



DEPARTMENT OF EDUCATION

GRADE 12

PHYSICS

MODULE 4



ELECTROMAGNETISM



PUBLISHED BY FLEXIBLE OPEN AND DISTANCE EDUCATION
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FOR DEPARTMENT OF EDUCATION
PAPUA NEW GUINEA
2017

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GRADE 12

PHYSICS

MODULE 4

ELECTROMAGNETISM

IN THIS MODULE, YOU WILL LEARN ABOUT:

12.4.1: MAGNETIC FIELD AND FORCE DUE TO CURRENT

12.4.2: ELECTROMAGNETIC INDUCTION

**12.4.3: TRANSFORMERS AND POWER LOSSES IN
TRANSMISSION LINES**



Acknowledgement

We acknowledge the contribution of all Lower and Upper Secondary teachers who in one way or another helped to develop this Course.

Our profound gratitude goes to the former Principal of FODE, Mr. Demas Tongogo for leading FODE towards this great achievement.

Special thanks are given to the staff of the Science Department of FODE who played active roles in coordinating writing workshops, outsourcing of module writing and editing processes involving selected teachers of Central Province and NCD.

We also acknowledge the professional guidance and services provided through-out the processes of writing by the members of:

Science Subject Review Committee-FODE
Academic Advisory Committee-FODE
Science Department- CDAD

This book was developed with the invaluable support and co-funding of the GO-PNG and World Bank.

DIANA TEIT AKIS
Principal-FODE



Flexible Open and Distance Education
Papua New Guinea

Published in 2017

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Printed by the Flexible, Open and Distance Education
ISBN 978-9980-89-565-3
National Library Services of Papua New Guinea



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SECRETARY'S MESSAGE

Achieving a better future by individual students, their families, communities or the nation as a whole, depends on the kind of curriculum and the way it is delivered.

This course is part of the new Flexible, Open and Distance Education curriculum. The learning outcomes are student-centred and allows for them to be demonstrated and assessed.

It maintains the rationale, goals, aims and principles of the National Curriculum and identifies the knowledge, skills, attitudes and values that students should achieve.

This is a provision by Flexible, Open and Distance Education as an alternative pathway of formal education.

The Course promotes Papua New Guinea values and beliefs which are found in our constitution, Government policies and reports. It is developed in line with the National Education Plan (2005 – 2014) and addresses an increase in the number of school leavers affected by lack of access into secondary and higher educational institutions.

Flexible, Open and Distance Education is guided by the Department of Education's Mission which is fivefold;

- To develop and encourage an education system which satisfies the requirements of Papua New Guinea and its people
- To establish, preserve, and improve standards of education throughout Papua New Guinea
- To make the benefits of such education available as widely as possible to all of the people
- To make education accessible to the physically, mentally and socially handicapped as well as to those who are educationally disadvantaged

The College is enhanced to provide alternative and comparable path ways for students and adults to complete their education, through one system, two path ways and same learning outcomes.

It is our vision that Papua New Guineans harness all appropriate and affordable technologies to pursue this program.

I commend all those teachers, curriculum writers, university lecturers and many others who have contributed so much in developing this course.

UKE KOMBRA, PhD
Secretary for Education

**MODULE 12. 4****ELECTROMAGNETISM****Introduction**

Electromagnetism is a branch in physics which deals with electricity and magnetism and the interaction between them. It was discovered in the 19th century and has extensive application in today's world.

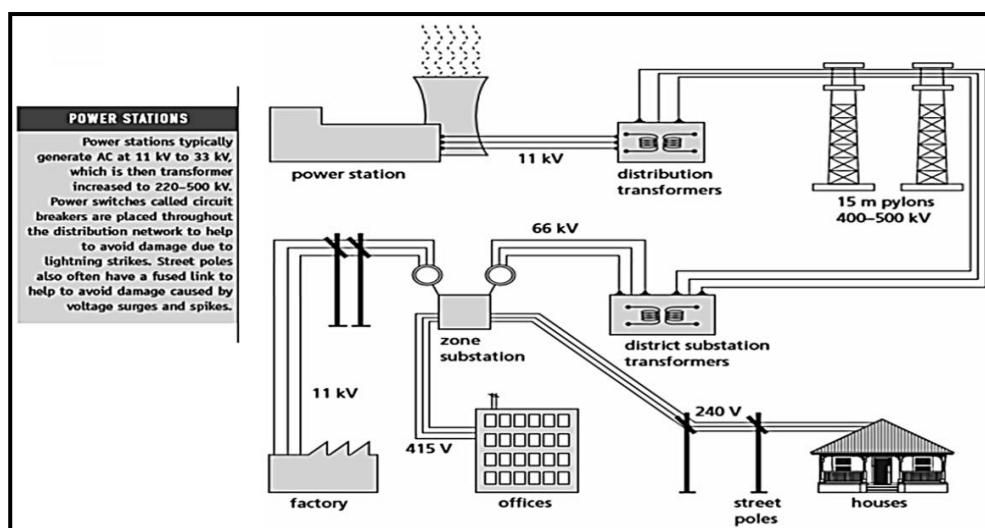
Electromagnetism is basically the science of electromagnetic fields. An electromagnetic field is produced by objects, which are charged electrically. Radio waves, infrared waves, ultraviolet waves and x-rays are all electromagnetic fields in a certain range of frequencies.

Electricity is produced by changing magnetic fields. This phenomenon is also called **electromagnetic induction**. Electromagnetism is basically the work of an underlying force known as the electromagnetic force. This force can be seen when an electric charge is moving. This movement of electric charges produces magnetism. It has been proved that electricity can give rise to electromagnetism and vice versa. A very clear example is that of a transformer which we will look at later.

Electromagnetism has numerous applications in today's world of science and physics. The very basic application of electromagnetism is in the use of motors. The motor has a switch that continuously switches the polarity of the outside of the motor.

An electromagnet does the same thing. We can change the direction by simply reversing the direction of the current. The inside of a motor has an electromagnet, but the current is controlled in such a way that the outside magnet repels it.

Transformers are extremely useful engineering devices as they allow for the changing or transforming of AC voltages, not only in small construction circuits but also on an electrical energy production and distribution level. Mains distribution high voltage transformers are a common sight on the poles of our electricity networks.



A typical power supply grid system



Learning Outcomes

After going through this module, you are expected to:

- define and explain a magnetic field.
- describe the shape of magnetic fields around a magnet and between two magnets.
- discuss the magnetic effect of an electric current.
- describe the shape of magnetic fields around current-carrying wires in different situations.
- explain why a current-carrying wire experiences a force in a magnetic field.
- calculate the size of this force.
- calculate the force between parallel wires carrying a current.
- draw a diagram of a simple DC motor and explain how it works.
- calculate the size of the force on a current carrying conductor passing through the magnetic field using the formula $F = BIL$ and $F = BIL \sin \theta$.
- demonstrate experimentally that current is induced in a straight wire when moved through a magnetic field.
- show experimentally that size of the induced current in a straight carrying conductor depends on the length of the wire, the strength of the field, and speed of the wire in the magnetic field.
- apply Lenz' Law and Fleming's Left and Right-hand Rules to explain the operation of the AC and DC generators.
- define a transformer and explain its main principles of operation.
- do calculations of step-up and step-down ideal transformers.
- give advantages of AC generators over DC generators in power transmission.
- solve problems involving power losses and voltage drop across the transmission lines.



Time Frame

Suggested allotment time: **10 weeks**

This module should be completed within 10 weeks.

If you set an average of 3 hours per day, you should be able to complete the module comfortably by the end of the assigned week.

Try to do all the learning activities and compare your answers with the ones provided at the end of the module. If you do not get a particular question right in the first attempt, you should not get discouraged but instead, go back and attempt it again. If you still do not get it right after several attempts then you should seek help from your friend or even your tutor.

DO NOT LEAVE ANY QUESTION UNANSWERED.



12.4.1 Magnetic Field and Force Due To Current

Whenever a current passes through a conductor a magnetic field is produced. This can be shown by placing a directional compass near a straight current-carrying wire or conductor. A compass placed near a current carrying conductor will always point in the direction of the magnetic field lines produced. However, a magnetic material like iron, cobalt or nickel when placed in the presence of the magnetic field will always experience a force acting on it.

Magnets and Magnetic Field

The idea of magnetism was first discovered by the Chinese as early as 2500 BC. They found that certain minerals can attract pieces of iron. When these minerals were allowed to be suspended (hung) freely they will always point in the north to south direction. Nowadays, we call these objects magnets. A bar magnet has two poles: the South Pole and North Pole.

There are many examples of the uses of magnets in today's world. Magnets are used in dynamos, motors, radios, TV, refrigerator, door locks and tape recorders among others.

A magnetic field is a region where a magnet exerts a force. This region is made up of lines of forces. This means that, if a magnetic material like iron, cobalt or nickel is placed in the magnetic field, it will experience a force acting on it.

The pattern a magnet makes can be shown using iron filings or a directional compass.

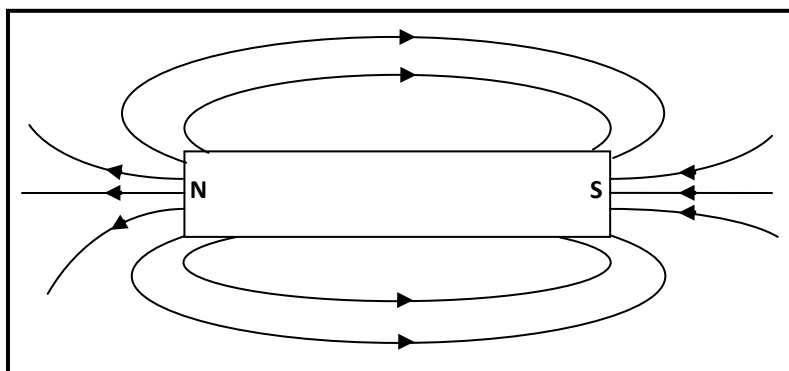


Figure 1 The magnetic field lines around a bar magnet.

You will note from the diagram that, the magnetic field starts from the North Pole and enter into the South Pole. The magnetic field is the strongest at the poles where the field lines are closer together.

When magnets are placed closer to each other, their magnetic fields interact with each other. Very simple experiments can show us that, when like poles (N-N or S-S) are held closer to each other, they tend to repel. However, unlike poles (N-S or S-N) attract each other. This brings us to the law of magnetism which states:

Like poles repel and unlike poles attract.

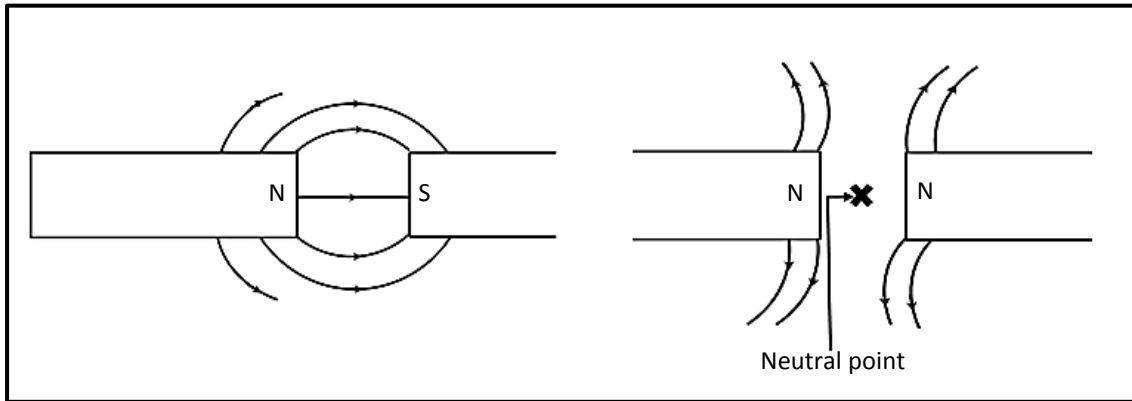


Figure 2 The magnetic fields around unlike poles facing each other are almost uniform in strength. However, between like poles, there is a neutral point where the combined field strength is zero.

You will have learnt in electricity that when a current passes through a conductor, it produces heat and light energies. We will now learn how electricity produces some magnetic effects. The connection between electricity and magnetism has many important applications in today's world.

In electromagnetism (this unit) the current we are referring to is the conventional current which flows from the positive terminal of the power supply.

Consider a directional compass is allowed to settle in its normal north-south direction. When a wire is placed over the compass and a current is allowed to flow, the compass needle deflects. It is noticed that the compass needle is deflected at 90° to the wire (i.e. east-west direction). When the current is switched off, the compass needle returns to its original north-south direction. This shows us that a wire carrying a current has a magnetic effect.

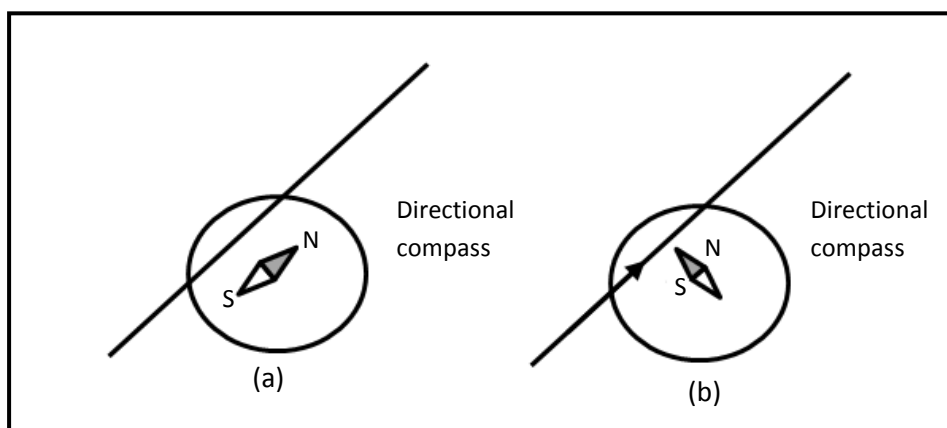


Figure 3 (a) No current in the wire (b) Current passing through the wire.

The magnetic effect can further be investigated using a vertical current – carrying wire. The wire passes through a hole in a piece of cardboard (which is placed horizontally). When iron filings are sprinkled on the cardboard and tapped gently, they arrange themselves in a circular pattern.

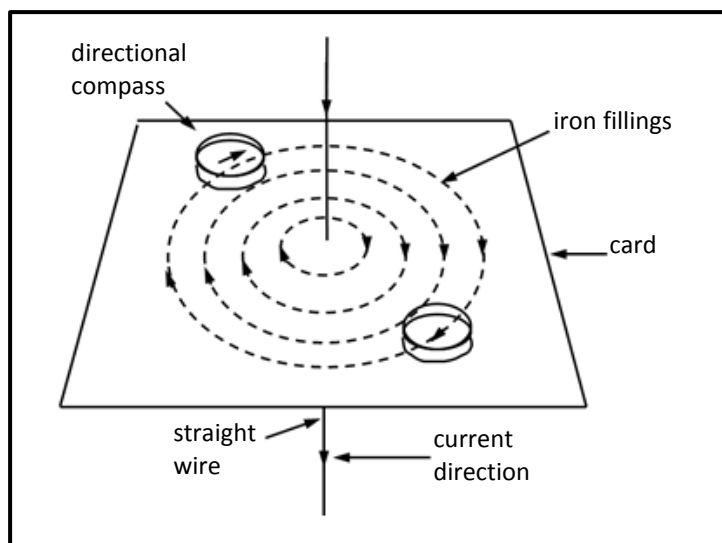


Figure 4 The magnetic field around a straight wire.

This circular pattern represents the magnetic field around the wire. A compass needle can also be used to find the direction of the magnetic field. It is found that if the direction of the current is reversed, the direction of the magnetic field is also reversed.

The direction of a magnetic field around a wire carrying a current is given by **Fleming's Right Hand Grip Rule**. This rule states that, if you grip a straight wire with your right hand, then your extended thumb points in the direction of the current. Your fingers wrapped around the wire will point in the direction of the magnetic field lines.

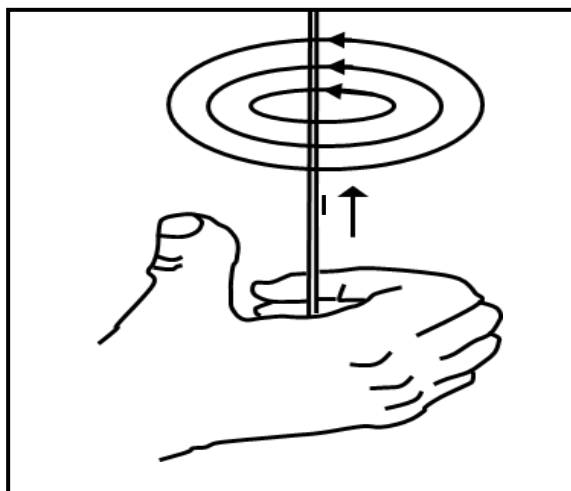


Figure 5 Applying the right hand grip rule to find the direction of the magnetic field around a wire.

The characteristics of the magnetic field produced by a current flowing in a straight wire.

- The magnetic field lines form a circular pattern.
- The magnetic field strength increases when current increases.
- The magnetic field strength is stronger near the wire and weaker further away.
- When the direction of the current is reversed, the direction of the magnetic field is reversed too.



We can view the direction of the current as represented by a point \odot or as a cross \otimes :

- A point \odot represents the current flow in an upward direction out of the paper. It can be seen as looking at a sharp point (or tip) of an arrow coming towards you.
- A cross \otimes represents the current flow in a downward direction into the paper, like looking at the tail end of an arrow away from you.

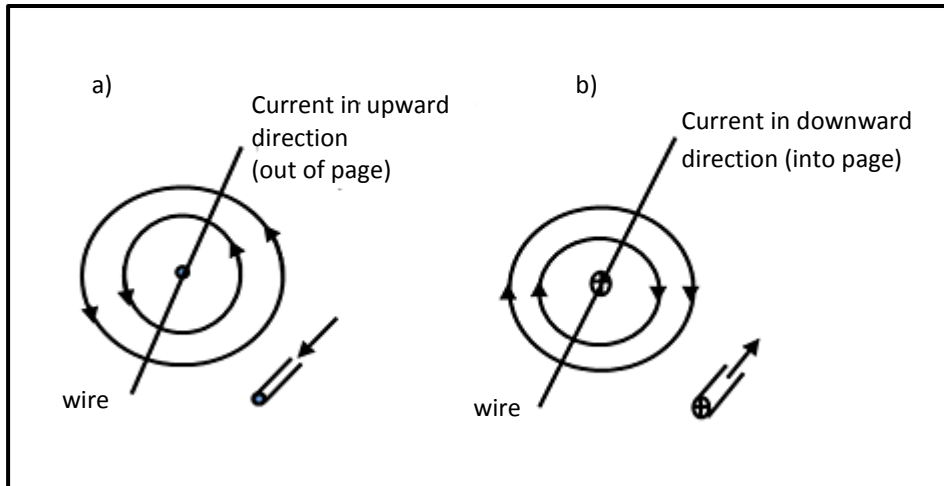
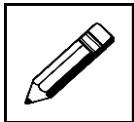


Figure 6 (a) Current in upward direction. (b) Current in downward direction.

Now check what you have just learnt by trying out the learning activity below.



