERENCES AND FURTHER READING

Downloadable resources

A pdf version of this booklet 'Understanding Electrical Transmission: a Guide to the National Grid Transmission Model' is available on the National Grid website. Also available is a set of PowerPoint presentations that can be used in the classroom to support each of the demonstrations and to provide questions for class discussion.

http://nationalgrideducation.com/resources/

Practical resources

The National Grid Transmission Model is available for purchase from Mindsets (product code NAT GRID1).

http://www.mindsetsonline.co.uk

National Grid leaflets

There is a very useful set of information leaflets on the educational resourc section of the National Grid website.

http://nationalgrideducation.com/resources/

Those which are of particular relevance to the topics addressed in this booklet are:

How electricity is made and transmitted
Electricity transmission National Grid assets
Delivering current electricity
Balancing supply and demand
Energy flow chart
Where's electrical energy going to come from in the future?

National Grid data

The National Grid website contains a wealth of data about electricity usage including a graph which shows real-time frequency data for the last 60 minutes. This is the web page that is used in Demonstration E1 'Monitoring the National Grid Frequency'.

http://www2.nationalgrid.com/uk/Industry-information/electricity-transmission-operational-data

There is also real-time data showing the UK demand (in MW), as well as historical demand data with half-hourly values going back from the present to 2005. Analysing the archive of power demand data gives a lot of opportunities for exploring the patterns of usage over the course of a day, a week and a year.

http://www2.nationalgrid.com/uk/Industry-information/Electricity-transmission-operational-data/Data-Explorer

The following website gives a breakdown in real time of the total power supply by category (i.e. gas, coal, nuclear, wind, etc. and via interconnectors). There is also an interactive map (and satellite view) with information about larger power stations including real-time data of current generation.

http://www.ukenergywatch.org/Electricity/Realtime
http://www.ukenergywatch.org/Electricity/PowerStations

Health and Safety

Members of CLEAPSS can obtain further information about the use of high-voltages in the CLEAPSS Laboratory Handbook: Section 6.1.1 Shocks and burns, and Section 12.9.6 Power line (National Grid) simulation.

Teaching about electricity

The following chapter provides lots of straightforward advice about the teaching of electricity, magnetism and electromagnetism including guidance about teaching sequences, practical activities and how to develop the ideas with students.

Strawson, R (2011) 'Electricity and magnetism' in Sang, D 'Teaching Secondary Physics (Second Edition)' (Association for Science Education / Hodder Education)

Additional practical work

The generation and transmission of electricity serves as a useful context for learning a wide range of concepts related to electricity and electromagnetism. Other practical activities that support the work described in this booklet can be found in the following sections of the Practical Physics website (a partnership between the Nuffield Foundation and the Institute of Physics).

Electric circuits and fields:

http://www.nuffieldfoundation.org/practical-physics/electric-circuits-and-fields

Examples of activities include the use of instruments to measure current and voltage, the heating effect of a current, and the nature of d.c. and a.c currents:

Simple electric circuits (e.g. Using ammeters, Learning to use voltmeters)
Current and charge (e.g. Series and branching circuits)
Potential difference (e.g. Lamp brightness comparison)
Ohm's law and resistance (e.g. Temperature change and resistance)
Introductory experiments on AC (e.g. The waveform of AC on a demonstration oscilloscope, Bicycle dynamo and oscilloscope, Comparing rms value and peak value of AC).

Electromagnetism:

http://www.nuffieldfoundation.org/practical-physics/electromagnetism

Examples of activities include the relationship between magnetic fields and electric currents, the generation of electricity, and the construction and behaviour of transformers:

Magnetic fields due to currents in wires (e.g. Magnetic field due to an electric current in a wire, Oersted's experiment, Magnetic field due to a coil carrying a current)
Electromagnets and their uses (e.g. Simple electromagnet, Electromagnets: field pattern)
Forces on moving charges (e.g. Force on a wire carrying a current in a magnetic field, The electric motor)
Electromagnetic induction (e.g. The motor as a dynamo, Magnet and coil, Cutting a magnetic field with a wire, An electric motor used as a generator)
Transformers (e.g. A model transformer, Transformer: dependence on number of turns, Oscilloscope and alternating voltage from transformer).

Energy:

http://www.nuffieldfoundation.org/practical-physics/energy

Examples of activities include the measurement of power using a voltmeter and ammeter:

Power (e.g. Measuring the power of a lamp, Measuring the power of a motor).

In addition, there are a number of helpful guidance pages in the above sections, including 'Quantitative ideas in electricity', 'Explaining rms voltage and current' and 'Explaining how a transformer works'.

SOURCES

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The practical resources can be purchased from Mindsets. See the website for further details:

www.mindsetsonline.co.uk

IMAGINE CREATE LEARN™

Mindsets (UK) Ltd
Unit 10
The IO Centre
Lea Road
Waltham Cross
Herts
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The accompanying booklet and other e-resources can be downloaded from the National Grid website:

www.nationalgrideducation.com

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