UNDERSTANDING HOW ELECTRICITY IS GENERATED

At Aghada Generating Station, Whitegate, Co. Cork

esb.ie

CONTAINING

- Link to Presentation
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- Quiz Questions
- Past Examination Questions and Suggested Answers

September 2016

Dear Teacher,

ESB is an integral part of communities throughout Ireland and beyond. We have been supplying power to industry, communities and homes for almost 90 years. Our position as Ireland's foremost energy company makes us a vital part of building a brighter and more sustainable future.

We aim to build brighter possibilities by supporting young people and adults in engaging with science, technology and engineering so that they can become the entrepreneurs, innovators and researchers of the future. We do this through our partnerships with organisations like the Science Gallery in Trinity College Dublin, Engineers Ireland and Tech Space. We have developed this presentation to help people understand how electricity is generated in a gas-fired power station. A major focus of the content is to explain the scientific principles behind electricity generation and to help those studying physics and chemistry for their Leaving Certificate examinations.

The content will be published on www.esb.ie and available at www.ESBGeneration.esb.ie.

These supplementary notes augment the presentation and are designed to help teachers cover specific curriculum topics in a creative and engaging way.

I hope that you and your students find this to be a useful resource.

If you require any additional copies of these notes or if you have any feedback or suggestions we would be delighted to hear from you at esbwebmaster@esb.ie.

Pat O'Doherty
Chief Executive

Junior Cycle and Primary School Teachers

In order to allow teachers of younger students to utilize the site we have a table quiz with the questions set to a level accessible to Junior Certificate students as well as higher classes in primary schools. These quiz questions are not overtly technical and they mainly focus on the acronyms and simple numeric statistics that are readily available on the website.

Senior Cycle Teachers

The Aghada website is a teaching resource that has attached Leaving Cert Curricular points to an actual real word model. The site involves sufficient material for it to be used as the centre piece of a module looking at the science behind the generation of electricity. The material has been written mainly with a post-primary school audience in mind. The following manual augments the website and it supplies the teacher with supplementary notes, hyperlinks to videos and some additional information that goes beyond the national curriculum.

The manual can thus be utilized for the purpose of lesson planning and where deemed appropriate, to the ability of your group, you may wish to introduce higher level ideas so as to encourage and enable students to think a bit more about the science involved. These higher level sections are marked as “PLC Material” as the ideas are Post Leaving Cert issues. This site has been set out so that it can be used as the basis to an innovative Transition Year module or it can simply act as a creative way in a senior cycle setting to recap on several laws and ideas from the Curriculum itself. Please note that the PLC sections are there to allow teachers to challenge higher level students and to aid you in differentiating your lesson plans which is in keeping with educational best practice.

This site will allow teachers to step away from the textbook and it offers a great platform through which educational practitioners can cover some laws of physics and chemistry in a dynamic and creative fashion. It affords the teacher an opportunity to seamlessly connect various parts of the curriculum together, thus displaying to students an authentic real world application of the scientific theory they are studying. It demonstrates vividly to students that scientific principles in the curriculum are not stand alone issues but rather the curriculum is a body of laws all of which are interconnected. This website shows in living colour a chorus of laws and scientific ideas all operating in harmony. It shows how a group of laws can be used in a collective movement to generate electricity. This website displays neatly how the curriculum is a body of ideas that can be put together so as to complete valuable and practical work in the world around us. This detailed explanation of the operation at Aghada Power Plant demonstrates to students how the theory of their course has very strong real world applications.

Direct curricular references can be found via the “learn more” tab which is available on many of the slides.

1. Fire Triangle (in Aghada the triangle is made up of methane, air and the ignitor)
2. Ohm’s Law
3. The water cycle (in Aghada there is a closed water steam cycle using a finite amount of liquid)
4. Latent heat and states of matter
5. Magnetic Flux and Induction
6. Pressure = Force/Area (an application of this can be seen in the steam turbine /aerofoil)
7. Faraday’s Law
8. Lenz’s Law
9. Transformer Law
10. Methane (hydrocarbon)
11. Stoichiometry (Leaving Cert Chemistry)
12. Sine Function and phasing (Project Maths Leaving Cert Honours)
13. Gay-Lussac’s Law
14. The electric motor versus the generator (two sides of the same coin)
15. There are also many examples of energy conversions at Aghada.