Learning Activity 1



10 minutes

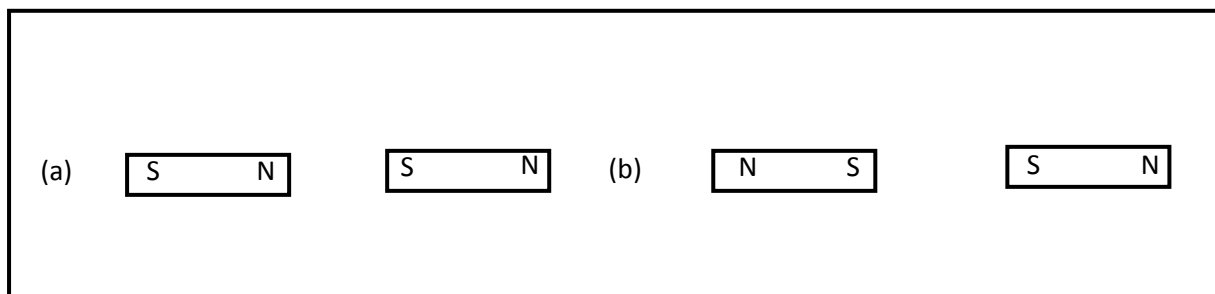
Answer the following questions on the spaces provided.

1. What is meant by the term magnetic field?

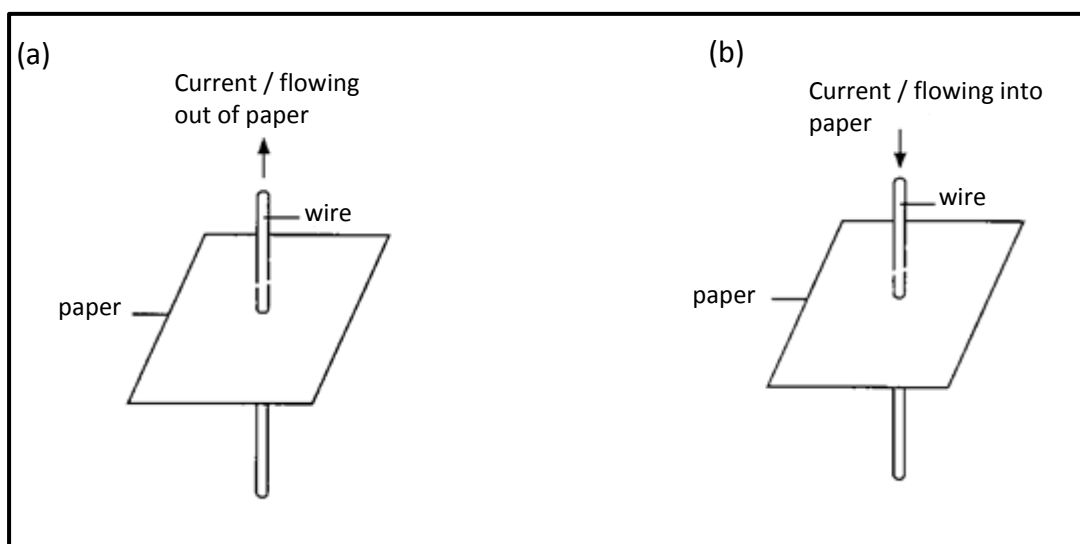
2. What sort of materials when placed in a magnetic field will experience a force?



3. Draw the magnetic field patterns of the magnets shown below.



4. Sketch the magnetic field pattern of a steady electric current flowing in a long straight wire in the directions shown:



Thank you for completing learning activity 1. Now check your work. Answers are at the end of the module.

Force Due To Current in a Magnetic Field

We have learnt earlier that, when a current passes through a conductor, a magnetic field is produced. However, if the current carrying conductor is placed inside a magnetic field a force is produced that will act on the conductor.

The conductor experiences a force because the magnetic field around the conductor interacts with the magnetic field of the magnet. This causes weaker and stronger effects on two sides of the conductor. Thus, the conductor will move in the direction of the weaker field.

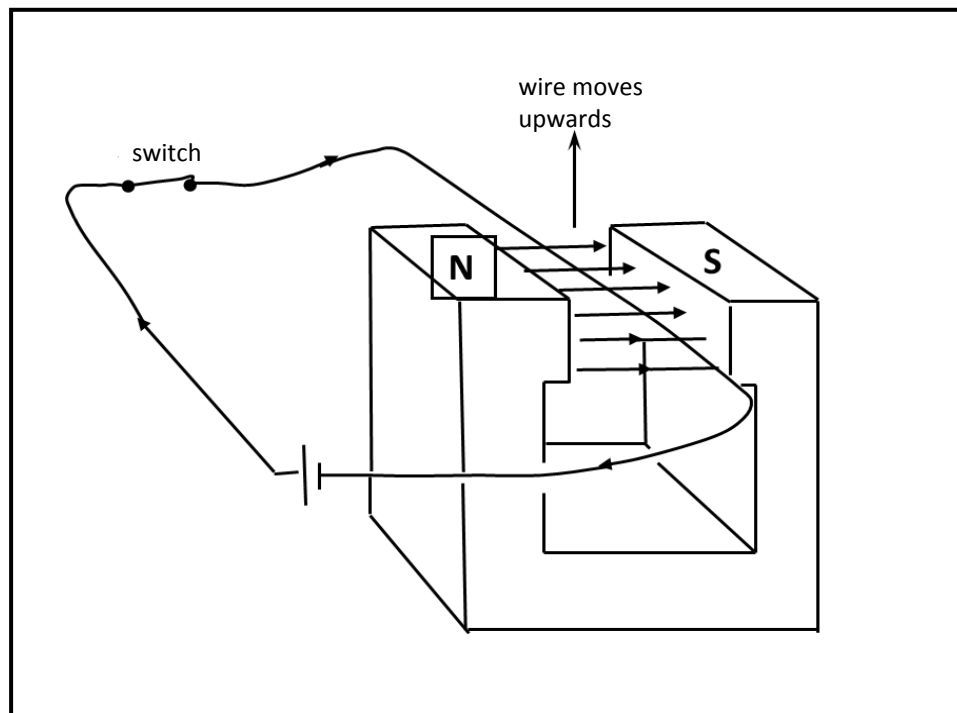


Figure 7 A force acts on a current carrying conductor in a magnetic field.

The force causes the wire to move at right-angles (90°) to the magnetic field. If you reverse the direction of the current in the wire, the direction of the force reverses. This means that the wire will move in the opposite direction.

You must note that, the direction of the current, the magnetic field and the force must always be at right – angles to each other. What we are trying to talk about here are three physical quantities: **current**, **magnetic field** and the **force**. We will try to see how these quantities relate to each other in terms of their directions.

From figure 7 above, at least the direction of two quantities (current and magnetic field, current and force or force and magnetic field) must be known to predict the direction of the third quantity. The third quantity can be predicted using the Fleming's Left Hand Rule as illustrated on the next page.

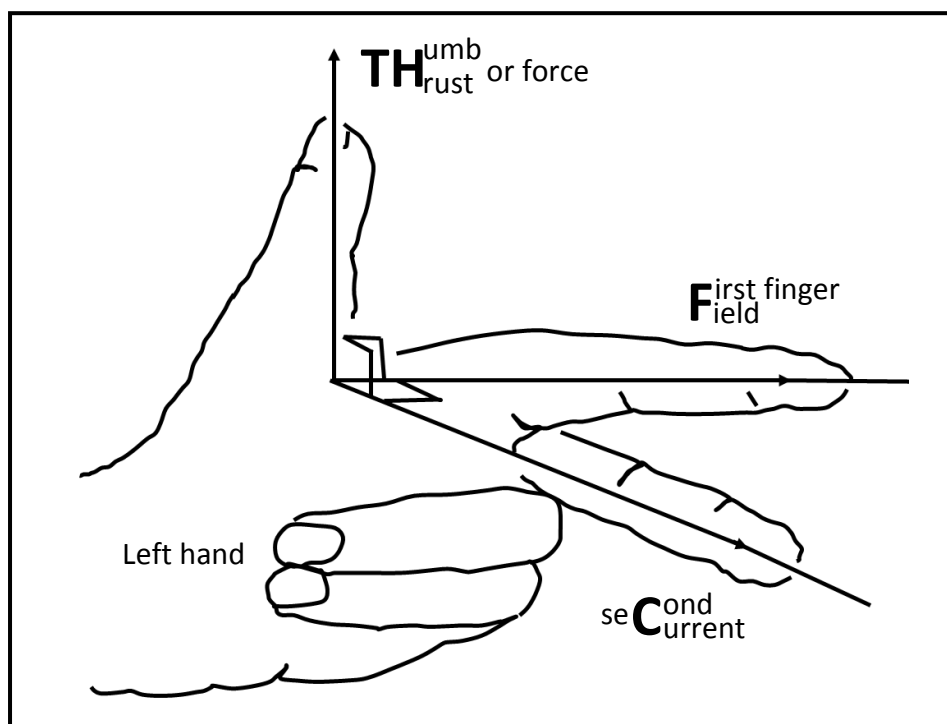


Figure 8 Fleming's Left Hand Rule indicates the link between force, field and current directions.

The rule can be used as follows:

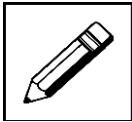
- The thumb and the first two fingers must be held at right angles (90°) to each other
- The thumb gives the direction of the force
- The first finger gives the direction of the magnetic field and
- The second finger gives the direction of the current.

For example, in figure 7, if the directions of the current and the magnetic field are known, then using the Fleming's Left Hand Rule, we can very easily predict or identify the direction of the force. In this case, the direction of the force is out of the page or moving upwards.

When you apply the rule, you must always remember:

- The magnetic field direction is always from the North Pole to the South Pole.
- The current direction is always from the positive terminal of the battery.
- The rule applies when the current, magnetic field and force are at right angle to each other.

Now check what you have just learnt by trying out the learning activity on the next page!

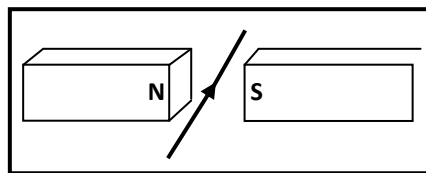
**Learning Activity 2**

10 minutes

Answer the following questions on the spaces provided.

1. Why does a current carrying conductor experience a force when placed in an external magnetic field?

2. Use Fleming's LHR to show direction of force in the diagram below. Use either a dot (towards you) or a cross (away from you) to indicate the direction of the force on the conductor.



Thank you for completing learning activity 2. Now check your work. Answers are at the end of the module.

In our previous discussions, we have seen that when a current carrying conductor is placed in an external magnetic field, it will experience a force. We will now learn some factors that affect this force.

One of the factors that affect the size of the force is the length of the conducting wire in the magnetic field.

The second factor is the size or the magnitude of the current. The greater the current, the greater is the force.

The third factor is the strength of the magnetic field. This means that, if the magnetic field strength increases, the size of the force also increases. This can be achieved by using a bigger or stronger magnet with a stronger magnetic field.

The fourth factor is the angle (θ) to which the wire or the conductor is allowed to cut the magnetic field lines. If the wire cuts the magnetic field lines at right angles, it will produce



maximum force. However, if the wire passes through the magnetic field lines at some other angle other than right angle, it will produce minimum force. Also, note that if the wire moves parallel (180°) to the direction of the field lines, the force produced will be zero.

All the four factors that affect the size of the force are linked by the equation:

$$F = BIL\sin\theta$$

Here, the magnetic force F (in Newton) acting on a wire of length L (in metre) carrying a current I (in Ampere) in a magnetic field of strength B (in tesla) and θ is the angle between the wire and the direction of the magnetic field. Note: The magnetic field strength B is also called the magnetic flux density.

Examples

1. A 20cm length of a wire carries a current of 4A in a magnetic field strength of 3T.

Calculate the force at

- a) right angles and
- b) at 30° to the field.

Solution

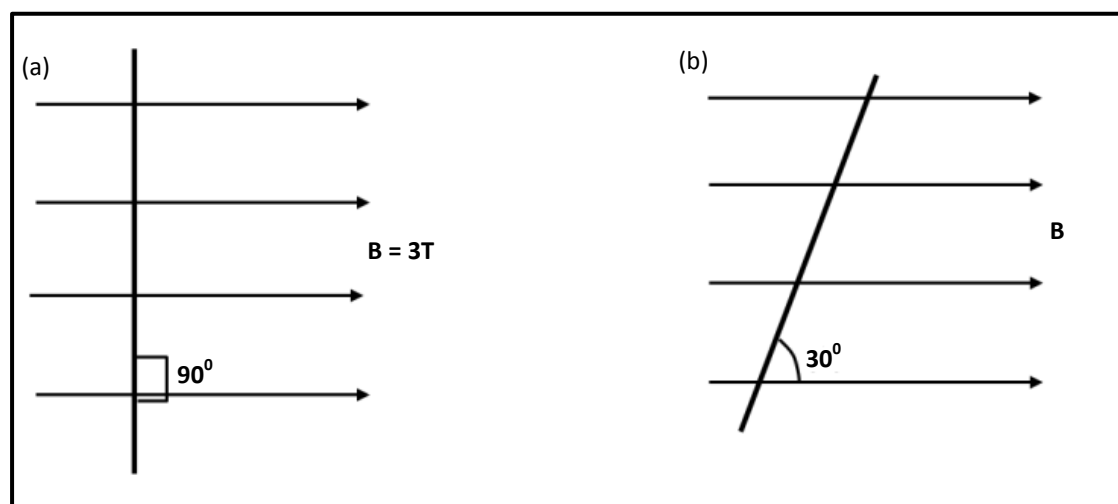


Figure 9 Wire cutting the magnetic fields at 90° and 30° respectively.

- a) $F = BIL \sin \theta = 3 \times 4 \times 0.2 \times \sin 90^\circ = 2.4\text{N}$
- b) $F = BIL \sin \theta = 3 \times 4 \times 0.2 \times \sin 30^\circ = 1.2\text{N}$



2. A 25cm wire, placed at 60° to a magnetic field, experiences a 3N force when a current of 1.5A flows. Calculate the magnetic field intensity.

Solution

$$F = BIL \sin \theta, \text{ so } B = \frac{F}{IL \sin \theta} = \frac{3}{1.5 \times 0.25 \times \sin 60^\circ} = 9.24 \text{ T}$$

You can now see from our examples that, if we increase our angles from 0° to 90° , the force F increases. The force also increases if we increase the size of either the magnetic field (B), the current (I) or the length (L) accordingly. Note carefully here that the equation: $F = BIL \sin \theta$ relates the size of the force with respect to the magnetic field, the length of the conductor and the angle of the conductor through the magnetic field for a single and straight current carrying-wire or conductor.

If we now increase the length of the wire by having more turns or coils instead of a single straight wire, then the equation becomes: $F = nBIL \sin \theta$

Where n represents the number of turns in a coil in the magnetic field and L is the length which is the circumference of a single turn of a coil of wire.

Example

Figure 10 shows a rectangular coil of wire carrying a current of 0.26A that has 150 turns. The coil is parallel to a magnetic field of flux density 0.36T.

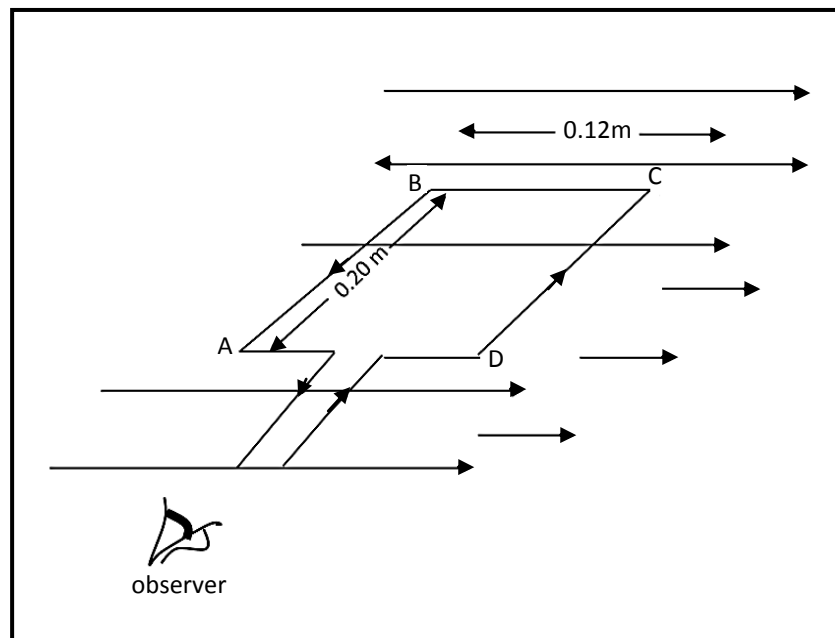


Figure 10 A rectangular coil of wire in the magnetic field.

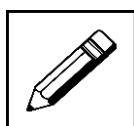
- a) Will the coil rotate clockwise or anticlockwise to the observer?
- b) What is the size of the force on the side AB?

**Solution**

- a) Using the Fleming's left hand rule on the side AB shows that it moves upwards. Side CD moves downwards. So the coil rotates clockwise to the observer.
- b) Force on the single coil $F = BIL = 0.36 \times 0.26 \times 0.20 = 0.0187\text{N}$.

Note, here the coil cuts the field at an angle of 90° (Since $\sin 90^\circ = 1$), so $F = BIL \sin \theta$ reduces to $F = BIL$.

Now check what you have just learnt by trying out the learning activity below!

**Learning Activity 3****10 minutes**

Answer the following questions on the spaces provided.

1. List the factors that affect the size of the force experienced by a current-carrying wire.

2. What happens to the size of the force when the:

- a) current through the wire increases?

- b) magnetic field cutting across the wire increases?

Thank you for completing learning activity 3. Now check your work. Answers are at the end of the module.



AC and DC Electric Motors

We have learnt earlier that when a current passes through a conducting wire, a magnetic field will be created around the wire. To determine the direction of the magnetic field, the Right-Hand Grip Rule can be used.

Let us once again consider a single straight current carrying wire as shown below with the current direction as indicated.

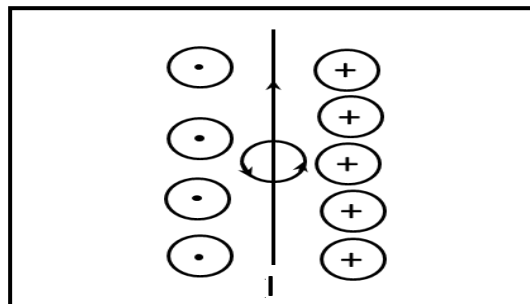


Figure 11 Direction of magnetic field around a conductor.

Imagine gripping the wire with your right hand so that your thumb points in the direction of the current. Your curled fingers then point in the direction of the field lines. Let us apply the same idea of a dot \odot and a cross \otimes to indicate the direction of the field lines on both sides of a current-carrying wire.

Note that on the right hand side of the wire, your curled fingers will be going away from you. This can be represented with a cross \otimes . While on the left hand side of the wire, your curled fingers will be coming out and towards you. This can be indicated with a dot \odot .

Figure 12 shows two parallel wires (P and Q) each carrying a current in the same direction. The wires are free to move. Each wire produces its own magnetic field.

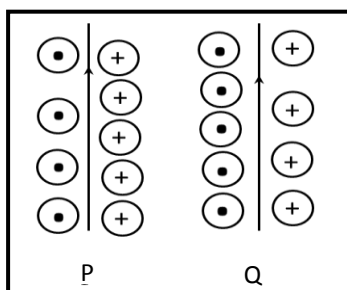


Figure 12 Currents in the same direction.

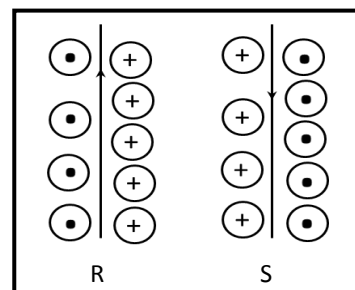


Figure 13 Currents in the opposite direction.

Applying the Right Hand Grip Rule together with the signs of the dot \odot and the cross \otimes you will easily see that, the magnetic fields in between the two wires will cancel out. This is because the magnetic field is a vector quantity. Thus, the region between the two wires (P and Q) has magnetic fields travelling in the opposite directions and cancelling each other



out. The field now between the wires become weaker. The field outside of each wire remains in their normal strength. This causes each wire to move in a direction of the weaker magnetic field. Hence, the wires are forced towards each other. That is an **attraction**.

In figure 13, we see the opposite situation. Here fields between wires travel in the same direction. Thus, fields between the wires reinforce or add on each other to give a greater size of the field. Outside the wires, the fields are at normal strength. Hence, the wires are forced apart by the stronger field between them. This gives a **repulsion**.

Experiments show that the magnetic force (F) between two current carrying wires (I_1 and I_2) is directly proportional to the product of their currents and to the length of wire common to them (L) and is inversely proportional to their distance apart (d). This is represented mathematically as:

$$F = \frac{kI_1I_2L}{d}$$

The force also depends on the material or medium between the wires. This is induced in the constant k ($k = \mu/2\pi = 2 \times 10^{-7} \text{NA}^{-2}$). It is often more useful to know the magnetic force acting per unit length, and hence the equation below is usually used.

$$\frac{F}{L} = \frac{\mu I_1 I_2}{2\pi d}$$

This formula can be used to define the ampere.

One ampere is the current which flows in two infinitely long parallel wires separated by one metre in a vacuum, causes a magnetic force per unit length of $2 \times 10^{-7} \text{Nm}^{-1}$.

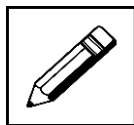
Example

Two long parallel current carrying wires are separated by 6.3cm. One wire carries a current of 3.4A up the page and the other carries a current of 2.5A down the page. Find the force acting on a 45cm length of these parallel wires.

Solution

$$F = \frac{kI_1I_2L}{d} = \frac{2.0 \times 10^{-7} \times 3.4 \times 2.5 \times 0.45}{6.3 \times 10^{-2}} = 1.2 \times 10^{-5} \text{N repulsion}$$

Now check what you have just learnt by trying out the learning activity on the next page!

**Learning Activity 4****15 minutes**

Answer the following questions on the spaces provided.

1. A compass needle is placed due west of a vertical wire. A current flows through the wire. What is direction of the current if the compass needle points:
 - a) south? _____
 - b) north? _____

2. Two long parallel wires carry equal currents in opposite directions. The magnitude of the force between the wires due to the currents is F . The separation between the wires is now doubled. The force between the wires due to the currents is now which of the following?
 - a) $\frac{F}{2}$ and attractive
 - b) $\frac{F}{2}$ and repulsive
 - c) $\frac{F}{4}$ and attractive
 - d) $\frac{F}{4}$ and repulsive

3. Two long straight wires, each carrying a current of 9A in the same direction, are placed parallel to each other.
 - a) Find the magnitude of the force on 1m of each wire when separated by 10cm.

 - b) Draw the magnetic field around each wire and show why they are attracted to each other.

Thank you for completing learning activity 4. Now check your work. Answers are found at the end of the module.



AC and DC motors

We have just discovered in our discussions that magnetic fields are produced when currents are allowed to pass through two parallel wires. The currents can either be in the same direction or in the opposite direction to each other. The interaction of these magnetic fields between the wires produces what we usually call resultant forces. These resultant forces are solely responsible for the attraction or repulsion of the two parallel wires.

A famous Englishman Michael Faraday discovered these facts. The attraction or repulsion of two parallel current carrying wires is called the **Motor Principle**, because it is the basis of operation of all electric motors and generators.

The action of the force on a conductor can be summarised in the following statement called the motor principle:

The force exerted on a current carrying conductor in the presence of an external magnetic field, is perpendicular to both the directions of the current and the direction of the magnetic field lines.

The motor principle or rule now leads us to electric motors and generators. What is an electric motor and an electric generator?

Generators and motors are identical in construction, but they have two opposite purposes. The purpose of a generator is to convert mechanical energy into electrical energy, while a motor is to convert electrical energy into mechanical energy.

When a current is allowed to flow through a coil with many turns or loops in an armature, the armature turns. This electrical device is a motor. However, when an armature is turned in the presence of an external magnetic field, an electric current is produced. This device is an electric generator.

In other words, when a current causes motion, the device is a motor. On the other hand, when a motion causes current, the device is a generator. Both of these electrical devices can only operate in the presence an external magnetic field.

A motor is connected to a power supply to produce a current and causes motion. A generator does not have a power supply. The coil is connected to a load (resistor, meter or a bulb). The coil of the generator is rotated to produce a current.

Figure 14 and figure 15 illustrate the basic structure of a DC motor and a DC generator respectively.

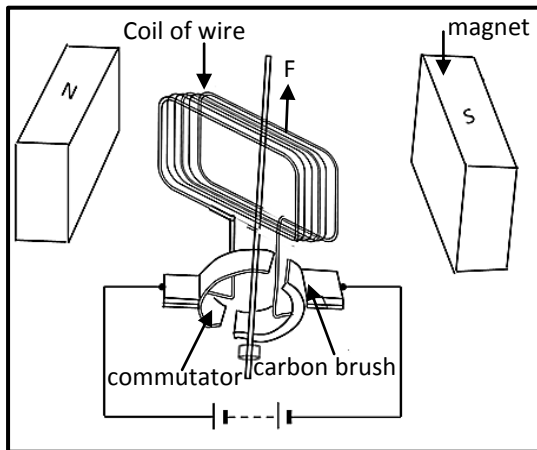


Figure 14 A simple dc motor.

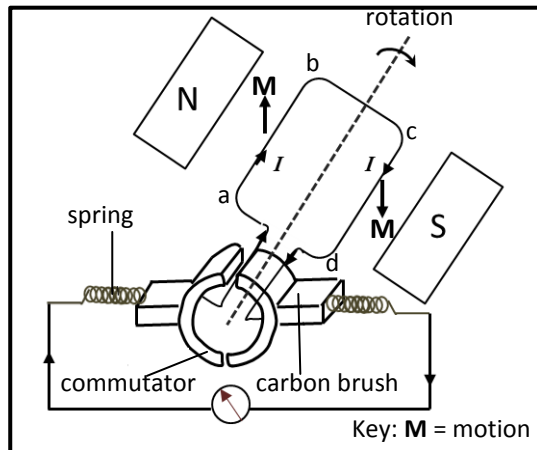


Figure 15 A simple dc generator.

The direct current (DC) motor

Electric motors in fans, refrigerators, air-conditioners and many toys make use of force acting on a current carrying conductor in a magnetic field.

A simple DC motor in figure 16 below contains a rectangular coil of wire. The coil is mounted on an axle between two poles of a permanent magnet. The current passes through the coil via two carbon brushes which are pressed against a split-ring commutator. The current enters one side of the loop and out the other side.

Applying the Fleming's Left Hand Rule (motor principle) to each side of the coil, we find that one side of the coil is forced down while the other side is forced upwards. As a result, the coil rotates. An electric DC motor operates on this principle.

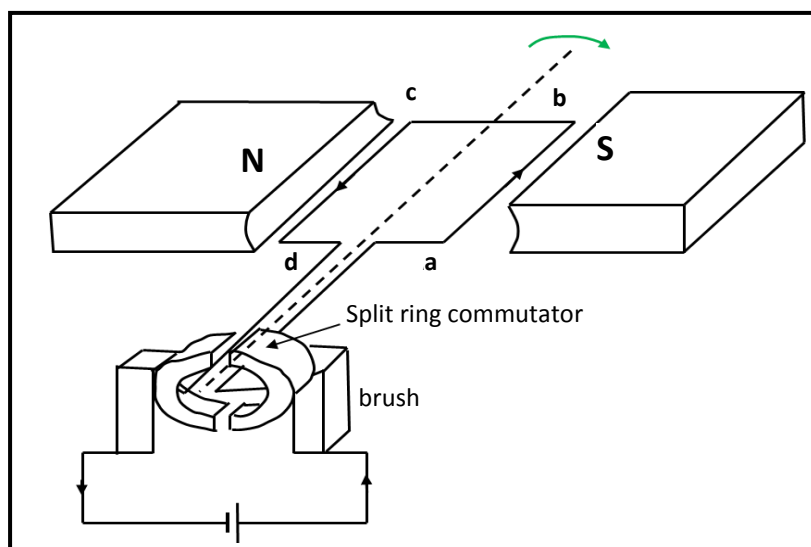


Figure 16 A simple dc motor with a rectangular coil of wire.

Principle of operation of a simple d.c motor

Stage1:

Horizontal Position

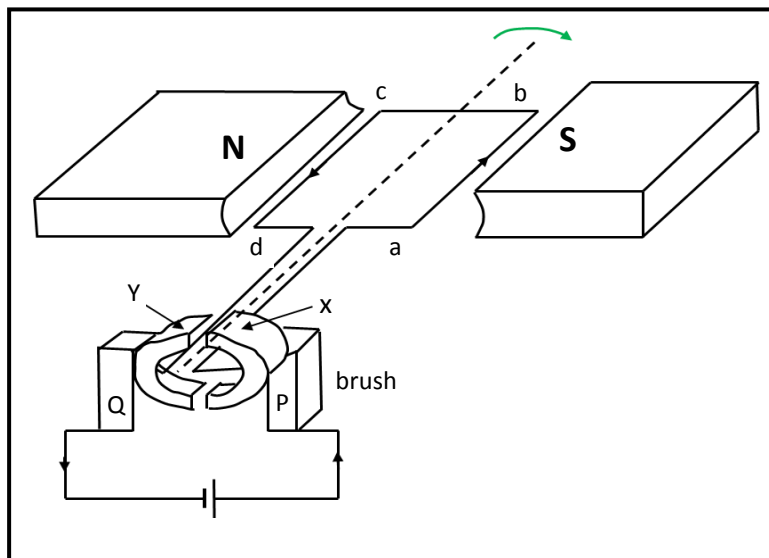


Figure 17 The current is maximum and is leaving the loop through split-ring Y and brush Q.

You will have noted from the figure that, as soon as the switch is closed the current starts to flow in the direction ABCD as indicated on the coil. This is the conventional current flow from the positive to the negative side of the power supply.

The current flows through brush P and then to one half of the split-ring commutator marked X. From the split-ring X, it passes through and out the coil via the other half of the split-ring Y and the brush Q.

As in our earlier discussions, the current flowing through the coil creates magnetic fields along the sides AB and CD of the coil respectively. These magnetic fields interact with the external magnetic field supplied by the permanent magnet to produce two forces. The two forces will be acting in the opposite directions to each other.

If we apply the Fleming's Left Hand Rule (motor principle) to both sides (AB and CD) of the coil, the force on side AB will be down wards while the force on the side CD will be upwards. Thus, the two forces will produce a turning effect called the torque. The torque then rotates the coil in the clockwise direction. The coil rotates until it reaches the vertical position as in figure 18.

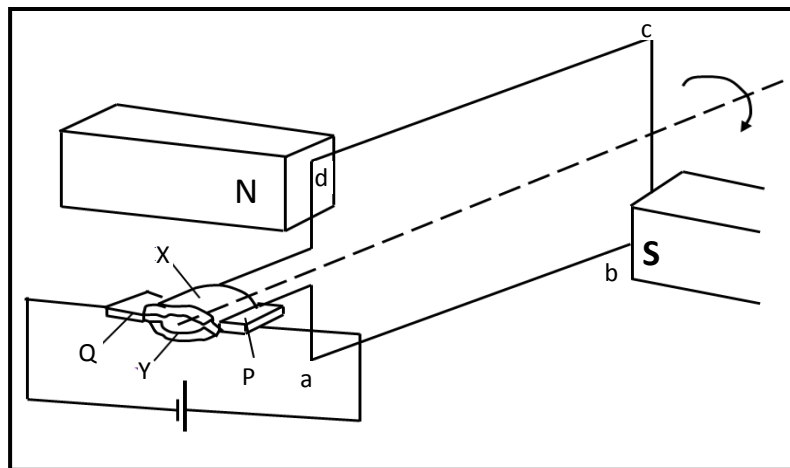
**Stage 2: Vertical Position**

Figure 18 The current is zero, split-ring Y is about to touch brush P, split-ring X is about to touch brush Q.

You will now notice that at this vertical position, the two split-rings X and Y are no longer in contact with the brushes P and Q. Hence, no current flows through the coil. But the coil continues to rotate even though there is no turning effect. This is because of its inertia.

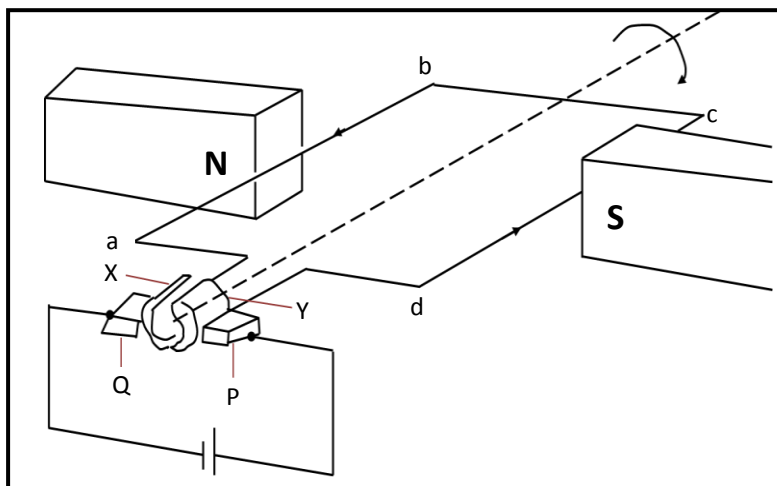
Stage 3: Horizontal position

Figure 19 The current is maximum again and is leaving the loop through split-ring X and brush Q. Therefore, the current is in the same direction as in stage 1.

At this position, the split-ring X and the side AB of the coil will be in contact with the brush Q. Also, the split-ring Y and the side CD will be in contact with the brush P. The current flows again in the direction DCBA. Here the current changes direction.

At this stage, the current now travels from B to A of one side of the coil and from D to C on the other side of the coil. This means that, the forces created will also change directions.



In stage 1, the force acting on side AB of the coil was downwards. But in stage 3, the force on side BA of the coil is upwards because of the change in direction of the current. The same is also true for the side CD in stage 1 and side DC in stage 3.

So the split-ring commutator is a device that reverses current at every half turn along the sides of the rotating coil through the brushes. Hence, the coil is rotating in a clockwise direction. You may verify these by applying the motor principle to sides BA and DC in stage 3 with respect to the direction of the current.

Stage 4: Vertical Position

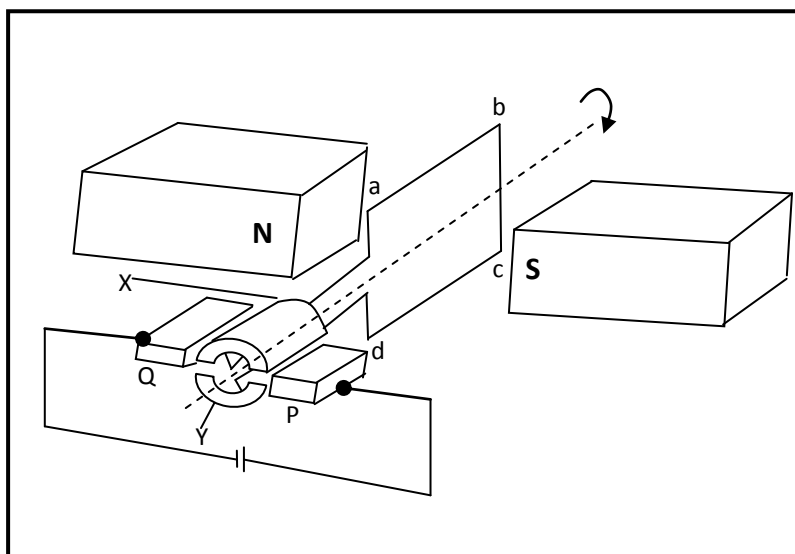
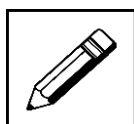


Figure 20 Again the current is zero, and the cycle is about to start again.

In this position, the contact between the carbon brushes and the commutator is broken again. Current flow is cut off but the coil continues to rotate because of its inertia. The processes are repeated and the motor continues to rotate until the current is switched off.

Now check what you have just learnt by trying out the learning activity below!



Learning Activity 5



10 minutes

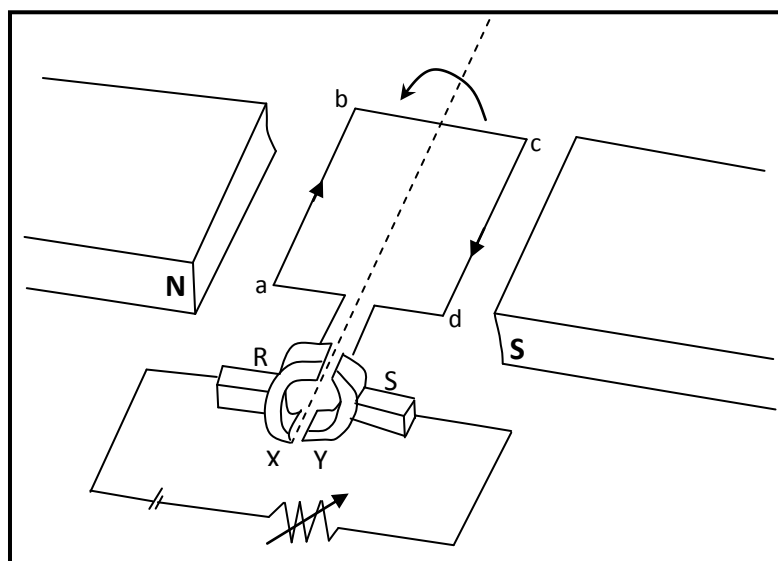
Answer the following questions on the spaces provided.

1. State Fleming's Left Hand Rule.



2. One of the important applications of the force on a current-carrying rectangular coil in a magnetic field is the D.C motor. In the figure, label the following parts:

- a) Split-ring commutator
- b) A carbon brush.



3. What are the functions of a:

- a) Split-ring commutator?

- b) Carbon?

Thank you for completing learning activity 5. Now check your work. Answers are at the end of the module.

Alternating current (AC) motor

Alternating current (AC) motors are more common and operate in the same manner as direct current (DC) motors. The main differences are that:

- AC motors use **slip rings** while DC motors use **split rings** (commutator),
- AC motors are connected to an alternating current power supply while DC motors are usually connected to direct current power supply.

In an AC motor the stator (stationary coil) is connected directly to an alternating current power supply. The alternating current in the stator winding induces an alternating current also in the rotor (rotating magnet) without any physical contact between them. The magnetic field of the current induced in the rotor interacts with the stator to produce motion.

The alternating current motor usually starts up with the help of a capacitor. The capacitor supplies an out of phase alternating current just for starting up the motor and then it automatically switches off.