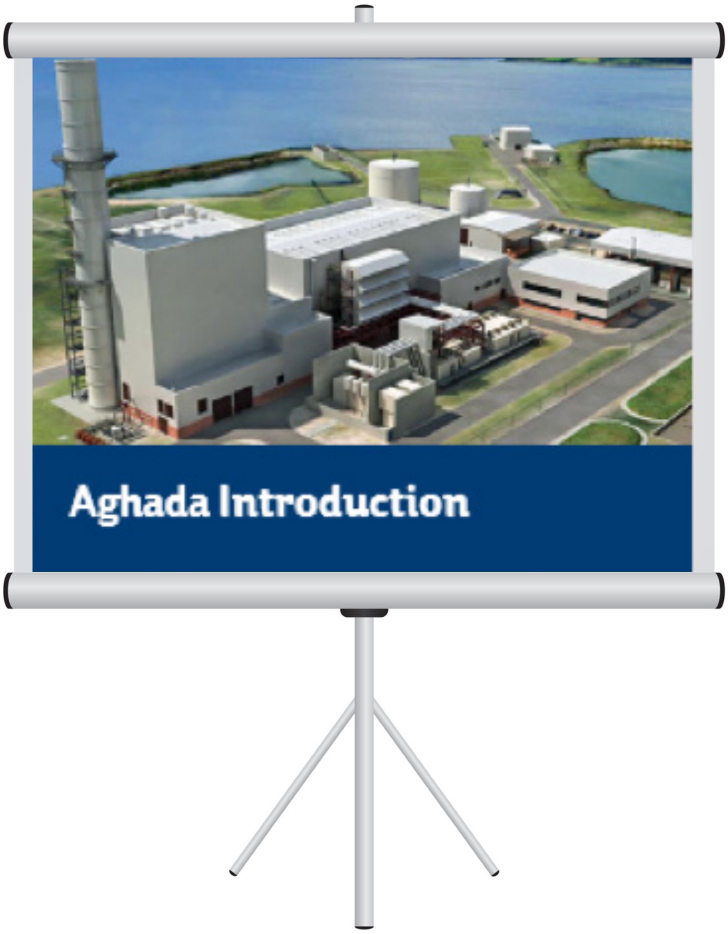
Suggested Pathway through the Website

1. Aghada Introduction
2. The Complete Power Plant
3. The Generator
4. Gas Turbine
5. The HRSG
6. The Steam Turbine

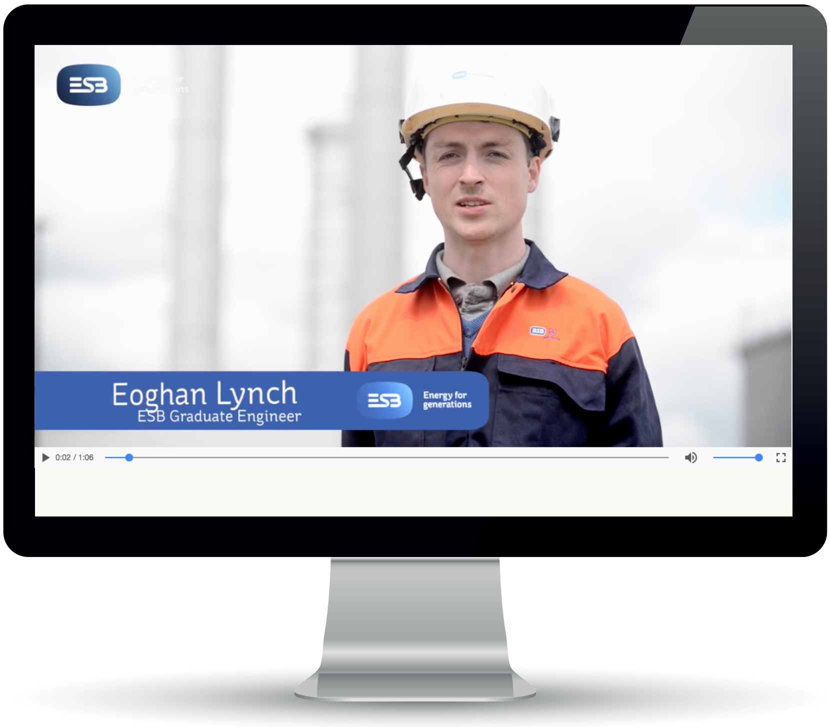
Section 1

Start the presentation by clicking here http://esbgeneration.esb.ie.

Go to Main Menu. Click Aghada Introduction.



From here view the short video from an ESB graduate engineer



Section 2

The Complete Power Plant

After watching the short introduction film you should move to the “Complete Power Plant” tab. This gives an overview of the process by way of a well-illustrated schematic. It is very important to impress on students at the outset that the generation of electricity in Aghada does not physically follow the line of the animation directly from left to right, though instinctively one might think that to be the case. In order to bring this idea home to students, the teacher should click on the tab and then go through the points below with the class using the animation as a backdrop while detailing the overall cycle of the operation.

Electricity Generation at Aghada follows the steps listed below.

From time to time the Power Plant will be shut down for maintenance or for some other reason. You will see below is the step by step process that is followed when the plant is being started up again.

Aghada Overview Step by Step

1.) When starting up the plant after a shut-down, the generator (at the centre of the animation) is initially operated in reverse so as to function as a motor and in this case electrical energy is converted into mechanical / rotational energy. This energy conversion is utilized so as to power up the gas turbine (GT) to a sustainable speed. So the starting point for the operation is actually at the centre of schema.

2.) The GT positioned to the right of the generator as you look at the animation, burns methane while rotating and the exhausts from this process then enter the Heat Recovery Steam Generator (HRSG) which is on the extreme right of the animation. (The HRSG was added during the Aghada extension in 2010: Prior to that, the exhausts were lost to the atmosphere.)

3.) The Heat Recovery Steam Generator (HRSG) simply does what it says on the tin. It captures the exhaust heat from the GT and makes use of this thermal energy in order to generate steam.

4.) The steam rises and exits the top of the HRSG where it then travels along a system of pipes from right to left. The steam travels over the GT and over the generator. At this stage it enters the second turbine (steam turbine) via 3 entry points these are a HP an IP and an LP pressure lines. (HP = high pressure IP = intermediate and LP = low)

5.) The second turbine (which is on the extreme left of the animation) rotates under the influence of falling steam and when the steam turbine is in operation it connects to the generator via a synchronous self-shifting clutch. This engine in tandem with the GT sends rotational energy to the generator. (Working together, they allow Aghada to operate at an efficiency of 58.7% in combined cycle. In open cycle, with GT only, the efficiency is only 37%.)

6.) Once the steam has passed through the turbine it enters the condenser where it is converted back into water and then pumped back to the HRSG.

7.) Note that there is a finite amount of water involved. It is simply recycled over and over as it travels within a closed system (this is akin to the water cycle in nature).

8.) Process Summary: Once the GT is up and running it supplies heat to the HRSG where it is used to convert water into steam. This steam travels back along an overhead pipe to the second engine where it is used to drive the second turbine. After this the steam is converted back into water and it is pumped across to the HRSG so that the cycle can continues indefinitely.

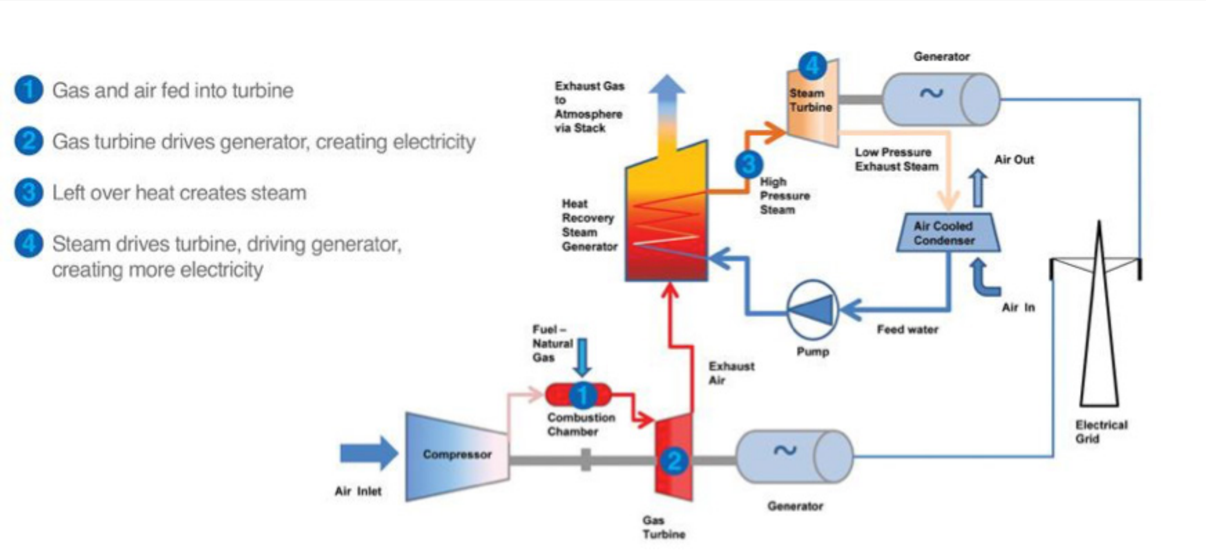
What is Open Cycle versus Combined Cycle?

There are references to two different cycles on the Complete Power Plant schematic. When Aghada Power Plant was commissioned in 1980 it consisted initially of a gas-fired conventional turbine which operated in Open Cycle. This is to say that the exhaust of the gas turbine was open to the atmosphere and with this set-up only 37% of the thermal energy from burning the methane was actually converted into electrical energy. This shorter cycle is marked on the bottom of the Complete Power Plant slide, the open cycle involves the use of the gas turbine only without transfer of the exhaust to the HRSG.

In 2010 the capacity of the station was increased from 528MW to 963MW. This was achieved through the establishment of a Combined Cycle at Aghada. The power plant still maintains the option to operate in open cycle and during peak demand the Combined Cycle can be utilized. In the Combined Cycle the exhaust is not open but rather it is funnelled into the HRSG and in the Combined Cycle the steam turbine in used in unison with the gas turbine so that the plant operates with a thermal efficiency of 58.7%.

Open Cycle = generator being powered by the gas turbine only
Closed Cycle = the generator is powered by both the gas and the steam turbine.