The principle of operation of an **AC motor** is exactly the same as that of an **AC generator**. The only difference between the two is that, an AC motor is connected to an AC power supply to start it up, while an AC generator is connected to a load (example a resistor or a meter). It is usually started by physically rotating the rectangular coil to induce an alternating current.

The operation principle of an alternating current (AC) motor

Stage 1:

Coil in the horizontal position

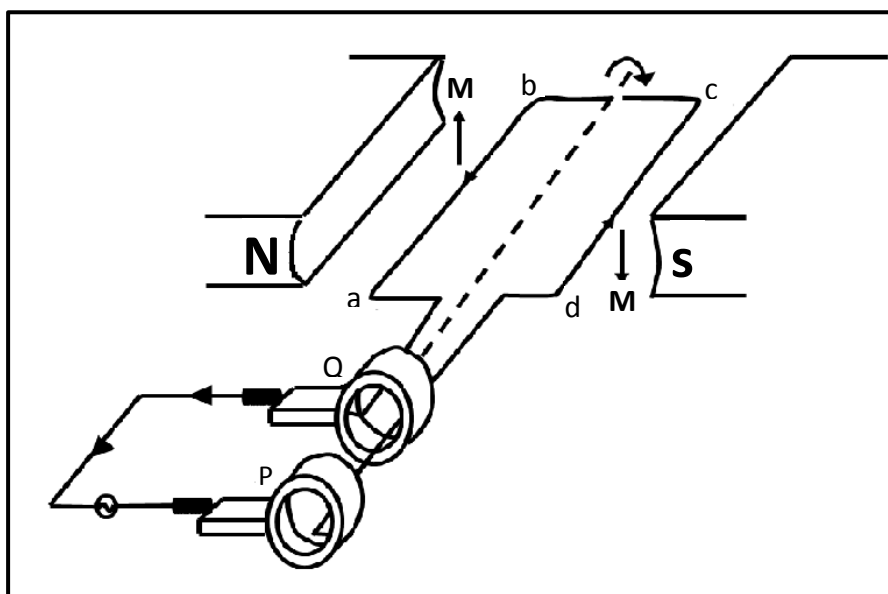


Figure 21 The current is maximum and is leaving the loop through brush Q.



- Side ab moves upwards and side cd moves downwards, cutting across the magnetic field lines and produces an induced current.
- Applying the Fleming's left-hand rule to side ab , the induced current flows from d to c and from b to a .
- In the external circuit, the current flows from brush Q to brush P .
- The current at this instant is maximum.
- After this position, the current decreases.

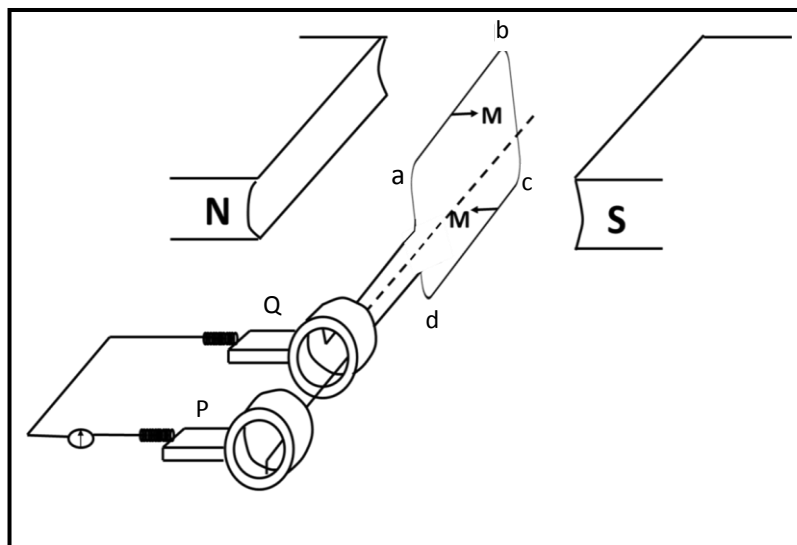
Stage 2:**Coil in the vertical position**

Figure 22 The loop is vertical and the current is zero.

- Sides AB and CD moves in parallel with the magnetic field lines.
- No induced current is produced because there is no cutting of field lines.
- After this position, the current increases.

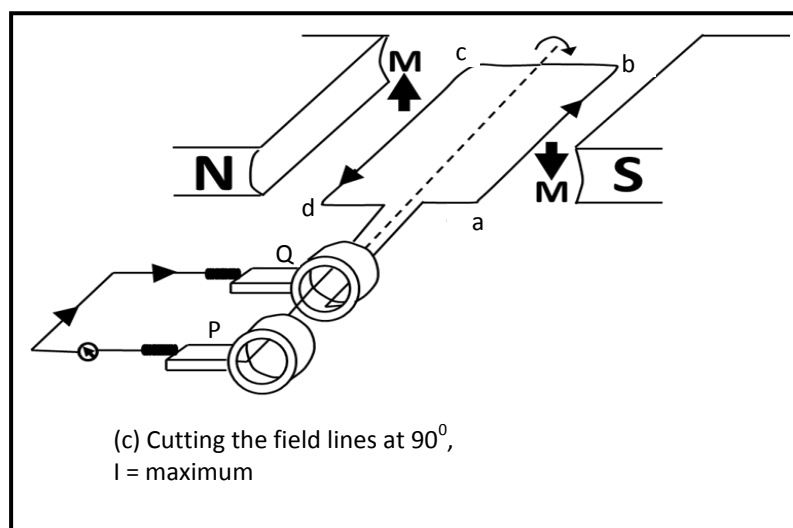
Stage 3:**Coil in the horizontal position**

Figure 23 The current is maximum and is leaving the loop through brush



- Side AB moves downwards and side CD moves upwards, cutting across the magnetic field lines again.
- The current now flows from A to B and from C to D.
- In the external circuit, the current flows from brush P to brush Q.
- The direction of the current is reversed.
- After this position, the current decreases.

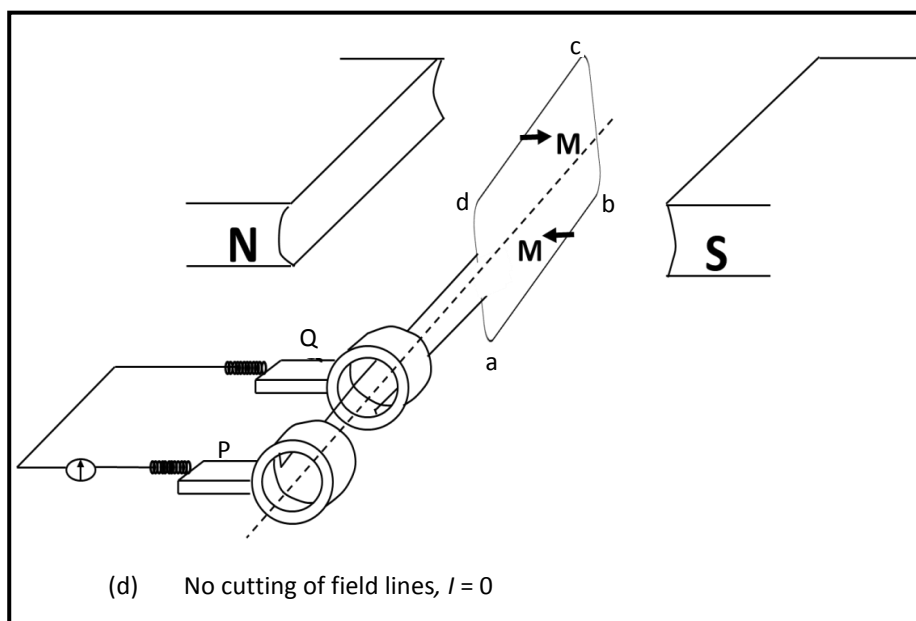
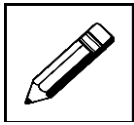
Stage 4:**Coil in vertical position**

Figure 24 The loop is vertical, the current is zero.

- Again no current is induced, as there is no cutting of magnetic field lines.
- After this position, the current increases and the process is repeated.

Now check what you have just learnt by trying out the learning activity on the next page!



Learning Activity 6

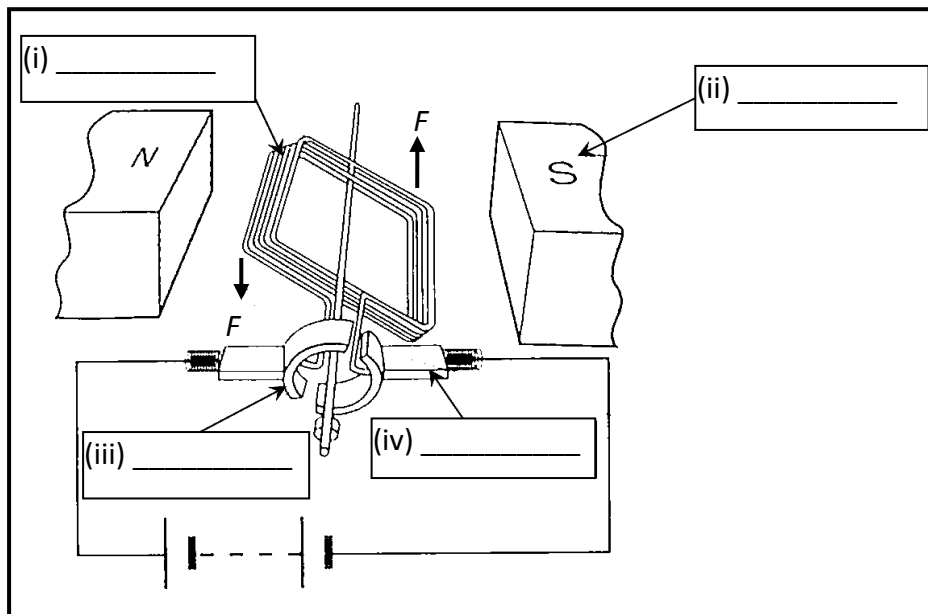


15 minutes

Answer the following questions on the spaces provided.

1. What are some of the similarities and differences between a DC and an AC motors?

2. Label the parts in the given diagram below.



3. Identify the type of motor given in question 2 above and state its basic operational principle.

Thank you for completing learning activity 6. Now check your work. Answers are at the end of the module.

12.4.2 Electromagnetic Induction

In our previous discussions, we have seen how a current flowing through a conductor can produce a magnetic field around it. How about the reverse? Can a magnetic field produce a current in a conductor? In 1831, Michael Faraday discovered that magnets could be used to generate electricity. He showed that a changing or varying magnetic field can produce an electromotive force (e.m.f). This e.m.f will produce an induced current in a closed circuit. We call this effect **electromagnetic induction**. This discovery led Faraday to invent the dynamo (generator) by using Electromagnetic Induction.

In this section, we will discuss electromotive force that results from magnetic interactions. Many of the present day systems including generators, transformers and motors depend directly on magnetically induced emfs.

The central principle here is the Faraday's Law. This law relates induced emf to changing magnetic field in a circuit. We will use the Lenz's Law also to help us understand and predict the directions of induced emfs and currents.

Finally, we will look at the principles of operations of some electrical energy conversion devices such as, motors, generators and transformers.

Current Induced In The Presence of a Magnetic Field.

Let us observe electromagnetic induction in the following cases.

A. A straight wire moving in the presence of a magnetic field.

Apparatus/materials

Magnadur magnets, U-shape iron yoke, PVC insulated copper wire, a bar magnet, cardboard tube and a centre-zero galvanometer.

Arrangement of apparatus

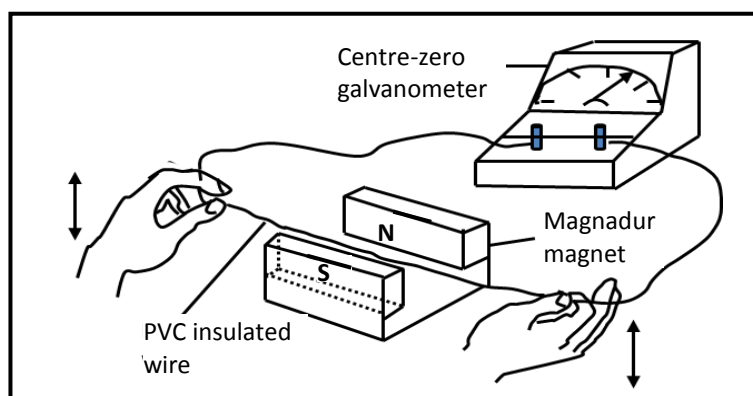


Figure 25 Investigation of the effect of relative motion between a straight conductor and a magnet.



Procedure

1. A pair of Magnadur magnets with unlike poles facing each other is placed in the iron yoke.
2. A PVC insulated copper wire is connected to a centre-zero galvanometer as shown above.
3. The actions taken in the investigation, observations and interpretations are recorded in the table below under observations.

Observations

Action	Observation: Momentary deflection of galvanometer (Left/Right)	Interpretations
a) The wire is moved downwards.	Right	Current flows in the wire.
b) The wire is moved upwards.	Left	Current flow is reversed.
c) The wire is moved horizontally sideways.	No deflection	No current is generated.
d) Magnet is moved upwards.	Right	Current flows in the wire as in (a).
e) Magnet and wire are moved at the same speed in the same direction.	No deflection	No current is generated.
f) The wire is held stationary between the Magnadur magnets.	No deflection	No current is generated

Discussion

1. Since there is no current source, the current (shown by the momentary deflection of galvanometer) must have been induced by the magnetic field.
2. The current is induced when there is relative motion between the wire and the magnetic field. The current induced is the same whether the wire moves downwards (to cut the magnetic field lines) or the magnet moves upwards (so that the field lines cut the wire) because it is their relative motion which causes an induced current.

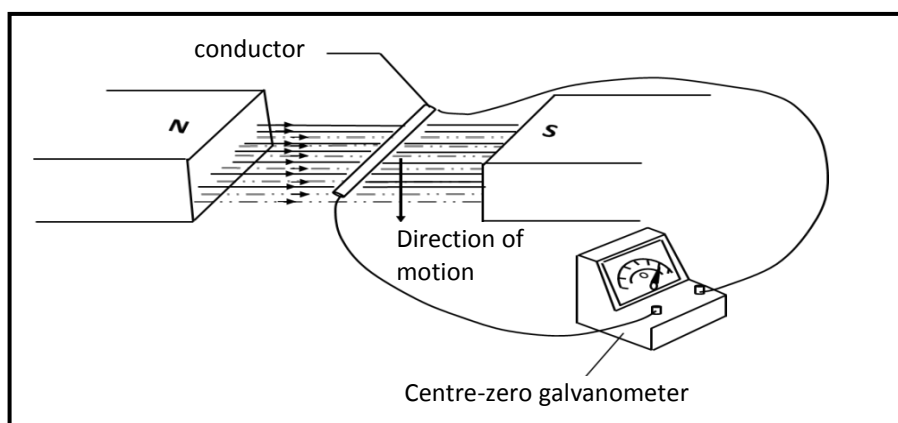


Figure 26 The relative motion between the wire and the magnetic field.

3. When the wire is moved horizontally across the gap from N pole to S pole, it slides in between the magnetic field lines. There is no cutting of magnetic field lines (magnetic flux) and no current is induced.

Conclusion

1. Current is only induced when the conductor cuts the magnetic flux.
2. The direction of the induced current depends on the direction of motion of either the conductor or the magnetic lines.

B. A stationary coil with a varying or changing magnetic field.

Arrangement of apparatus

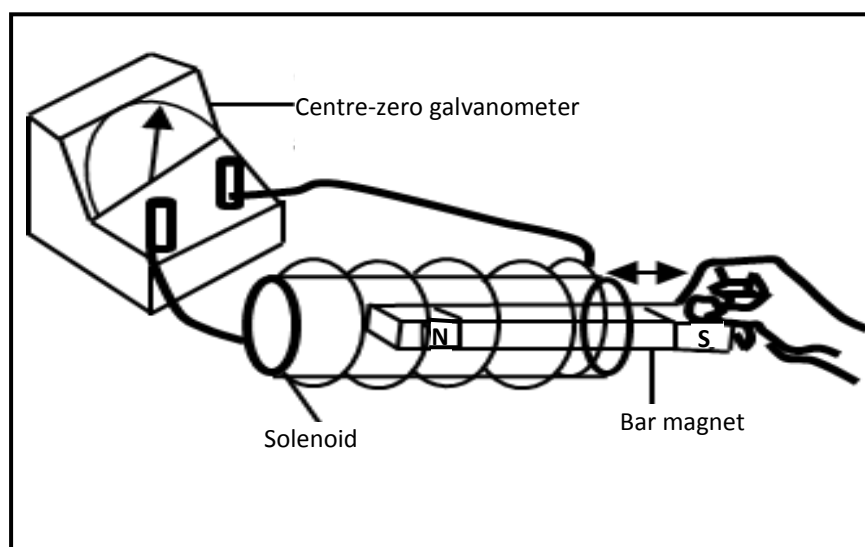


Figure 27 Effect of moving a solenoid (coil) relative to a magnet.



Procedure

1. A PVC insulated copper wire of length 2 m is wound round a cardboard tube of diameter 5 cm to form a solenoid with 50 turns.
2. The ends of the copper wire are connected to a centre-zero galvanometer as shown in the figure above.
3. The actions taken in the investigation, observations and inferences are recorded in the table below in the observations.

Observations

Action	Observation: Momentary deflection of galvanometer (Left/Right).	Inference
a) The north pole of the magnet is moved into the solenoid.	Right(for example)	Current flows in the solenoid.
b) The bar magnet is moved out of the solenoid.	Left	Current flow in the solenoid is reversed.
c) The south pole of the magnet is moved into the magnet.	Left	Current flow in the solenoid is reversed.
d) The solenoid is moved towards the bar magnet which is held stationary.	Right	Current flows in the solenoid as in (a).
e) The magnet is held stationary in the solenoid.	No deflection	No current is generated.
f) The bar magnet and the solenoid are moved at the same speed in the same direction.	No deflection	No current is generated.

Discussion

1. In the above activities, an induced current is produced when there is a relative motion between the bar magnet and the solenoid.
2. When there is linkage of magnetic flux in the solenoid, the magnetic field lines pass through the turns of wire in the solenoid.
3. The induced current is due to the change in the magnetic flux linkage in the solenoid:
 - a) When the bar magnet is pushed into the solenoid, the magnetic flux linkage in the solenoid increases and a current is induced.



- b) When the bar magnet is pulled out of the solenoid, the magnetic flux linkage in the solenoid is decreased and a current is induced in the opposite direction.
 - c) When there is no relative motion, there is no change in magnetic flux linkage in the solenoid and no induced current is produced.
4. The change in magnetic flux linkage produces the induced current.

Conclusion

1. Induced current is produced when there is relative motion between a solenoid and a magnet.
2. The direction of the induced current depends on the pole of the magnet used and the direction of motion of either the magnet or the coil.

From our investigation you will have noted that, the following relationships can be obtained:

1. The e.m.f is required to drive the current in a closed circuit.
2. The greater the induced e.m.f is, the greater the induced current.
3. The magnitude of the induced e.m.f and the direction of the induced current can be determined by application of the **laws of electromagnetic induction**.

Laws of electromagnetic induction

There are two principle laws of electromagnetic induction:

- a) Faraday's law
- b) Lenz's Law

Faraday's laws of electromagnetic induction

1. Faraday's law states that the magnitude of the induced electromotive force (e.m.f) is directly proportional to the rate of change of magnetic flux linkage in the solenoid or the rate at which a conductor cuts through the magnetic flux.
2. The induced e.m.f increases when the rate of change of flux increases. Hence, the induced current is increased when:
 - a) a stronger magnet is used
 - b) the speed of relative motion is increased.
3. The induced e.m.f increases when the number of turns increases because an e.m.f is induced in each turn of wire.



Lenz's law of electromagnetic induction

1. Lenz's law states that an induced current always flows in such a direction so as to oppose the change (or motion) causing it.
2. The table below gives an explanation of Lenz's law:

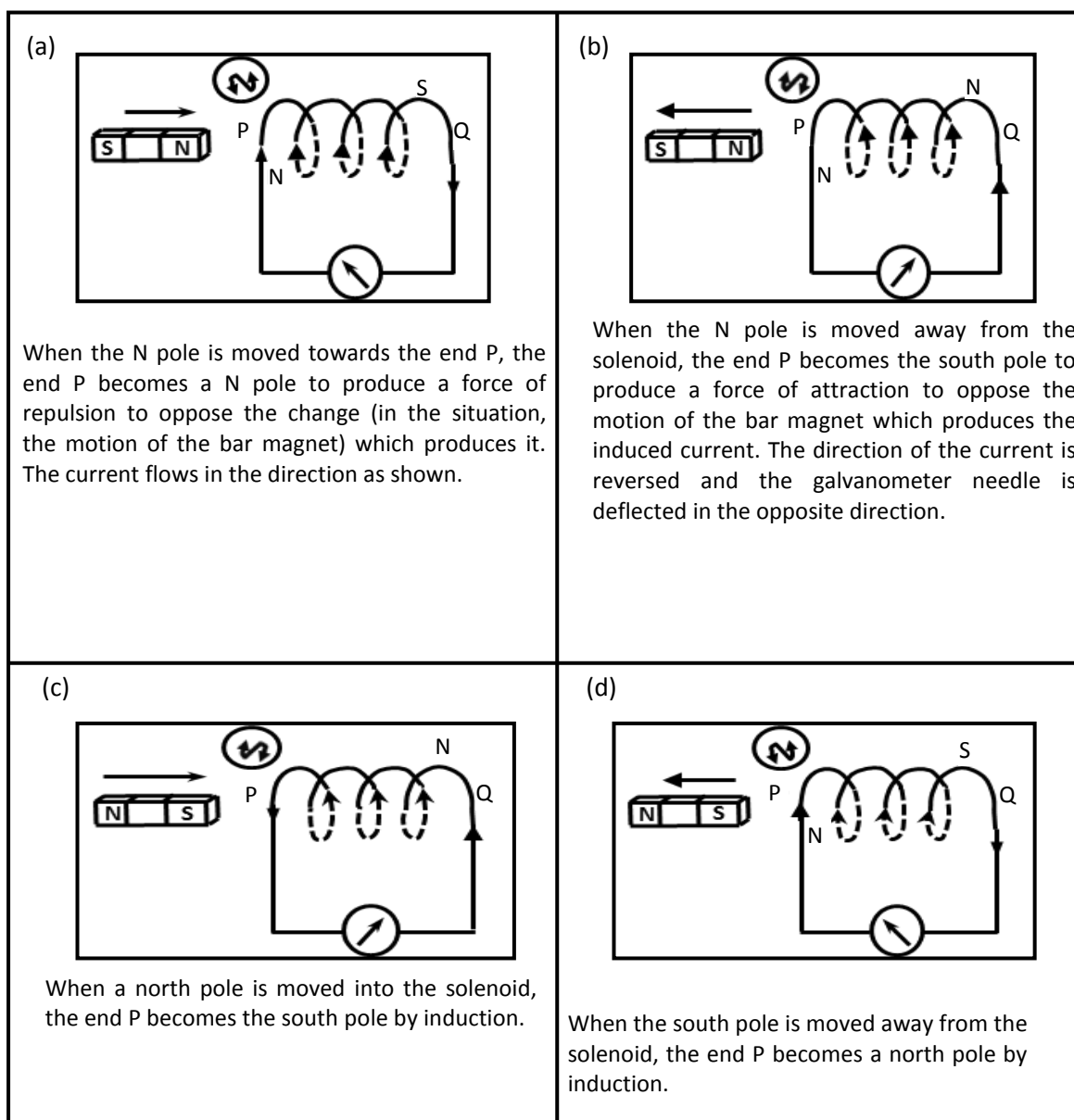


Figure 28 An illustration of Lenz's law.

Note, Fleming's Right hand Grip Rule can be used here to determine the polarities of the solenoid if the current direction is given. Also, the rule can be used to establish the direction of the induced current if the polarities of the solenoid are known. This is because, once a current is induced in the solenoid, it will behave like a magnet.



When the rule is used, the curled fingers point in the direction of the current and, the extended thumb points in the direction of the North Pole.

3. Lenz's law is a form of the law of **conservation of energy**. It can be explained by the principle of conservation of energy.
 - a) When the magnet is moved into the solenoid, current is induced in the solenoid. Why does this occur? Electrical energy cannot be created without any form of work being done. Hence, the end P must be induced to become the north pole so that a force of repulsion exists between the solenoid and the magnet.

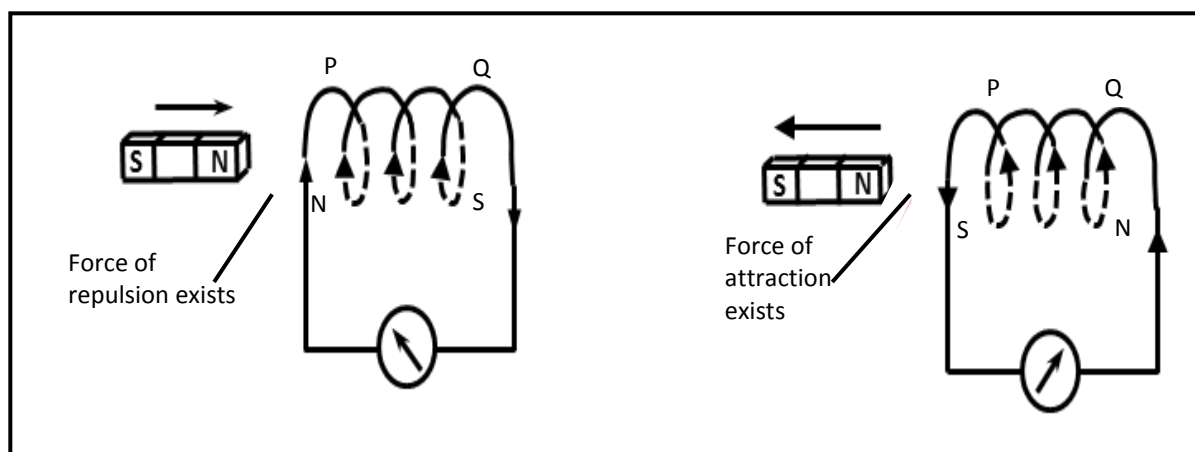


Figure 29 Principle of conservation of energy

- b) When the magnet is moved away from the solenoid, the end P is induced to become the south pole so that a **force of attraction** exists between the solenoid and the magnet.
- c) Therefore, when a magnet is moved towards or away from a solenoid, **work** must be done to overcome the **opposing force**.
- d) The work done is converted into **electrical energy** which creates the induced current.

Factors affecting the magnitude of the induced current in a conductor and a coil

- A. Let us investigate how the factors: **speed of the conductor**, **strength of the magnetic field**, **cutting angle** and the **length of the conductor** affect the magnitude of the induced current in a **straight current carrying conductor**.

A PVC insulated copper wire, Madnador magnets, a U-shaped iron yoke and a centre-zero galvanometer are arranged as shown in figure 30 (a) to investigate how the above factors affect the magnitude of the induced current in a conductor.

Arrangement of apparatus

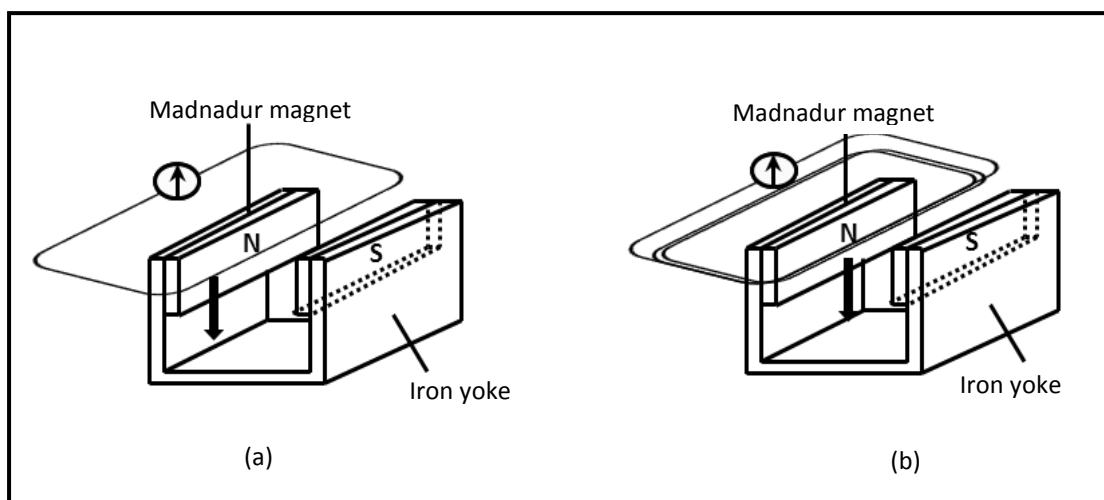


Figure 30 (a) A magnet with a single coil, (b) a magnet with many coils.

Similar actions were carried out on the two different arrangements in figure 30 (a) and (b). Observations were made and conclusions drawn. These actions, observations and conclusions are tabulated below. Note that in both figures the magnadur magnets are arranged with opposite poles facing each other.

Observations

Factor	Action (In figure 30a)	Angle of momentary deflection of galvanometer	Observation and Conclusion
Speed of conductor	(i) The wire is moved downwards slowly.	Small	<i>Observation:</i> The galvanometer deflection increases when the conductor moved at a faster rate.
	(ii) The wire is moved downwards quickly.	Large	<i>Conclusion:</i> The size of the momentary deflection of the galvanometer indicates the magnitude of the induced current.



			Therefore, the induced current increases when the speed of the conductor is increased.
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Factor	Action	Angle of momentary deflection of galvanometer	Observation and conclusion
Strength of the magnetic field	(i) The wire is moved downwards at fixed speed.	Small	<i>Observation:</i> The galvanometer needle increases when more magnets are used.
Strength of the magnetic field	(ii) Two more magnets are added to increase the strength of magnetic field. The speed of wire is the same as in (i).	Large	<i>Conclusion:</i> The induced current increases when the strength of the magnetic field is increased .

Factor	Action	Angle of momentary deflection of galvanometer	Observation and conclusion
Cutting angle	(i) The wire is moved downwards at 90° to the magnetic field at a fixed speed.	Large	<i>Observation:</i> The galvanometer needle deflection decreased when the angle between the motion of the conductor and the magnetic field decreases.
	(ii) The wire is moved at the same speed as in step(i)	Small	



	but at an angle of less than 90° .		<i>Conclusion:</i> The induced current is maximum when the cutting angle is at 90° .
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Factor	Action	Angle of momentary deflection of galvanometer	Observation and conclusion
Length of conductor	(i) A 50 cm wire is used. The wire is moved downwards at fixed speed.	Small	<i>Observation:</i> The galvanometer needle increases when the length of the conductor is increased.
Length of conductor	(ii) The wire is wound into a coil with many turns as in figure 30 (b) above. The speed of wire is the same as in (i). This is equivalent to cutting the magnetic flux with a longer conductor.	Large	<i>Conclusion:</i> The induced current increases when the length of the conductor is increased .

Conclusion

1. The magnitude of the induced current increases when the:

- speed of the relative motion increases
- strength of the magnetic field increases
- length of the conductor increases
- cutting angle is at 90°

B. Let us investigate how the factors: **speed of the conductor**, **strength of the magnetic field**, **cutting angle** and the **length of the conductor** affect the magnitude of the induced current in a **coil**(solenoid).

PVC insulated copper wires (3m x 1.5m x1), two bar magnets, cardboard tube and centre-zero galvanometer.

Arrangement of apparatus

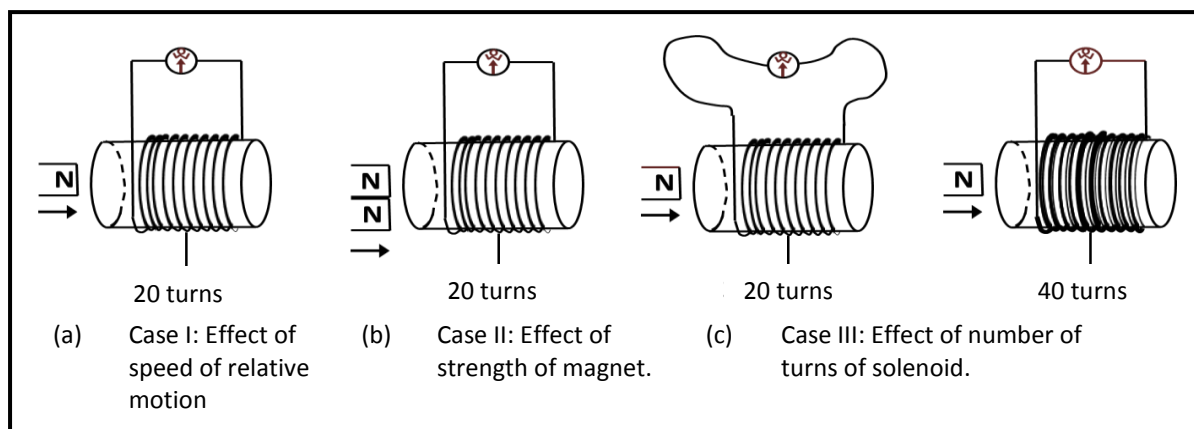


Figure 31 Factors affecting the size of induced current in a solenoid.

Observations

Factor	Action	Angle of momentary deflection of galvanometer	Observation and conclusion
Speed of conductor (relative motion)	(i) The wire is moved downwards slowly.	Small	<i>Observation:</i> The galvanometer deflection increases when the conductor moved at a faster rate.
	(ii) The wire is moved downwards quickly.	Large	<i>Conclusion:</i> The size of the momentary deflection of the galvanometer indicates the magnitude of the induced current. Therefore, the induced current increases when the speed of the relative motion increased .



Strength of the magnetic field	(i) The wire is moved downwards at fixed speed.	Small	<p><i>Observation:</i> The galvanometer needle increases when more magnets are used.</p> <p><i>Conclusion:</i> The induced current increases when the strength of the magnetic field is increased.</p>
	(ii) Two more magnets are added to increase the strength of magnetic field. The speed of wire is the same as in (i).	Large	

Factor	Action	Angle of momentary deflection of galvanometer	Observation and conclusion
Cutting angle	(i) The wire is moved downwards at 90° to the magnetic field at a fixed speed.	Large	<p><i>Observation:</i> The galvanometer needle deflection decreased when the angle between the motion of the conductor and the magnetic field decreases.</p> <p><i>Conclusion:</i> The induced current is maximum when the cutting angle is at 90°.</p>
	(ii) The wire is moved at the same speed as in step(i) but at an angle of less than 90° .	Small	



Length of conductor	(i) A 50 cm wire is used. The wire is moved downwards at fixed speed.	Small	<i>Observation:</i> The galvanometer needle increases when the length of the conductor is increased.
	(ii) The is wound into a coil with many turns as in figure(b) above. The speed of wire is the same as in (i). This is equivalent to cutting the magnetic flux with a longer conductor.	Large	<i>Conclusion:</i> The induced current increases when the length of the conductor is increased .

Conclusion

- The magnitude of the induced current increases when the:
 - speed of the relative motion is increased.
 - strength of the magnetic field is increased.
 - length of the conductor is increased.
- The magnitude of the induced current is maximum when the conductor cut across the magnetic field perpendicularly (conductor cuts the magnetic field at an angle of 90°)

As stated earlier, whenever the magnet moves relative to the coil, an induced e.m.f is generated in the circuit. This conclusion is summarised in the Faraday's Law of electromagnetic induction which states that:

The emf induced in a conductor is directly proportional to the rate at which the magnetic field lines are cut by the conductor.

However, the direction of the induced emf (taken to be the direction of the induced current) is such that the magnetic field created always opposes the motion which produces it. The direction of this current can be predicted using Lenz's Law:

An induced current always flows in a direction such that it opposes the change or motion which produces it.



Note from the discussions on Faraday and Lenz's laws, a current is induced or generated whenever a magnet is being pushed into or out of the solenoid (coil). When this happens the solenoid will behave like a magnet. This means that one end of the solenoid will be a south pole while the other will be north pole.

The coil will behave like a magnet even if it is connected directly to a power supply as shown below.

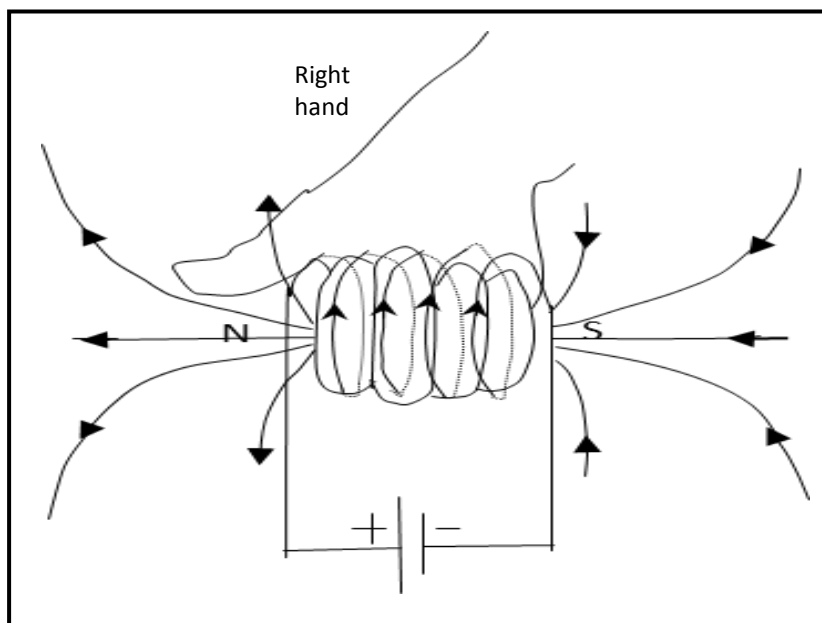


Figure 32 A current carrying coil produces magnetic field

On both occasions, the Fleming's Right Hand Grip rule can be used to establish the polarities of the solenoid. Fleming's Right Hand Grip Rule states that, when gripping the coil with your right hand the curled fingers point in the convention current direction and your extended thumb points in the direction of the north pole of the coil.

Induced current direction: Fleming's Right Hand Rule

The direction of a current induced in a conductor moving at right angles through the magnetic field can be determined with Fleming's Right Hand Rule.

Fleming's Right Hand and Left Hand Rules applies to two different situations:

- When a **current** cause a **motion**, the left hand rule applies
- When **motion** cause **current**, the right hand rule applies.

**Example 1**

A bar magnet is pushed towards one end of the solenoid as shown below.