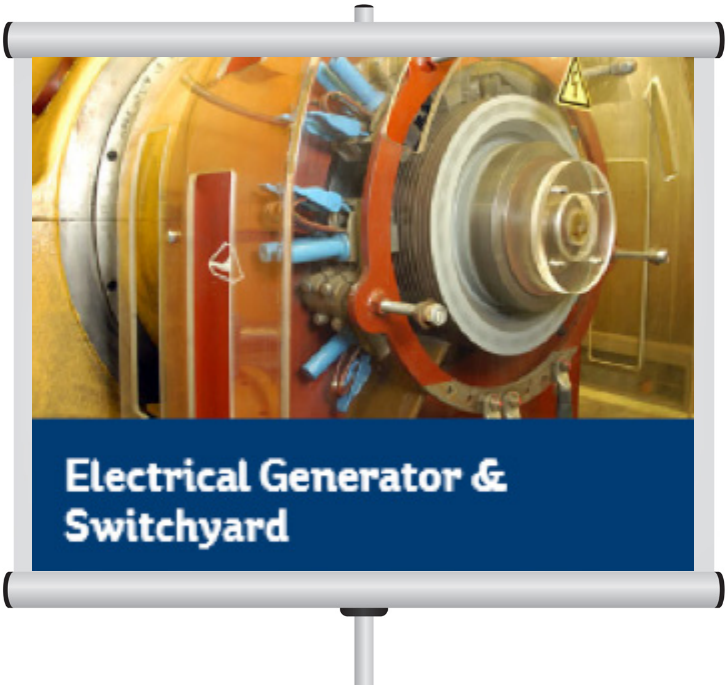
Fig 1 : This illustration of the CCGT differs from Aghada as this schema has two generators but Aghada has only one.



With a simple Open Cycle Gas Turbine there is no means to capture the waste heat from the exhaust of the turbine/engine: this means that the majority of the energy harvested from the methane is lost to the atmosphere. In thermodynamic terms, open cycle units are far less efficient than Combined Cycle Gas Turbines. With the Combined Cycle the exhaust is captured by the HRSG and the thermal energy is used to generate steam that in turn drives a second turbine. The second turbine in Aghada raises the efficiency of the plant up to 57.8% whereas in open cycle the plant only has an efficiency of 37%. The new plant with the HRSG and second turbine was constructed over a 30-month period at a cost of €360m and it entered commercial operations in 2010.

Section 3

The Generator



The Start-Up Motor at Aghada (Running the Generator in Reverse)

The generator consists of a rotor and a stator and therefore it is a full electromagnetic system so it can be operated in reverse so as to work as a motor allowing electrical energy to be converted into mechanical (rotational) energy. The motor option is used to power up the gas turbine during a start (much like a starter on a car engine). Once the turbine is operating at a self-sustaining speed there is no longer a need for the motor. When the gas turbine is running at this sustainable level the electromagnetic system reverts back to its primary function which is that of a generator. In order to start up the gas turbine, some electricity (electrical energy) is drawn from the national grid and converted into rotational energy by the motor. The initial need to draw this electricity in order to run up the gas turbine means that Aghada cannot be set to work in a black-start situation, i.e. the gas turbine can only be powered up at Aghada when there is access to the national grid.

A motor: converts electrical energy into mechanical energy.
A generator: converts mechanical energy into electrical energy.

Faraday's Law and Lenz's Law

When looking at the slides concerning the generator at Aghada there are sections relating to Faraday's Law. You should take this opportunity to also look at Lenz's law as both ideas are naturally linked together. Below is a definition and a short video from MIT that demonstrates Lenz's law in action.

Lenz's law is a common way to understand how electromagnetic circuits obey Newton's third law and the conservation of energy. Lenz's law is named after Heinrich Lenz, and it says: An induced electromotive force (emf) always gives rise to a current whose magnetic field opposes the original change in magnetic flux. So this is a case that shows clearly that for every action there is an opposite and equal reaction.

https://www.youtube.com/watch?v=N7tli71-AjA

Section 4

The Gas Turbine

The Gas Turbine and the 4-Stroke Engine (PLC Material)

The gas turbine in Aghada is akin to the four-stroke car engine and you should run through this analogy with the class before tackling the detailed written slides about the gas turbine. Completing this overview in advance will aid the students in capturing and retaining more information about the gas turbine.

The 4 Stages of the Gas Turbine (Inlet, Compression, Combustion and Expansion)

Air is taken in and compressed before entering the combustion chambers where an exothermic reaction with methane occurs. The hot gases are used to drive the turbine shaft and finally the exhaust fumes are captured by the HRSG where they are put to work supplying steam to a second turbine at Aghada.

1. The inlet section is where a steady stream of air is drawn in to feed the compressor.
2. The compressor section uses a series of rotors and stators to densely pack the air in order to feed the combustion chamber sufficiently and efficiently with highly pressurised air.
3. Combustion chambers: Here the air is mixed with natural gas. The mixture is ignited and an exothermic reaction occurs. In Aghada there is a second combustion chamber to make the plant more environmentally friendly.
4. The expansion and exhaust section. The resultant hot gases expand (diffusion of gases) causing the gas turbine to rotate. Then the exhausts are directed to a heat recovery steam generator (HRSG).

3.2 Principles of Pressure (PLC Material)

You may wish to point out to students that pressure is in fact a form of energy and for this reason the principle of conservation applies. Pressure can neither be created nor destroyed but rather it can be converted from one form to another. Pressure can be used to establish high grade thermal energy stores as happens in Aghada where the 22-stage compressor assembly supplies highly pressurised air to the combustion chamber. The thermal energy carried by the compressed air and the potential energy of the gas are released by way of an exothermic reaction and this energy is used to drive the gas turbine, which in turn supplies rotational energy to the generator. This rotational energy is actually converted into electrical energy and then it is transported to the national grid. You might consider highlighting all the above energy conversions to students by making use of the Complete Power Plant schematic.

Stoichiometric Ratio of Air and Methane (Leaving Cert Chemistry)

Within the combustion chamber methane, which is a hydrocarbon reacts with the oxygen in air to release water and carbon. It is an exothermic reaction, thus there is also a release of heat and (by extension) pressure. The turbine shaft rotates under the influence of the expanding hot gases. The generator is coupled to the turbine shaft so it too rotates and the magnetic flux present enduces an EMF (electromotive force).

CH_4 + $2O_2$ --> $2H_2O$ + CO_2

Methane + Oxygen --> water + carbon dioxide

Hydrogen (H) = 1.008

- So 1 molecule of methane has a molecular weight of: 1 * 12.01 + 4 * 1.008 = 16.042
- One oxygen molecule weighs: 2 * 16 = 32
- The oxygen-fuel mass ratio is then: 2 * 32 / 1 * 16.042 = 64 / 16.042
- So we need 3.99 kg of oxygen for every 1 kg of fuel
- Since 23.2 mass-percent of air is actually oxygen, we need : 3.99 * 100/23.2 = 17.2 kg air for every 1 kg of methane.