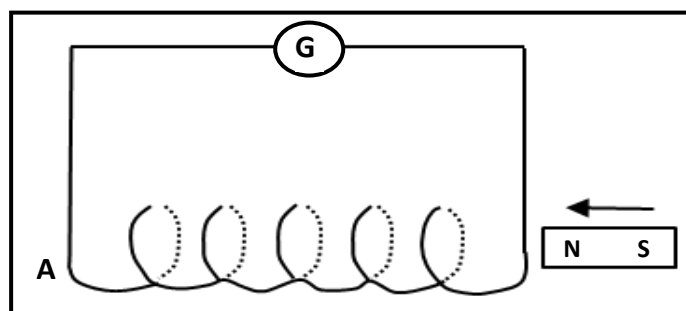


Figure 33 Work done by magnet is transformed into electrical energy.

- How would you increase the amount of deflection in the galvanometer?
- Would the induced current at end A flow clockwise or anticlockwise?

Solution

- The amount of deflection of the galvanometer needle can be increased by moving the magnet faster into the coils of the solenoid.
- The induced current would flow in an anticlockwise direction. This can be determined by using the Fleming's Right Hand Grip Rule.

Example 2

Below is a magnet being moved towards the coil.

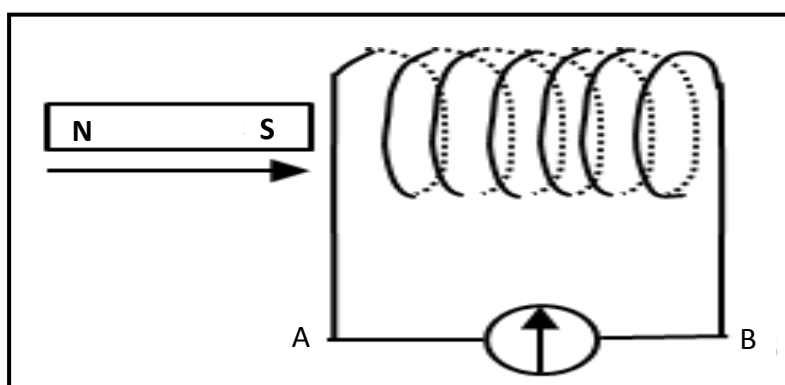


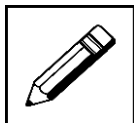
Figure 34 A magnet being moved towards the coil.

- As current is induced, what type of pole is formed at the left end of the coil? Give a reason for your answer.
- In which direction does the current (conventional) flow through the meter, AB or BA?

**Solution**

- a) The type of pole formed at the left end of the coil is the north pole. This is in line with Lenz's law which states that, the induced current direction in the coil will make the end of the coil facing the magnet behave like north pole so as to oppose the north pole of the magnet.
- b) The conventional current flows through meter in the direction BA (or clockwise).

Now check what you have just learnt by trying out the learning activity below!

**Learning Activity 7****30 minutes**

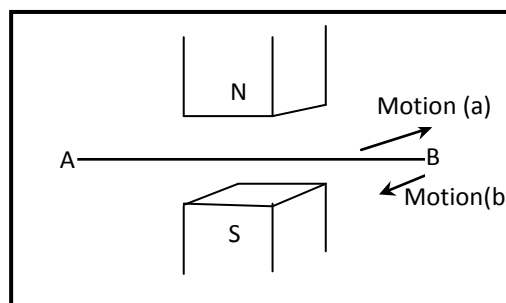
Answer the following questions on the spaces provided.

1. Which of the following actions does **not** cause an induced e.m.f to be set up in a coil of wire?
- a) Pushing a magnet into a stationary coil.
 - b) Moving a coil over a stationary magnet.
 - c) A steady current flowing through the coil.
 - d) Withdrawing a magnet from inside a coil.

2. A magnet is used to induce a current in a coil of wire. List three things that could be done to increase the current produced.

- i) _____
- ii) _____
- iii) _____

3. The diagram below shows a conductor AB in a magnetic field.





- a) Mark the direction of the magnetic field lines on the diagram.
- b) In which direction will a current be induced in the conductor AB when it moves:
 - i) into the page? _____
 - ii) out of the page? _____

Thank you for completing learning activity 7. Now check your work. Answers are at the end of the module.

Principle of operation of a DC generator (DC dynamo)

Stage 1:

Coil in horizontal position

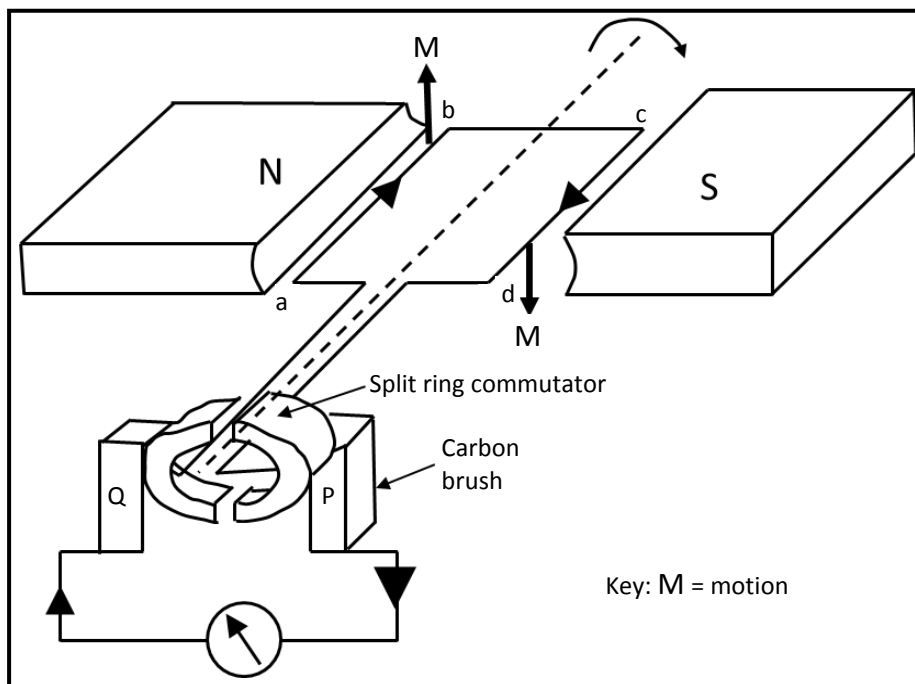


Figure 35 The coil is cutting the field lines at 90° , $I = \text{maximum}$

- Side AB move upwards and side CD move downwards, cutting across the magnetic field lines and produces an induced current.
- Applying the Fleming's right-hand rule at side AB, the current now flows from A to B and from C to D.
- In the external circuit, the current flows from brush P to brush Q. This is indicated by the galvanometer's needle which deflects to the left).
- Current at this instant is maximum. After this position, current decreases.



Stage 2: Coil in vertical position

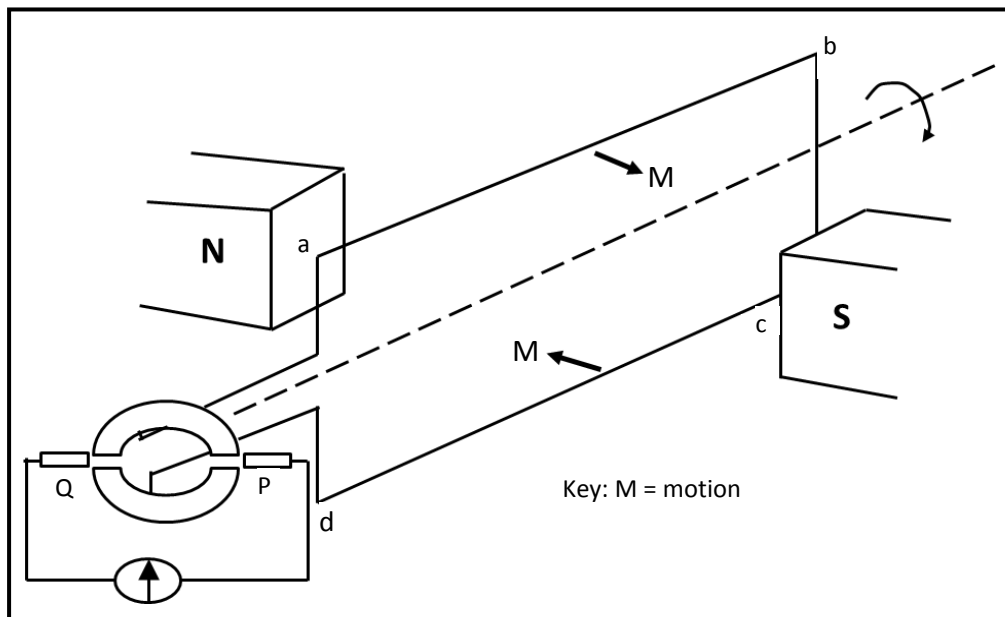


Figure 36 No cutting of field lines, $I = 0$

- The sides AB and CD move in parallel with the magnetic field lines. No induced current is produced because there is no cutting of magnetic field lines.
- The galvanometer needle returns to the zero mark.
- After this position, the split rings (commutator halves) changes contact with brushes P and Q.
- After this position, current starts to increase.

Stage 3: Coil in horizontal position.

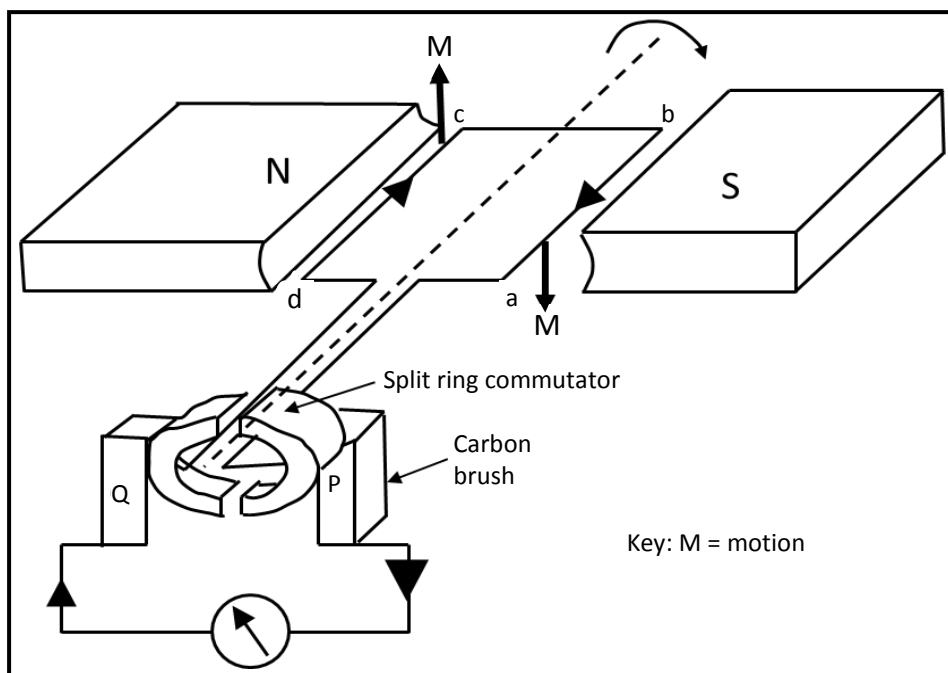


Figure 37 Cutting the field lines at 90° , $I = \text{maximum}$



- Side AB moves downwards and side CD moves upwards, cutting across the field lines again.
- Current now flows from B to A and from D to C. However, in the external circuit, the current still flows from brush P to brush Q.
- The direction of the current is maintained and galvanometer shows a deflection in the same direction.
- After this position, the current decreases.

Stage 4: Coil in vertical position

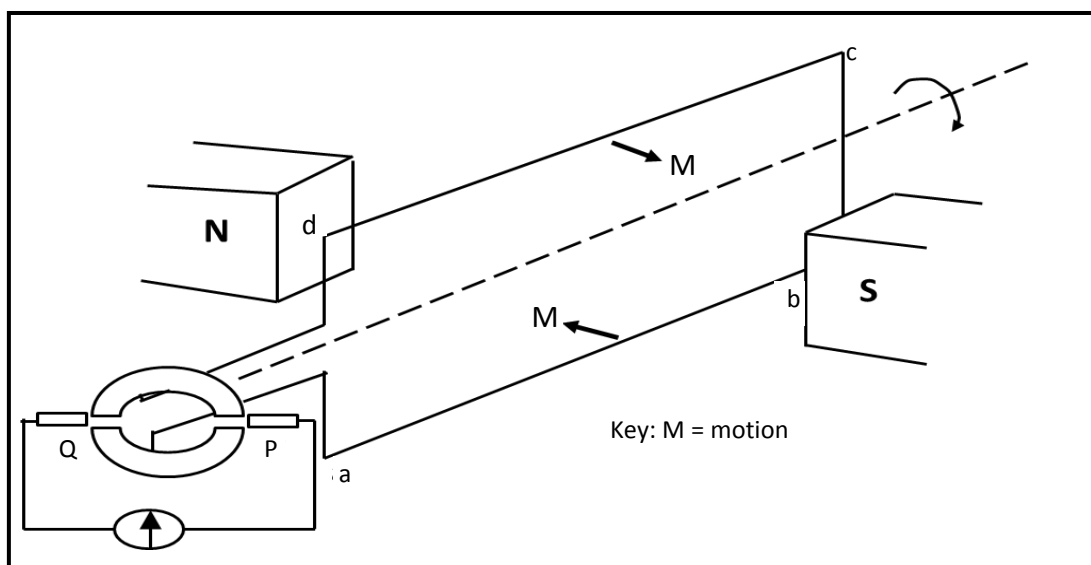


Figure 38 No cutting of field lines, $I = 0$

- Again, no current is induced as there is no cutting of magnetic field lines.
- After this position, the current increases and the process is repeated.

Operating principle of an Alternating Current Generator (AC Dynamo)

Stage 1: Coil in horizontal position.

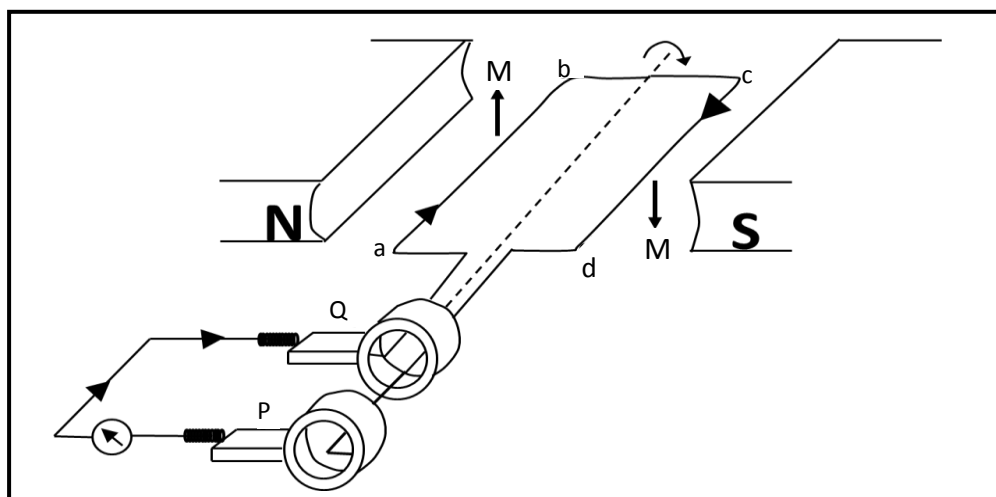


Figure 39 The coils cutting the magnetic field lines at 90° , $I = \text{maximum}$.



- Side AB moves upwards and side CD moves downwards, cutting across the magnetic field lines and produces an induced current.
- Applying Fleming's Right Hand Rule to side AB, the induced current flows from A to B and from C to D.
- In the external circuit, current flows from brush P to brush Q (the galvanometer pointer deflects to the left).
- The current at this instant is maximum.
- After this position, the current decreases.

Stage 2: Coil in vertical position

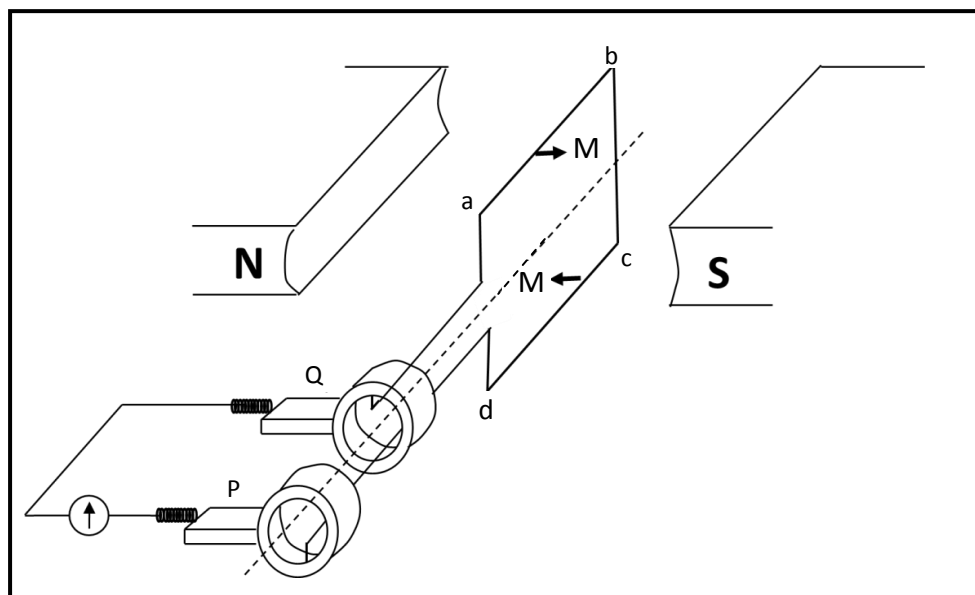


Figure 40 The magnetic field lines are not being cut, $I = 0$.

- The sides AB and CD moves parallel with the magnetic field lines.
- No induced current is produced because there is no cutting of field lines.
- The galvanometer returns to zero mark.
- After this position, the current increases.

Stage 3: Coil in horizontal position

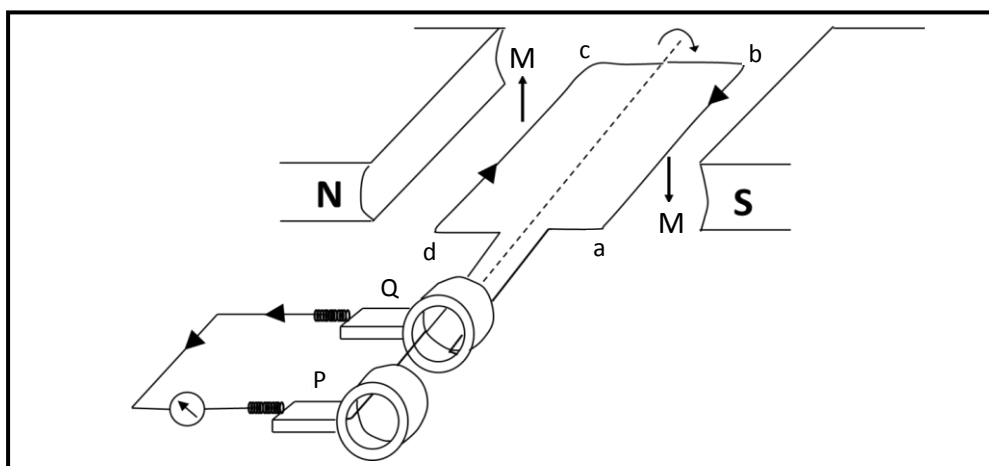


Figure 41 The coils cutting the magnetic field lines at 90° , $I = \text{maximum}$.