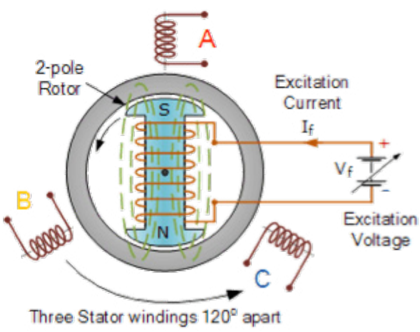
So the stoichiometric air-fuel ratio of methane is 17.2 : 1

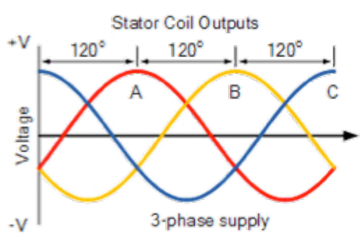
In order to achieve this ratio and thus efficient use of the methane, we need to compress the air supply greatly, hence the use of the 22-stage Axial compressor which allows us to achieve the high ratio of 17.2 parts air to one part methane.

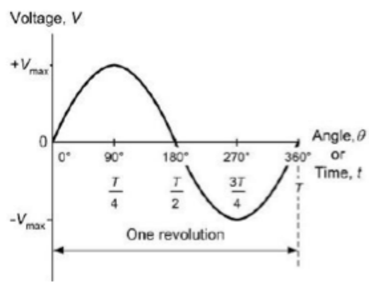
Alternating Current follows a sine wave function. (Honours Project Maths Trigonometric Functions):

For those doing honours maths you will have looked at the trig. functions asin(bx). Within this trig.function a is the multiplier/inverter of the magnitude and b affects the period of the wave. As outlined in the maths course, the period of sinx = 360o but the period of sin2x =180o.

We can also delay the starting point of the trig. Function. This would be written as sin(x + no. of degrees), the number of degrees is called the shift. In the 3-phase synchronous generator at Aghada we make use of the function sin(x), sin(x+1200) and sin(x +240O). This arrangement of the 3 stator windings allows for the rotational energy to be converted into electrical energy in the most economically efficient manner. Below is a diagram of the 3-phases and they are clearly illustrated using colour coding. The electrical phase for winding A is illustrated by the red-line while B is illustrated by the yellow line and C by the blue line. This 3-phase electrical supply leads to a steady smooth power supply whereas a single phase function would be periodically crossing the x-axis. Thus the voltage would be zero and the power supply would not be steady or smooth.







Section 5

There are no supplementary notes for the HRSG as everything needed is on the website.

Section 6

The Steam Turbine

Slide 6.5 Specific Heat Capacity of Water

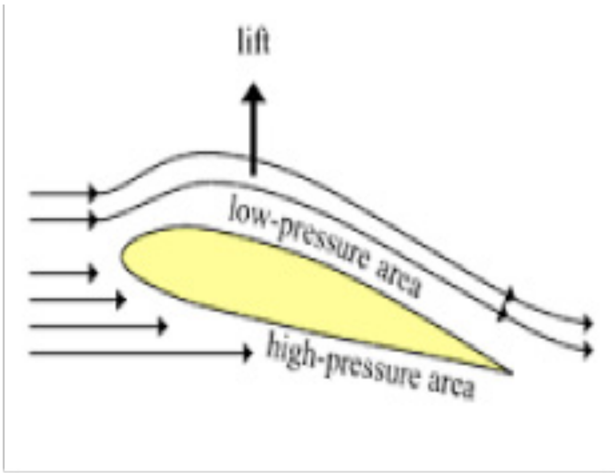
The Specific Heat Capacity (SHC) of water is very high and this allows the material to carry a large volume of thermal energy within a small mass quantity. The SHC of H2O per degree increases exponentially when it is superheated thus allowing H20 (in a superheated state) to carry even greater volumes of energy. The density of the thermal energy in the superheated steam allows the second turbine in Aghada to supply good quantities of energy to the generator

$E = m.c.\theta$			
Substance	S.H.Cap (J/(kgK)	Substance	Specific heat capacity (J/(kgK)
Water	4200	Aluminium	913
Cast iron	500	Brick	840
Copper	385	Concrete	880
Lead	126	Marble	880
Table 1: Specific Heat Capacity of various materials. Note the SHC of water is 8 times higher than cast iron.			

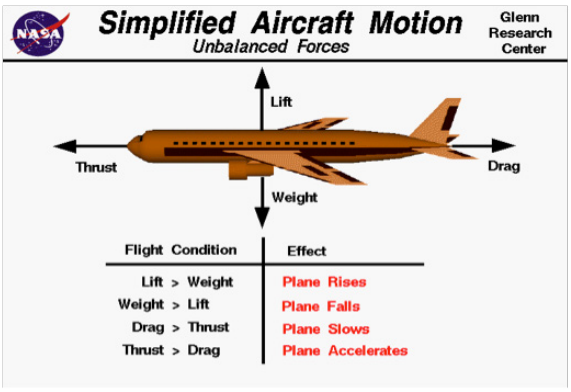
Bernoulli's Law / The Bernoulli Principle (PLC material)

In order to draw in the students, it may be an idea to go through the Bernoulli principle in the context of how an aeroplane takes off and then to move to the steam generator which operates in an identical manner. In fact, each blade on the steam turbine is shaped like a small aeroplane wing; ergo there is an aerofoil present within the steam turbine.

How planes take off……………



The job of the aeroplane engine is to cause thrust so as to move the body forward in the same way an engine moves a car forward. But the lift force that causes the plane to actually leave the ground is generated by the shape of the wings which are designed to be aero-dynamic and as air (a fluid) passes over a pressure difference (pd) is established. This pd occurs due to the cross section of the wing being tear shaped (as are the blades of the steam turbine.) The underside of the wing is essentially flat while the top side has a pronounced curve. The micro airstream travelling over the top is more spaced out (less dense) then the air under the wing. Thus the densely packed air underneath is more pressurised. This pd supplies the plane with an upward force known as lift. The faster the plane travels the greater the pd. Therefore the thrust forward must be sufficient for the lift to be greater than the weight of the plane. Remember weight is a downward force where mass x gravity = weight. The take-off speed of a Boeing 737 is 250km/hr. At this point the lift eclipses the weight of the plane. The flight speed of the 737 is 522 mph or 840 kph this maintains the pressure difference at a safe level during the flight.



The steam turbine rotates under the influence of an aerofoil and the physical principle at play here is identical to how lift is generated when a plane is taking off. This idea is known at the Bernoulli Principle. In this case, the flow path of the fluid is perpendicular to the movement of the body. (This is true for both the plane and the turbine.) It is certainly worth highlighting to students that the steam does not push the blades (like running water pushes the wheel in an old mill), but rather the steam is used to establish a pressure difference across each blade. So in terms of motion the steam passes over the turbine blades exactly as air passes over the wings of a plane. The blades are shaped to act as aerofoils and they rotate around the shaft to which they are attached. This rotating motion is perpendicular to the flow path of the steam.

Synchronous Self-shifting Clutch (SSS Clutch)

The Closed Cycle Gas Turbine (CCGT) plant in Aghada is built around a single shaft with the generator and the gas turbine coupled together at all times by a permanent connection. The shaft from the generator can also clutch on and off the steam turbine as necessary to meet the output needs of the plant. This is done using a Synchronous Self-Shifting (SSS) clutch. The SSS clutch action can be compared to what happens when a nut grips onto a bolt. When the main shaft is rotating with sufficient torque (turning force) it engages the ratchet teeth of the steam turbine and it moves along the main shaft like a rotating nut moves along the axis of a bolt. Once the steam turbine is fully meshed with the main shaft, the steam turbines can transfer rotational energy to the generator.

https://www.youtube.com/watch?v=iA1o6aJehAg

Table Quiz

(Junior Cert or Higher Classes in Primary Schools)

The following 5 rounds of questions are suitable for use with a Junior Cert or high primary school class. The quiz should be conducted after giving the students ample time and opportunity to study the facts and figures outlined in the site.

As you guide students through the material you should advise them to focus on the numbers and acronyms used in the presentation. These two areas form the basis for the table quiz below. For the questions with numerical answers you may give students two or three options to pick from if you want to simplify the quiz a little bit. Some notes are given with certain answers and you should refer to these notes only when correcting the round and not at the point when the question is asked. This quiz is not overly technical but it provides a fun way for the students to engage with the material. In preparing for the quiz, students will learn a lot about Aghada Power Plant.

Round 1

1. How tall is the chimney stack in the HRSG? 70 metres
2. When was Aghada power station first opened? 1980
3. At what temperature do the exhaust fumes enter the HRSG? 620 degrees Celsius
4. What are the three components of the fire triangle? Fuel, heat and oxygen
5. When was the second turbine added to the power plant at Aghada? 2010.
6. How many turbines are used when Aghada is operating the Combined Cycle? Two (gas and steam)
7. From what material are the cooling tubes in the condenser made of? Titanium
8. In what year was the relationship between magnetism and electrical current discovered? 1819

Round 2

1. In electrical terms what do the letters in AC stand for? Alternating Current
2. What do the letters DC stand for in electrical terms? Direct Current
3. In which county in Munster is Aghada power plant? Cork
4. How many phases are there on the generator? Three
5. What is the scientific shorthand for water? H_2O
6. What is the scientific shorthand/notation used for carbon dioxide? CO_2
7. What is the thermal efficiency of Aghada Power Plant? 58.7%
8. What is an exothermic reaction? It's a reaction that gives out heat. (Burning wood, for example.)

Round 3

1. What do the letters HRSG stand for? Heat recovery steam generator
2. Which turbine (steam or gas) is permanently connected to the generator? Gas turbine
3. How many stages are there in the compressor before reaching the combustion chamber? 22 stages
4. What does SEV stand for? Sequential Environmental.
5. What captures the gas turbine exhaust fumes during a closed cycle? The HRSG
6. What type of fuel is burnt in the gas turbine? Methane. Note: the answer is not gas.
7. Into which section does the steam travel once it has passed through the steam turbine? Into the condenser.
8. What do the letters SHC stand for? Specific Heat Capacity.

Round 4

1. At what temperature does the exhaust exit the chimney stack? 79 degrees Celsius
2. At what voltage level does the national grid operate? 220Volts or 220V
3. Are the titanium cooling pipes in the condenser set horizontally or vertically? Horizontally
4. What are the three main parts of the electrical generator? Stator, rotor and brush compartment
5. Which part of the generator is in fixed or stationary position? The stator
6. What do the letters rpm stand for? Revs per minute. Note: revs = revolutions / rotations
7. To what speed (in rpms) does the motor drive the gas turbine? 2,700 rpm
8. The steam turbine and generator are connected by an SSS clutch but what does this stand for? Self Shifting and Synchronising

Round 5

1. What is the thermal efficiency of Aghada in open cycle (gas turbine only)? 37%. Note: This means that in open cycle 37% of the heat from burning the methane is converted to electricity while 63% is lost to the atmosphere.
2. How many annular EV burners are there in the gas turbine? 30
3. How many annular SEV burners are there? 24
4. What is the temperature of the steam entering the High pressure steam turbine? 565 degrees Celsius.
5. What is the temperature of the steam entering the low pressure turbine? 284 degrees Celsius
6. What is the pressure on the steam entering the LP turbine? 4.9 bar. Note: 1 bar is slightly less then atmospheric pressure at sea level on the planet earth.
7. Name the type of water that is pumped through the cooling pipes in the condenser? sea water
8. Which sticky food is traditionally annular shaped? The doughnut

Physics Electromagnetic Induction Questions

2015 - 2002

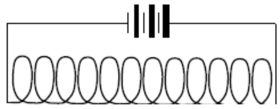
2015 Question 12 (d) [Ordinary Level]

A solenoid (long coil of wire) is connected to a battery as shown.

(i) Copy the diagram into your answer book and draw the magnetic field in and around the solenoid.

(ii) Explain the term electromagnetic induction.

(iii) A magnet and a solenoid can together be used to produce electricity.
Describe, with the aid of a diagram, how this can be done.



2014 Question 9 [Ordinary Level]

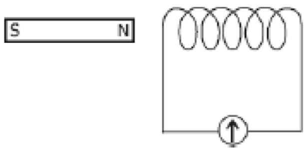
(i) A magnetic field exists around a current-carrying conductor.
What is a magnetic field?

(ii) How does a compass indicate the direction of a magnetic field?

(iii) Describe an experiment to show that there is a magnetic field around a current-carrying conductor and sketch the field lines around the conductor.

(iv) Sketch the magnetic field around a bar magnet.

(v) A coil of wire is connected as shown in the diagram to a galvanometer.
A bar magnet is placed near the coil.
What is observed when the magnet is moved towards the coil?



(vi) What is observed when the magnet is stationary?

(vii) Explain these observations.

(viii) How would increasing the speed of movement of the magnet alter the observations?

2010 Question 11 [Ordinary Level]

Read this passage and answer the questions below.

In 1819 the Danish physicist Hans Christian Oersted discovered that an electric current flowing through a wire deflected a compass needle.

A year later the Frenchman François Arago found that a wire carrying an electric current acted as a magnet and could attract iron filings. Soon his compatriot André-Marie Ampère demonstrated that two parallel wires were attracted towards one another if each had a current flowing through it in the same direction. However, the wires repelled each other if the currents flowed in the opposite directions.

Intrigued by the fact that a flow of electricity could create magnetism, the great British experimentalist Michael Faraday decided to see if he could generate electricity using magnetism. He pushed a bar magnet in and out of a coil of wire and found an electric current being generated. The current stopped whenever the magnet was motionless within the coil.

(Adapted from 'Quantum' by Manjit Kumar, Icon Books 2008)

(i) Who discovered that an electric current can deflect a compass needle?

(ii) What did Arago discover?

(iii) What happens when currents flows in the same direction in two parallel wires?

(iv) How could two parallel wires be made to repel each other?

(v) Draw a sketch of the apparatus Michael Faraday used to generate electricity.

(vi) What name is given to the generation of electricity discovered by Michael Faraday?

(vii) What energy conversions that take place in Faraday's experiment?

(viii) How does Faraday's experiment show that a changing magnetic field is required to generate electricity?

2011 Question 9 (a) [Ordinary Level]

State Faraday's law of electromagnetic induction.

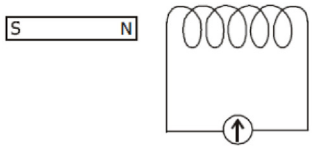
A coil of wire is connected to a sensitive meter, as shown in the diagram.

(i) What is observed on the meter when the magnet is moved towards the coil?

(ii) What is observed on the meter when the magnet is stationary in the coil?

(iii) Explain these observations.

(iv) How would changing the speed of the magnet affect the observations?



2005 Question 9 [Ordinary Level]

(i) What is a magnetic field?

(ii) Draw a sketch of the magnetic field around a bar magnet.

(iii) Describe an experiment to show that a current carrying conductor in a magnetic field experiences a force.

(iv) List two factors that affect the size of the force on the conductor.