- Side AB moves downwards and side CD moves upwards, cutting across the magnetic field lines again.
- The current now flows from B to A and from D to C.
- In the external circuit, the current flows from brush Q to brush P.
- The direction of the current is reversed and the galvanometer shows a deflection in the opposite direction.
- After this position, the current decreases.

Stage 4: Coil in vertical position

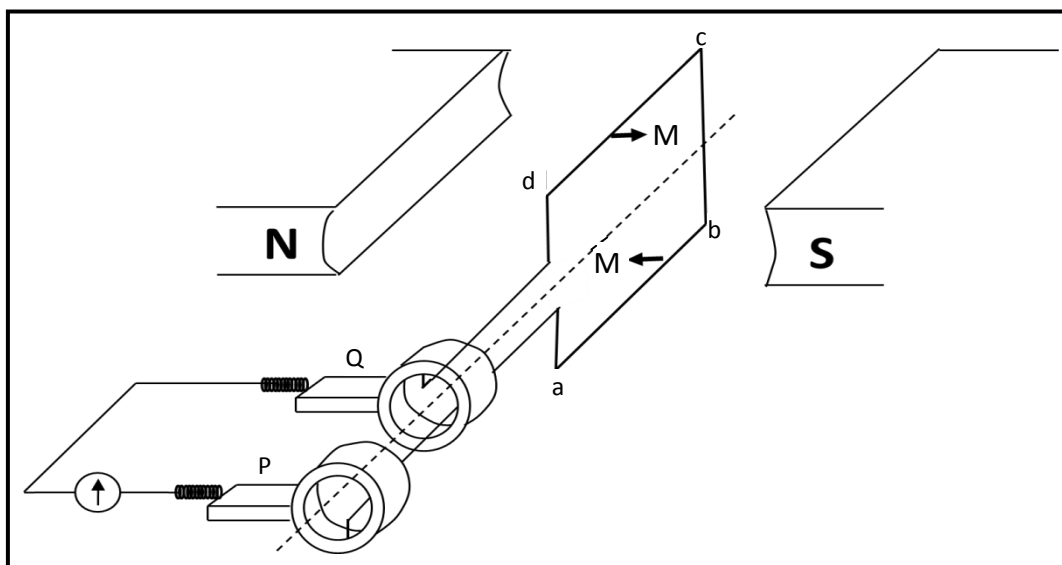


Figure 42 The magnetic field lines are not being cut, $I = 0$.

- Again, no current is induced as there is no cutting of magnetic field lines.
- After this position, the current increases and the process is repeated.

Now check what you have just learnt by trying out the learning activity below!



Learning Activity 8



10 minutes

Answer the following questions on the spaces provided.

1. Explain in your own words the operation principle of a DC generator (DC dynamo).



2. Explain in your own words the operation principle of an AC generator (DC dynamo).

Thank you for completing learning activity 8. Now check your work. Answers are at the end of the module.

12.4.3 Transformers and Power Losses in Transmission lines

The mains supply voltage we receive at our homes in Papua New Guinea is 240V. However, we know that different electrical appliances need different working voltages. For example, a CD player may need only 12V, while a television set may need several hundred volts. To convert the mains supply voltage to a suitable voltage for the different appliances, transformers are used.

Transformers

Definition: One method used to produce an induced emf used two coils placed side by side so that the magnetic field produced by one of the coil passes through the other. This effect is called the **mutual induction**.

A transformer is an electrical device that makes use of mutual induction to vary voltage. That is, it raises or lowers voltage of an alternating current. When this happens it transfers electrical energy from the circuit to another.

A transformer is used for:

1. Electrical power transmission from power station to households and factories.
2. Regulating voltages for proper operation of electrical appliances such as the TV and CD player.

Transformer operation

The operating principle of a transformer is based on electromagnetic induction. The current from the electrical supply that is connected to the primary coil is an alternating current. An alternating current is a current whose magnitude and direction varies or changes continuously at a certain frequency.

The alternating current produces a flux or magnetic field lines which link the primary and the secondary coils. The magnetic flux varies in magnitude and direction.

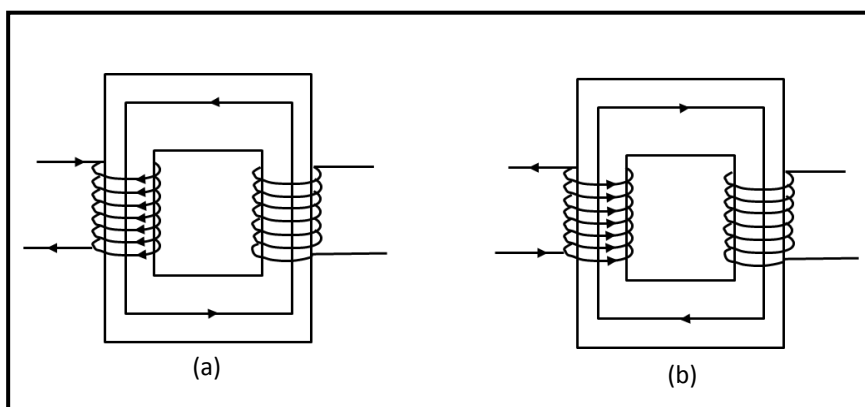


Figure 43 Direction of magnetic flux linking the coils changes when the current directions in the primary coil changes.

The changing magnetic flux produces an induced e.m.f across the secondary coil. This induced e.m.f also varies in magnitude and direction. As a result, the secondary (output) voltage is also an alternating voltage. If the secondary circuit is closed, an alternating current flows in the circuit with the same frequency as the electrical supply.

There are two main types of transformers:

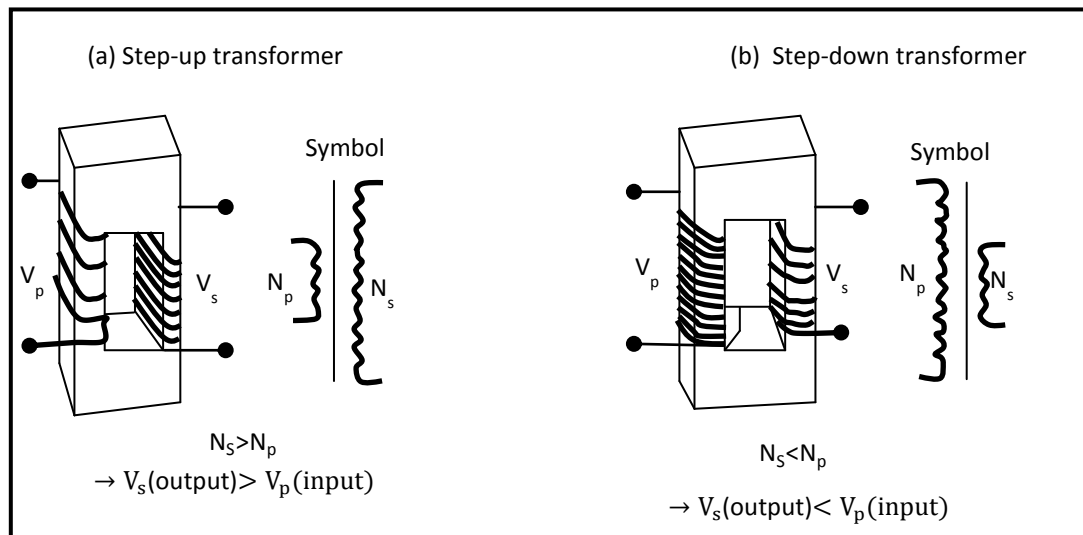


Figure 44 The structure and the symbols of a step-up and step-down transformers.

For an **ideal transformer** (efficiency of 100%), the relationship between the primary voltage (V_p), secondary voltage (V_s), number of turns in the primary coil (N_p) and the number of turns in the secondary coil (N_s) is as follows:

$$\frac{\text{Secondary voltage}}{\text{Primary voltage}} = \frac{\text{Number of secondary turns}}{\text{Number of primary turns}}$$

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



or

$$\text{Voltage ratio (V)} = \text{Turns ratio (N)}$$

If the primary (input) voltage, V_p and the number of turns, N_p is fixed, then:

$$V_s \approx N_s$$

That is, the larger the number of secondary turns is, the higher the secondary (output) voltage will be. Every turn on the secondary coil has an e.m.f induced in it. The sum of the e.m.f across every turn on the secondary coil is the secondary (output) voltage.

Example 1

A transformer is used to lower the supply voltage from 240 V to 3 V for use with a 3 V lamp. If the number of turns on the primary coil is 1600 turns, what is the number of turns on the secondary coil?

Solution

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

$$\frac{3}{240} = \frac{N_s}{1600}$$

$$N_s = \frac{3 \times 1600}{240} = 20 \text{ turns}$$

Ideal transformer

If there is no loss of energy in a transformer, all the energy supplied to the primary coil will be transferred to the secondary coil. Such a transformer is known as an **ideal transformer** which has an efficiency of 100%.

$$\text{output power} = \text{input power}$$

$$P_o = P_i$$

$$V_s I_s = V_p I_p$$

Example 2

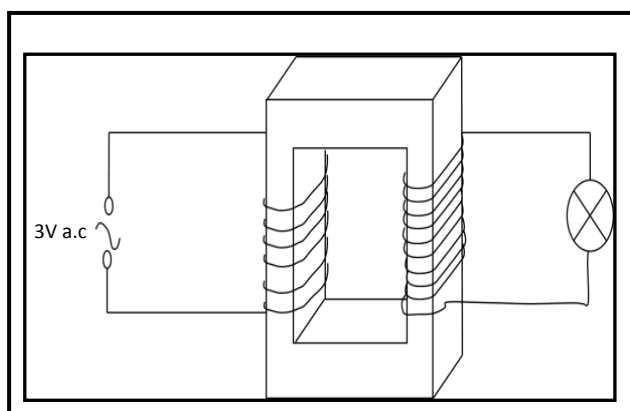
A transformer is used to lower the electrical supply voltage of 240V to supply power to a light bulb with a rated power of 12V, 2A. If the current in the primary coil is 0.15A, what is the efficiency of the transformer?

Solution

$$\text{Efficiency} = \frac{P_o}{P_i} \times 100\% = \frac{V_s I_s}{V_p I_p} \times 100\% = \frac{12 \times 2}{240 \times 0.15} \times 100\% = 67\%$$

**Example 3**

The bulb in the transformer shown in the diagram lights up at normal brightness.



What will happen if the ac input is replaced by a 3V battery?

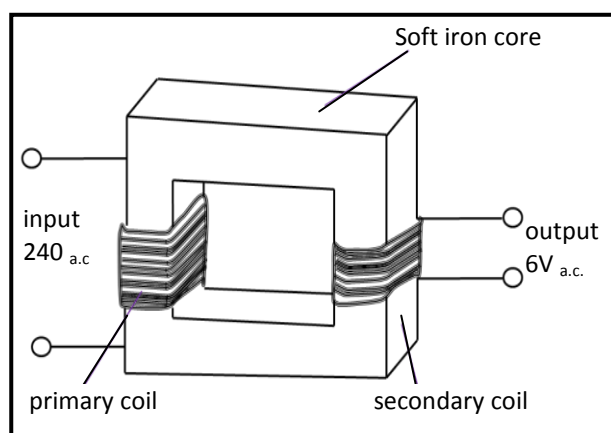
- A. The bulb blows
- B. The bulb does not light up
- C. The brightness of the bulb increases
- D. The brightness of the bulb remains unchanged

Solution

The transformer does not function when the input current is a steady direct current. A 3V battery supplies steady direct current. The transformer therefore does not work if the ac input is replaced by a 3V battery. Hence, the answer is **B**.

Example 4

The diagram below shows a simple transformer with two coils as shown.



- a) Name the type of transformer.
- b) Calculate the number of turns on the secondary coil if the number of turns on the primary coil is 1200.



- c) The secondary coil is connected to an electrical appliance. The current in the primary coil is 0.09A and the efficiency is 80%. Find the output power of the transformer.

Solution

- a) A step down transformer.

$$\begin{aligned} \text{b) } \frac{V_s}{V_p} &= \frac{N_s}{N_p} \\ \frac{6}{240} &= \frac{N_s}{1200} \end{aligned}$$

$$\text{therefore } N_s = \frac{6 \times 1200}{240} = 30 \text{ turns}$$

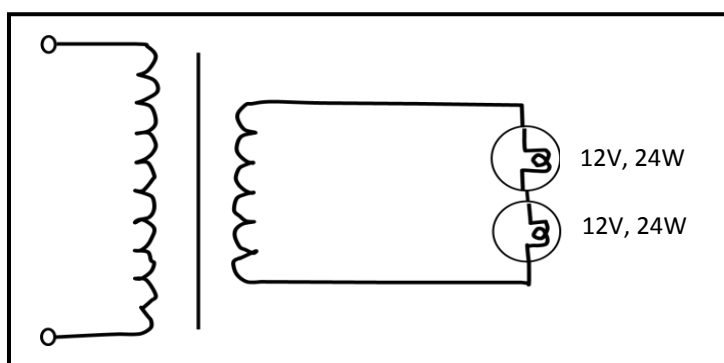
$$\text{c) Efficiency} = \frac{P_o}{P_i} \times 100\%$$

$$80\% = \frac{\text{output power}}{\text{input power}} \times 100\%$$

$$\text{therefore output power} = \frac{80\% \times \text{input power}}{100\%} = \frac{80 \times (240 \times 0.09)}{100} = 17.3\text{W}$$

Example 5

The figure shows an ideal transformer used to supply power to two 12V, 24W bulbs at their rated power.



If the voltage of the electricity supply is 240V and the current in the primary coil is 0.2A, then what is the current in the secondary coil?

Solution

$$V_s I_s = V_p I_p$$

$$24 \times I_s = 240 \times 0.2$$

$$I_s = 2\text{A}$$

Note that the voltage drop in the output across the two bulbs is 24V. It is because voltages in a series circuit are a sum of the two different voltages.

Now check what you have just learnt by trying out the learning activity on the next page!



Learning Activity 9



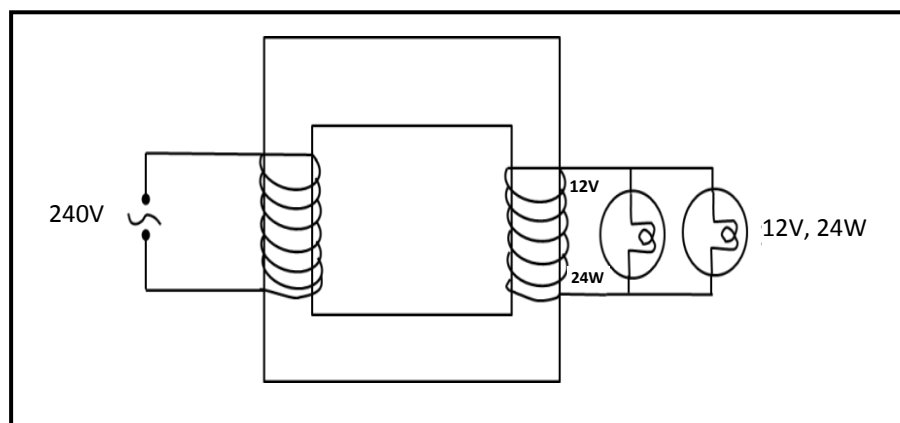
20 minutes

Answer the following questions on the spaces provided.

1. An electric door-bell for a home uses a 9V supply to function. The main voltage of the electrical supply is 240V. What is the turn's ratio of the transformer that must be used?

-
2. An ideal transformer steps down a voltage of 240V to supply to a lamp with a power rating of 3V, 0.3A. If the brightness is normal, what is the current flowing in the primary coil?

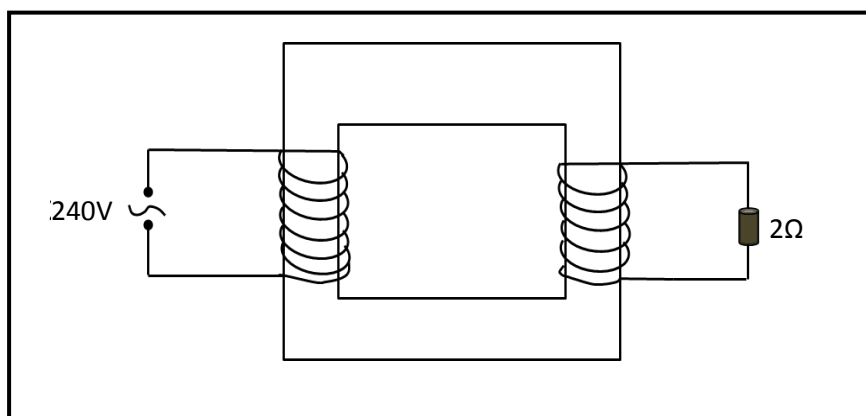
-
3. Two identical lamps of power rating 12V, 24W have the same brightness when power is supplied by a transformer as shown below.





If the efficiency of the transformer is 80%, what is the current flowing in the primary coil?

4. The transformer in the diagram below has an efficiency of 90%.



If the power given out by the resistor is 4.5Js^{-1} , calculate the:

- voltage across the resistor.
- current flowing in the primary coil.

Thank you for completing learning activity 9. Now check your work. Answers are at the end of the module.

Power Losses in Transmission Lines

Electrical power is transmitted by power lines from power stations to our homes. Because of the very long distances the current has to travel, the resistance of a power line cannot be neglected. When a current passes through it, power is lost because of the heating effect of the current. The power loss is proportional to the square of the current: $P = I^2R$.

For the same amount of power delivered by a power line, the current is smaller with a higher voltage. For this reason, a high voltage is used in power lines to reduce power loss.

The table below gives an example of the power loss at different transmission voltages.

Voltage (V)	500kV	220kV	66kV
Current (A)	600A	1364A	4545A
Power Loss ($P = I^2R$)	1.8MW	9.3MW	103MW

Table 1 The power loss increases as the transmission voltages decreases.

The figure 45 below shows an arrangement to demonstrate the power loss when power is transmitted at low voltage over long distances. The long-distance transmission lines are simulated by using resistance wires as transmission lines. The light bulb at the 'consumer end' is much dimmer than at the 'power station'.