(v) A coil of wire is connected to a sensitive galvanometer as shown in the diagram.
What is observed when the magnet is moved towards the coil?

(vi) Explain why this occurs.

(vii) Describe what happens when the speed of the magnet is increased.

(viii) Give one application of this effect.

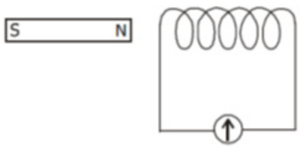
2008 Question 12 (d) [Ordinary Level]

(i) What is electromagnetic induction?

(ii) A magnet and a coil can be used to produce electricity.

(iii) How would you demonstrate this?

(iv) The electricity produced is a.c. What is meant by a.c?



2006 Question 11 [Higher Level]

Read the following passage and answer the accompanying questions.

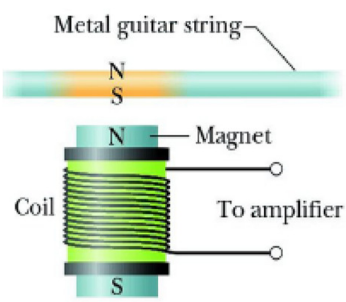
The growth of rock music in the 1960s was accompanied by a switch from acoustic guitars to electric guitars. The operation of each of these guitars is radically different.

The frequency of oscillation of the strings in both guitars can be adjusted by changing their tension. In the acoustic guitar the sound depends on the resonance produced in the hollow body of the instrument by the vibrations of the string. The electric guitar is a solid instrument and resonance does not occur.

Small bar magnets are placed under the steel strings of an electric guitar, as shown. Each magnet is placed inside a coil and it magnetises the steel guitar string immediately above it. When the string vibrates, the magnetic flux cutting the coil changes, an emf is induced causing a varying current to flow in the coil. The signal is amplified and sent to a set of speakers.

Jimi Hendrix refined the electric guitar as an electronic instrument. He showed that further control over the music could be achieved by having coils of different turns.

(Adapted from Europhysics News {2001} Vol. 32 No. 4)



(a) How does resonance occur in an acoustic guitar?

(b) What is the relationship between frequency and tension for a stretched string?

(c) A stretched string of length 80cm has a fundamental frequency of vibration of 400 Hz.
What is the speed of the sound wave in the stretched string?

(d) Why must the strings in the electric guitar be made of steel?

(e) Define magnetic flux.

(f) Why does the current produced in a coil of the electric guitar vary?

(g) What is the effect on the sound produced when the number of turns in a coil is increased?

(h) A coil has 5000 turns. What is the emf induced in the coil when the magnetic flux cutting the coil changes by 8×10^{-4} Wb in 0.1 s?

2005 Question 12 (b) [Higher Level]

(i) Define magnetic flux.

(ii) State Faraday's law of electromagnetic induction.

(iii) A square coil of side 5 cm lies perpendicular to a magnetic field of flux density 4.0 T.
The coil consists of 200 turns of wire.
What is the magnetic flux cutting the coil?

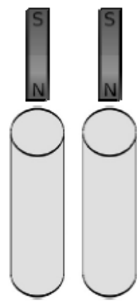
(iv) The coil is rotated through an angle of 90° in 0.2 seconds.
Calculate the magnitude of the average emf induced in the coil while it is being rotated.

2014 Question 12 (d) [Higher Level]

(i) State Faraday's law of electromagnetic induction.

(ii) Describe an experiment to demonstrate Faraday's law.

(iii) A hollow copper pipe and a hollow glass pipe, with identical dimensions, were arranged as shown in the diagram.
A student measured the time it took a strong magnet to fall through each cylinder.
It took much longer for the magnet to fall through the copper pipe.
Explain why.



2008 Question 8 [Higher Level]

(i) What is electromagnetic induction?

(ii) State the laws of electromagnetic induction.

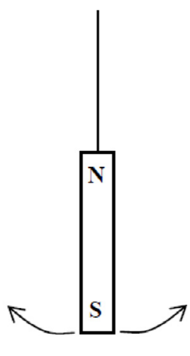
(iii) A bar magnet is attached to a string and allowed to swing as shown in the diagram. A copper sheet is then placed underneath the magnet.
Explain why the amplitude of the swings decreases rapidly.

(iv) What is the main energy conversion that takes place as the magnet slows down?

(v) A metal loop of wire in the shape of a square of side 5 cm enters a magnetic field of flux density 8 T.
The loop is perpendicular to the field and is travelling at a speed of 5 m s^{-1}.
How long does it take the loop to completely enter the field?

(vi) What is the magnetic flux cutting the loop when it is completely in the magnetic field?

(vii) What is the average emf induced in the loop as it enters the magnetic field?



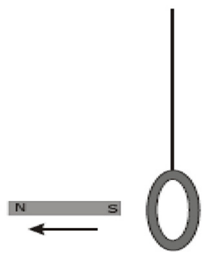
2004 Question 12 (c) [Higher Level]

(i) What is electromagnetic induction?

(ii) Describe an experiment to demonstrate electromagnetic induction.

(iii) A light aluminium ring is suspended from a long thread as shown in the diagram.
When a strong magnet is moved away from it, the ring follows the magnet.
Explain why.

(iv) What would happen if the magnet were moved towards the ring?

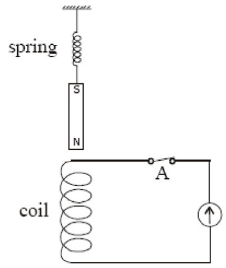


2003 Question 12 (d) [Higher Level]

(i) State the laws of electromagnetic induction.

(ii) A small magnet is attached to a spring as shown in the diagram.
The magnet is set oscillating up and down. Describe the current flowing in the circuit.

(iii) If the switch at A is open, the magnet will take longer to come to rest. Explain why.



Self-Induction

2007 Question 12 (c) [Higher Level]

(i) State Faraday's law of electromagnetic induction.

(ii) Describe an experiment to demonstrate Faraday's law.

(iii) A resistor is connected in series with an ammeter and an ac power supply. A current flows in the circuit. The resistor is then replaced with a coil. The resistance of the circuit does not change. What is the effect on the current flowing in the circuit? Justify your answer.

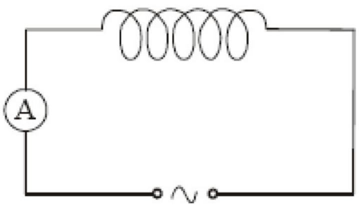
2002 Question 12 (c) [Higher Level]

(i) What is meant by electromagnetic induction?

(ii) State Lenz's law of electromagnetic induction.

(iii) In an experiment, a coil was connected in series with an ammeter and an a.c. power supply as shown in the diagram.
Explain why the current was reduced when an iron core was inserted in the coil.

(iv) Give an application of the principle shown by this experiment.



Transformers

2002 Question 9 [Ordinary Level]

(i) What is electromagnetic induction?

(ii) Describe an experiment to demonstrate electromagnetic induction.

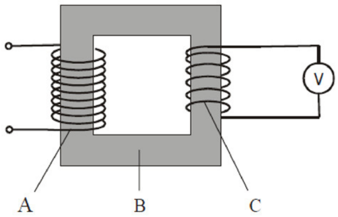
(iii) The transformer is a device based on the principle of electromagnetic induction. Name two devices that use transformers.

(iv) Name the parts of the transformer labelled A, B and C in the diagram.

(v) The mains electricity supply (230 V) is connected to A, which has 400 turns. C has 100 turns. What is the reading on the voltmeter?

(vi) How is the part labelled B designed to make the transformer more efficient?

(vii) The efficiency of a transformer is 90%. What does this mean?



2004 Question12 (c) [Ordinary Level]

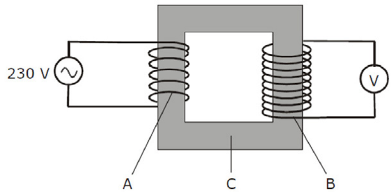
(i) A transformer is a device based on the principle of electromagnetic induction.

(ii) What is electromagnetic induction?

(iii) Name another device that is based on electromagnetic induction.

(iv) Name the parts of the transformer labelled A, B and C in the diagram.

(v) Part A has 400 turns of wire and part B has 1200 turns. Part A is connected to a 230 V a.c. supply. What is the voltage across part B?



2007 Question 12 (d) [Ordinary Level]

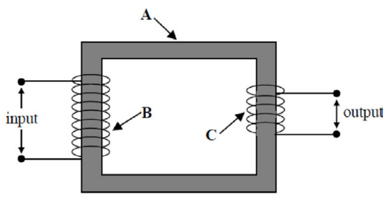
The diagram shows a transformer.

(i) What is electromagnetic induction?

(ii) Name the parts labelled A and B.

(iii) The input voltage is 230 V. Part B has 4600 turns and part C has 120 turns. Calculate the output voltage.

(iv) Name a device that uses a transformer.



2011 Question 9 (b) [Ordinary Level]

Transformers are used to step up or step down a.c. voltages.

(i) What is meant by a.c.?

(ii) Draw a labelled diagram showing the structure of a transformer.

(iii) The input coil of a transformer has 200 turns of wire and is connected to a 230 V a.c. supply. What is the voltage across the output coil, when it has 600 turns?

2013 Question 11 [Ordinary Level]

(i) Why are high voltages used to transmit power over the national grid?

(ii) Why is the power supplied to domestic customers at lower voltages?

(iii) Name two renewable and two non-renewable energy sources used to generate electricity.

(iv) The national grid uses alternating current (a.c.) rather than direct current (d.c.). What is the difference between them?

(v) Name the device used to convert high voltages to lower voltages.

(vi) Give the principle of operation of the device named in part (vi).

(vii) Name the unit of electrical energy that is used in the delivery of electricity to homes and businesses.

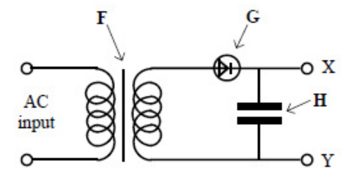
2013 Question 8 (a) [Higher Level]

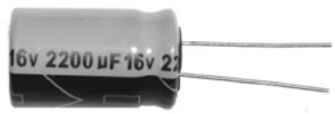
(i) The diagram shows a circuit used in a charger for a mobile phone. Name the parts labelled F, G and H.

(ii) Describe the function of G in this circuit.

(iii) Sketch graphs to show how voltage varies with time for the input voltage and the output voltage, V_{XY}.

(iv) The photograph shows the device H used in the circuit. Use the data printed on the device to calculate the maximum energy that it can store.

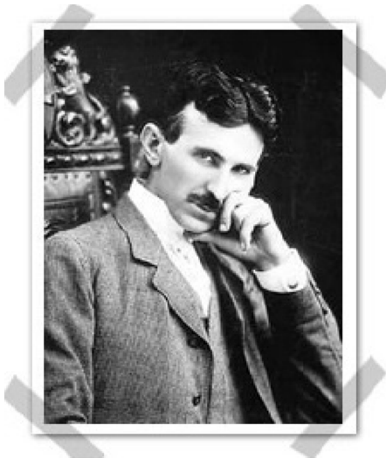




2015 Question 11 [Higher Level]

Read the following passage and answer the accompanying questions.

In the years since his death, Nikola Tesla (1856–1943) has enjoyed a curious legacy. On the one hand he is acknowledged for his contributions to alternating current and in 1960 “tesla” was adopted as the name of the unit of measure for magnetic flux density. On the other hand, thanks to the many colourful predictions he made about his inventions, Tesla has become a figure in popular culture.



Tesla was the champion of distributing electric power using alternating current rather than direct current. The problem with using direct current for electric lighting is that there is no easy way to transfer power from one d.c. circuit to another. Because the generator and the light bulbs must then be part of the same circuit, safety requires that the entire circuit uses low voltage and large current. Alternating current makes it easy to transfer power from one circuit to another, by electromagnetic induction in a device called a transformer.

The wires that carry the current a long distance are part of a high voltage, low current circuit and therefore waste little power.

As well as his work with alternating current, Tesla did pioneering work on the transmission of radio-waves and X-rays. In 1898 he demonstrated a radio-controlled boat.

The car manufacturing company, Tesla Motors, is also named in honour of Tesla. The Tesla Roadster uses an a.c. motor descended directly from Tesla’s original 1882 design.

It is the first production car to use lithium-ion cells and has a range of greater than 300 km.

(Adapted from Tesla: Inventor of the Electrical Age, W Bernard Carlson, Princeton University Press, 2013)

(a) Define the tesla.

(b) Sketch voltage-time graphs for (i) an a.c. supply and (ii) a d.c. supply.

(c) Explain the term electromagnetic induction.
(d) Why does a transformer not work with direct current?
(e) Why is it inefficient to use low voltage when transmitting electricity?
(f) The peak voltage of an a.c. supply is 321 V. Calculate the rms voltage.
(g Explain why it is necessary to use rms values when comparing a.c. and d.c. electricity.
(h) Give one advantage and one disadvantage of electric cars.

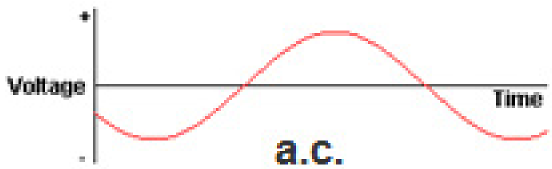
Solutions (For Higher Level Questions Only)

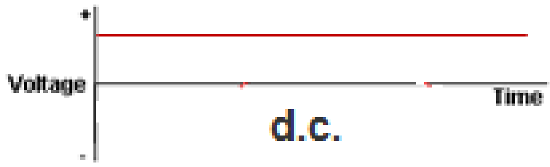
2015 Question 11

(i) Define the tesla.

A magnetic flux density of one Tesla corresponds to a current of 1 A flowing through a wire of length 1 m causing a force of 1 N.

(ii) Sketch voltage-time graphs for (i) an a.c. supply and (ii) a d.c. supply.





(iii) Explain the term electromagnetic induction.

Electromagnetic Induction occurs when an emf is induced in a coil due to a changing magnetic flux.

(iv) Why does a transformer not work with direct current?

Current not changing Magnetic flux / magnetic field not changing.

(v) Why is it inefficient to use low voltage when transmitting electricity?

Large current. More heat lost.

(vi) The peak voltage of an a.c. supply is 321 V. Calculate the rms voltage.

$V_{rms} = \frac{V_{max}}{\sqrt{2}}$ 2 = 227 V

(vii) Explain why it is necessary to use rms values when comparing a.c. and d.c. electricity.

So as to make the power output / Mean/average Equivalent between a.c. and d.c.

(viii) Give one advantage and one disadvantage of electric cars.

Advantage: e.g. fewer carbon emissions. Disadvantage: e.g. short range / expensive batteries

2014 Question 12 (d)

(i) State Faraday's law of electromagnetic induction.

(size of an) induced emf is proportional to the rate of change of flux (through a circuit)

(ii) Describe an experiment to demonstrate Faraday's law.

coil, meter, magnet reading on meter when coil is moved relative to magnet faster movement gives larger reading

(iii) Explain why.

(falling) magnet creates changing magnetic flux/field emf induced current flows in copper (only) generating magnetic fields which oppose the motion (of the falling magnet)

2013 Question 8 (a)

(i) Name the parts labelled F, G and H.

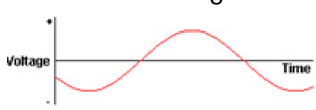
F: transformer / iron core G: diode H: capacitor

(ii) Describe the function of G in this circuit.

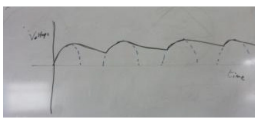
It acts as a rectifier: it converts a.c. to d.c.

(iii) Sketch graphs to show how voltage varies with time for the input voltage and the output voltage

Input voltage: As shown



Output voltage:



(iv) Use the data printed on the device to calculate the maximum energy that it can store.

$E = ½CV^2$

$E = ½ \times (2200 \times 10^{-6}) \times (16)^2$

$E = 0.2816\ J$

2008 Question 8

(i) What is electromagnetic induction?

Electromagnetic Induction occurs when an emf is induced in a coil due to a changing magnetic flux.

(ii) State the laws of electromagnetic induction.

Faraday's Law states that the size of the induced emf is proportional to the rate of change of flux.

Lenz's Law states that the direction of the induced emf is always such as to oppose the change producing it.

(iii) Explain why the amplitude of the swings decreases rapidly.

An emf is induced in the copper because is its experiencing a changing magnetic field.

This produces a current.

This current has a magnetic field associated with it which opposes the motion of the magnet.

(iv) What is the main energy conversion that takes place as the magnet slows down?

Kinetic (or potential) to electrical (or heat).

(v) time = dist/velocity = 5 cm / 500 cm s^{-1} = 0.01s

(vi) What is the magnetic flux cutting the loop when it is completely in the magnetic field?

$\Phi = BA = (8)(.05 \times .05) = 0.02$ webers.

(vii) What is the average emf induced in the loop as it enters the magnetic field?

Induced emf = (Final Flux –Initial Flux) / Time Taken

= (0 - 0.02)/0.01

= 2 Volts

2007 Question 12 (c)

(i) State Faraday's law of electromagnetic induction.

Faraday's Law states that the size of the induced emf is proportional to the rate of change of flux.

(ii) Describe an experiment to demonstrate Faraday's law.

Move the magnet in and out of the coil slowly and note a slight deflection.

Move the magnet quickly and note a greater deflection.

(iii) What is the effect on the current flowing in the circuit?

Current is reduced.

(iv) Justify your answer

An emf induced in coil which induces a current which opposes the initial current.

2006 Question 11

(i) How does resonance occur in an acoustic guitar?

Energy is transferred from the strings to the hollow body and both vibrate at the same frequency.

(j) What is the relationship between frequency and tension for a stretched string?

Frequency is proportional to the square root of tension.

(k) A stretched string of length 80 cm has a fundamental frequency of vibration of 400 Hz.

What is the speed of the sound wave in the stretched string?

$v = f\lambda$ $v = 400(1.6) = 640\ m\ s^{-1}$

(l) Why must the strings in the electric guitar be made of steel?

Because only metal strings can be magnitised.

(m) Define magnetic flux.

Magnetic flux is the product of magnetic flux density multiplied by area.

(n) Why does the current produced in a coil of the electric guitar vary?
Because the induced emf varies due to the amplitude of the vibrating string.

(o) What is the effect on the sound produced when the number of turns in a coil is increased?
A louder sound is produced.

(p) A coil has 5000 turns. What is the emf induced in the coil when the magnetic flux cutting the coil changes by 8 × 10–4 Wb in 0.1 s?
$E = -N(d\phi / dt)$
$E = 5000(8 \times 10^{-4} / 0.1) = 40\ V$

2005 Question 12 (b)

(i) Define magnetic flux.
Magnetic flux is defined as the product of magnetic flux density multiplied by area.

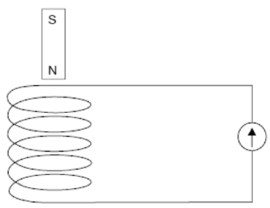
(ii) State Faraday's law of electromagnetic induction.
The size of the induced emf is proportional to the rate of change of flux.

(iii) What is the magnetic flux cutting the coil?
$A = (0.05)^2 = 0.0025$
ϕ (= BA) = (4)(0.0025)
ϕ = 0.01 Wb

(iv) Calculate the magnitude of the average emf induced in the coil while it is being rotated.
$E = N(\Delta\phi/\Delta t)$
$\Delta\phi / \Delta t = (0.01 - 0)/0.2 = 0.05$
E= 200(0.05) E = 10 V

2004 Question 12 (c)

(i) What is electromagnetic induction?
Electromagnetic Induction occurs when an emf is induced in a coil due to a changing magnetic flux.



(ii) Describe an experiment to demonstrate electromagnetic induction.
Set up as shown.
Move the magnet in and out of the coil and note the deflection in the galvanometer.

(iii) Explain why.
Current flows in the ring in such a direction as to oppose the change which caused it. Therefore the ring follows the magnet.

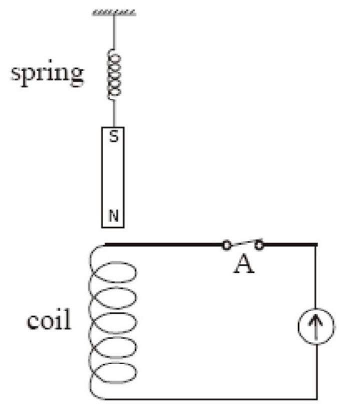
(iv) What would happen if the magnet were moved towards the ring?
The ring would be repelled.

2003 Question 12 (d)

(i) State the laws of electromagnetic induction.

Faraday's Law states that the size of the induced emf is proportional to the rate of change of flux.

Lenz's Law states that the direction of the induced emf is always such as to oppose the change producing it.



(ii) Describe the current flowing in the circuit.

Alternating current.

(iii) If the switch at A is open, the magnet will take longer to come to rest. Explain why.

There is no longer a full circuit, so even though there is an induced potential difference there is no (induced) current, therefore no induced magnetic field in the coil therefore no opposing force.

2002 Question 12 (c)

(i) What is meant by electromagnetic induction?

Electromagnetic Induction occurs when an emf is induced in a coil due to a changing magnetic flux.

(ii) State Lenz's law of electromagnetic induction.

Lenz's Law states that the direction of the induced emf is always such as to oppose the change producing it.

(iii) Explain why the current was reduced when an iron core was inserted in the coil.

There would normally be a back emf in the coil due to the alternating current being supplied.

When the core was inserted it increased the magnetic flux which in turn increased the self-induction (back emf) and this reduced the overall voltage and therefore the overall current.

(iv) Give an application of the principle shown by this experiment.

Dimmer switch, smooth d.c., tuning radios, braking trains, damping in balances, induction coil