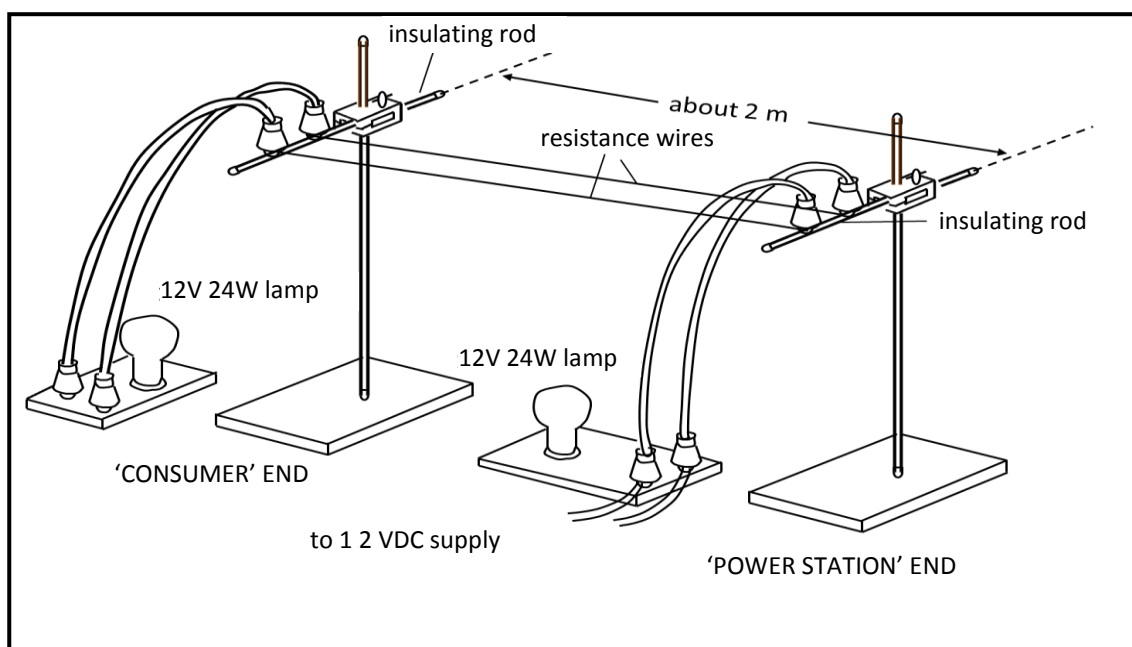


Figure 45 A DC low- voltage model power line. The lamp at the 'consumer' end is much dimmer than that at the 'power station'.



In figure 46, a model AC transmission line is shown. The voltage is raised by a step-up transformer at the power station. It is lowered by a step-down transformer at the consumer end. The lamp at the consumer end is now brighter. In stepping up the voltage, the transformer steps down the current and so the power loss is much smaller.

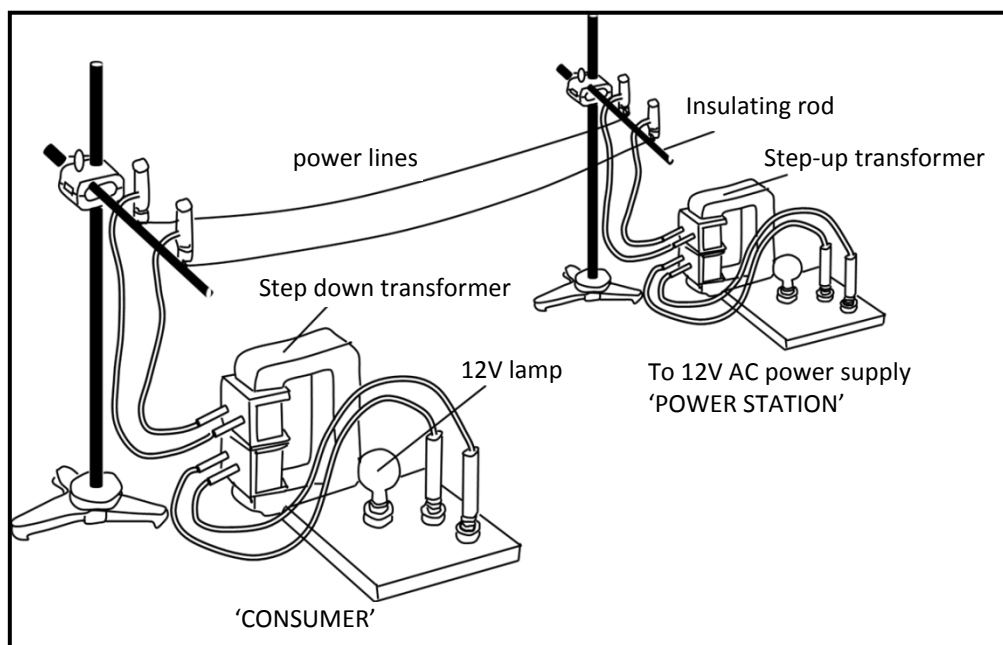


Figure 46 A model AC power line using step-up and step-down transformers. The lamp at the 'consumer' end is brighter than that in figure 45.

These model experiments show why AC rather than DC is used for long-distance power transmission. AC voltages can be changed easily and without much loss of power by transformers. AC generators are also simpler, cheaper, more reliable and more efficient than DC ones.

However, the high voltage in a power line is extremely dangerous. For safety purposes, electricity received by consumers should be at a lower voltage. Because of the need to vary voltages, power is transmitted by AC so that transformers can be used.

In practice, electricity is generated by AC generators at power stations at high voltages between 11kV and 33kV. It is further stepped up to a higher voltage between 220kV and 500kV by transformers. It is then transmitted by a grid (a network of power lines) to various towns.

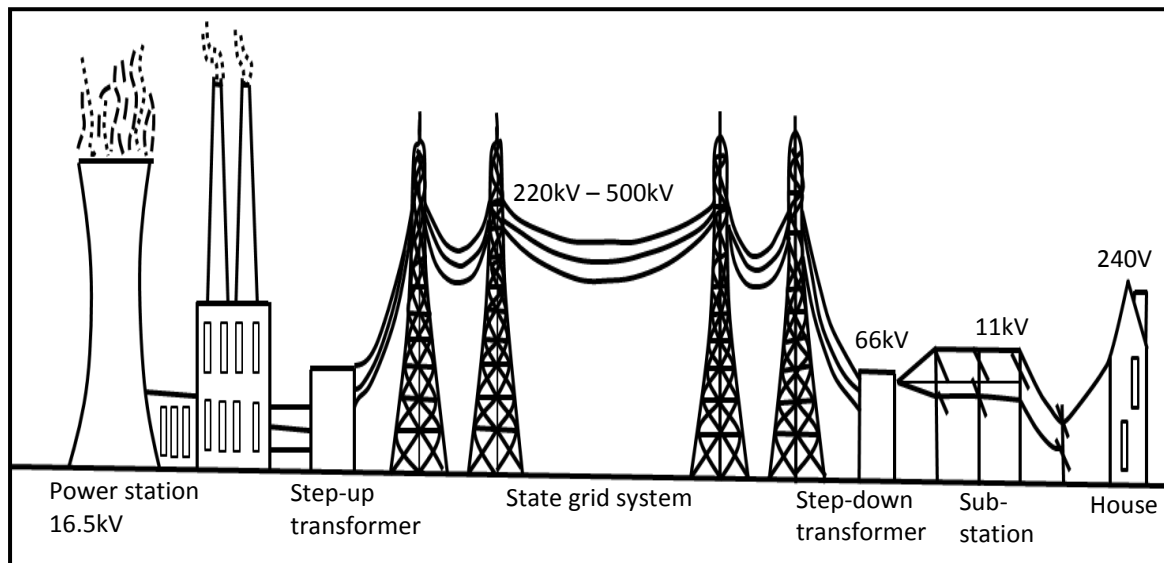


Figure 47 A typical grid system

The grid system consists of power lines supported by tower-like pylons. Subsequently, the voltage is stepped down in successive stages (66kV, 11kV) at substations by transformers. Electricity is conveyed to consumers at 240V in Papua New Guinea. This is much safer, but still dangerous to life.

Example1

Cables of resistance 2Ω supply 2kW of power. Calculate the power loss in the cable if power is transmitted at (a) 200V and (b) 2000V.

Solution

a)

$$P = VI \rightarrow I = \frac{P}{V} = \frac{2000W}{200V} = 10A$$

$$\text{Power loss} = I^2R = 10^2 \times 2 = 200W$$

b)

$$P = VI \rightarrow I = \frac{P}{V} = \frac{2000W}{2000V} = 1A$$

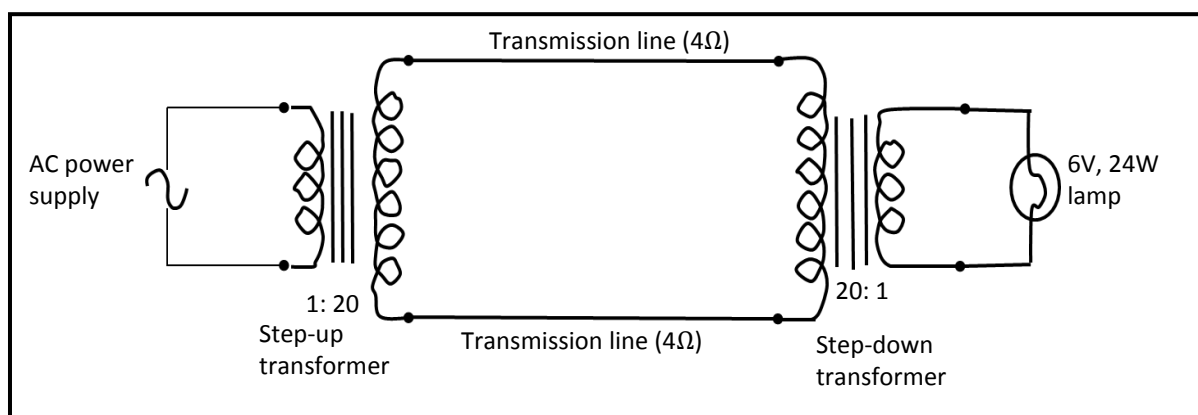
$$\text{Power loss} = I^2R = 1^2 \times 2 = 2W$$

Notice that in this example that the power loss at the higher voltage is much less.

**Example 2**

The diagram below shows an electrical transmission system. The resistance of the transmission wire on each side is 4Ω . The $6V$, $24W$ lamp is operated at its correct rating. Assume no energy loss in the transformers. Calculate the;

- current through the lamp.
- current through the transmission wire.
- power loss in the transmission wire.

**Solution**

a) $P = IV, \text{ so } I = \frac{P}{V} = \frac{24}{6} = 4A$

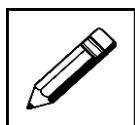
- b) The step-down transformer,

$$= I_s \times \frac{N_s}{N_p} = 4 \times \frac{1}{20} = 0.2A$$

This is the current through the transmission line.

c) $P = I^2R = (0.2)^2 \times (4 + 4) = 0.32W$

Now check what you have just learnt by trying out the learning activity on the next page!

**Learning Activity 10****20 minutes**

Answer the following questions on the spaces provided.

1. What is the advantage of high-voltage power transmission?

2. What is the main advantage of the AC power transmission over the DC transmission?

3. What is the function of transformers in domestic power transmission?

Thank you for completing learning activity 10. Now check your work. Answers are at the end of the module.

NOW REVISE WELL USING THE MAIN POINTS ON THE NEXT PAGE.



SUMMARY

You will now revise this module before doing **ASSESSMENT 4**.

Here are the main points to help you revise. Refer to the module topics if you need more information.

- A magnetic field is a region in which a magnetic material experiences a force.
- A current-carrying conductor produces a magnetic field around it. The right-hand grip rule is used to determine the direction of the magnetic field.
- The right-hand grip rule is used to determine the magnetic pole of a current-carrying solenoid (coil).
- The strength of an electromagnet increases when;
 - (a) current increases
 - (b) the number of turns on the solenoid increases.
- The direction of motion of a current-carrying conductor in a magnetic field can be determined by using Fleming's Left-Hand Rule.
- The force on a current-carrying conductor increases when the;
 - (a) current increases
 - (b) strength of the magnetic field increases
 - (c) length of the conductor increases.
- The production of an electric current by a changing magnetic field is called electromagnetic induction.
- Faraday's Law states that; the magnitude of the induced current is directly proportional to the rate of change of magnetic flux.
- Lenz' Law states that; an induced current always flows in such a direction so as to oppose the change causing it.
- The direction of the induced current can be determined by using Fleming's Right-Hand Rule.
- The induced current in a conductor increases when the;
 - (a) speed of the conductor increases
 - (b) strength of the magnetic field increases
 - (c) length of the conductor increases.
- Voltage ratio = Turn ratio
$$\frac{V_s}{V_p} = \frac{N_s}{N_p}$$
- Efficiency of a transformer = $\frac{\text{power output}}{\text{power input}} \times 100\%$
- Alternate current is used in transmission of electrical energy at a higher voltage because its voltage can be easily increased or decreased by using a transformer.

We hope you have enjoyed studying this module. We encourage you to revise well and complete Assessment 4.



**NOW YOU MUST COMPLETE ASSESSMENT TASK 4 AND
RETURN IT TO THE PROVINCIAL CENTRE CO-ORDINATOR**

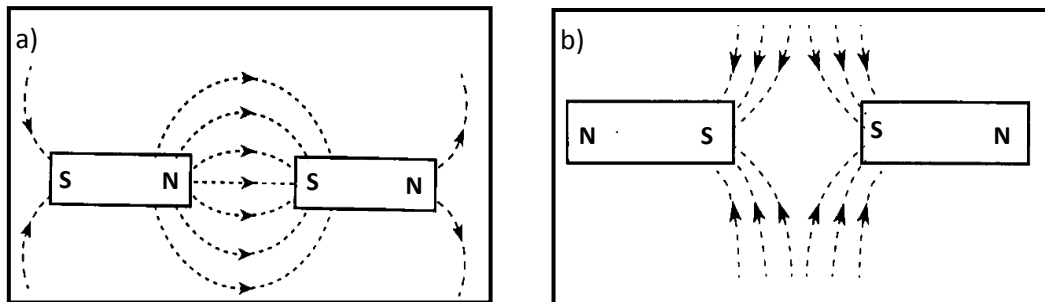


ANSWERS TO LEARNING ACTIVITIES 1 - 10

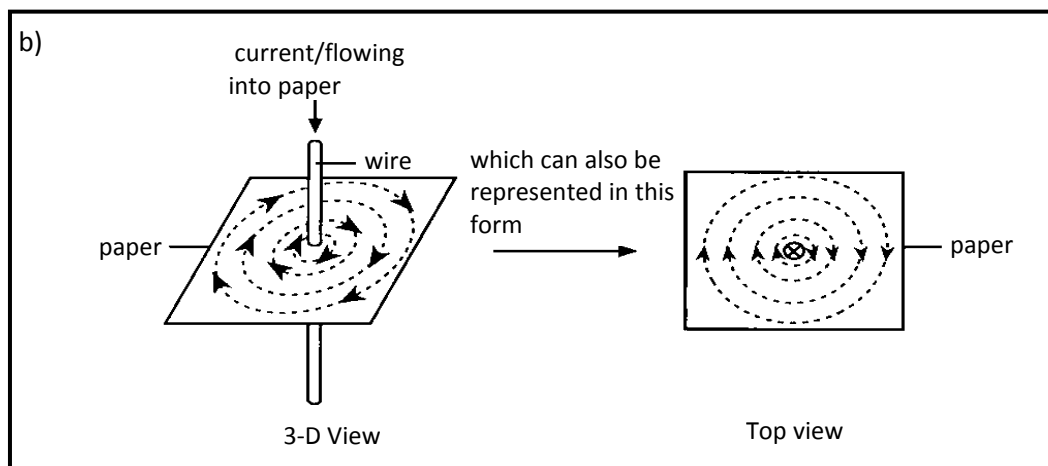
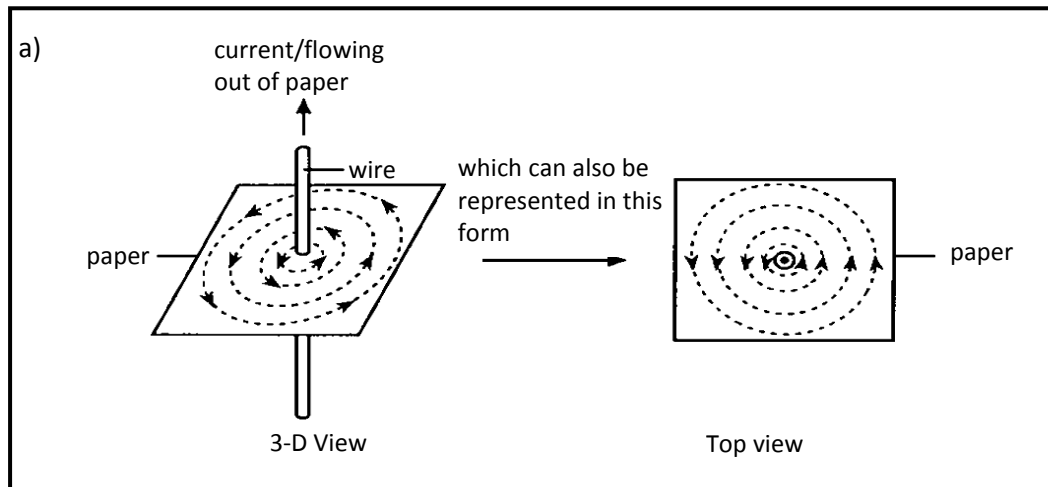
Learning Activity 1

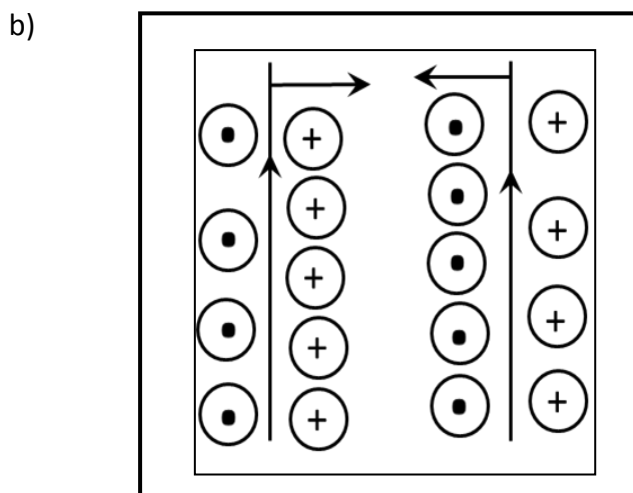
- A magnetic field is a region where a magnet exerts a force.
 - Magnetic materials like iron or cobalt.

2.



3.



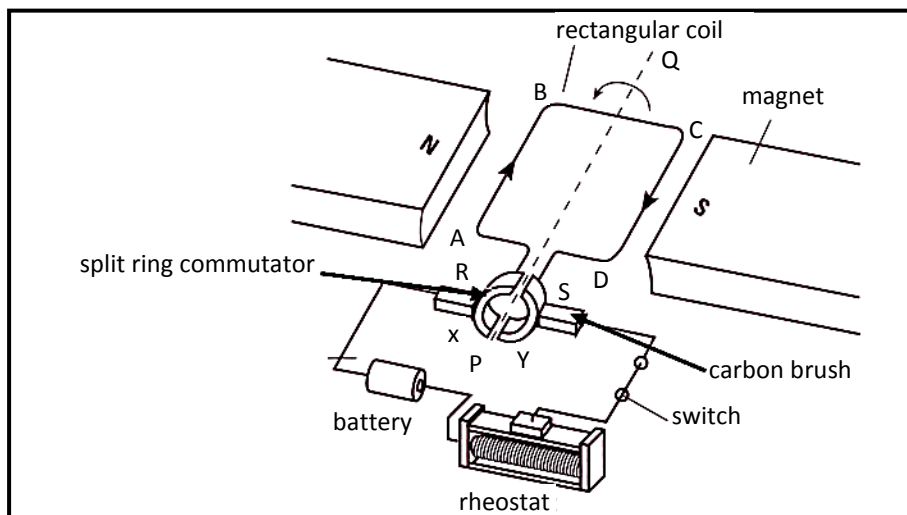


Magnetic fields between the wires are cancelled. The wires move in the direction of the weaker field. An **attraction**.

Learning Activity 5

1. Hold the thumb, the forefinger and second finger of the left hand at right angles to each other. Point the forefinger in the direction of the magnetic field and the second finger in the direction of the current. The direction of the motion of the wire is then pointed by the thumb.

2.

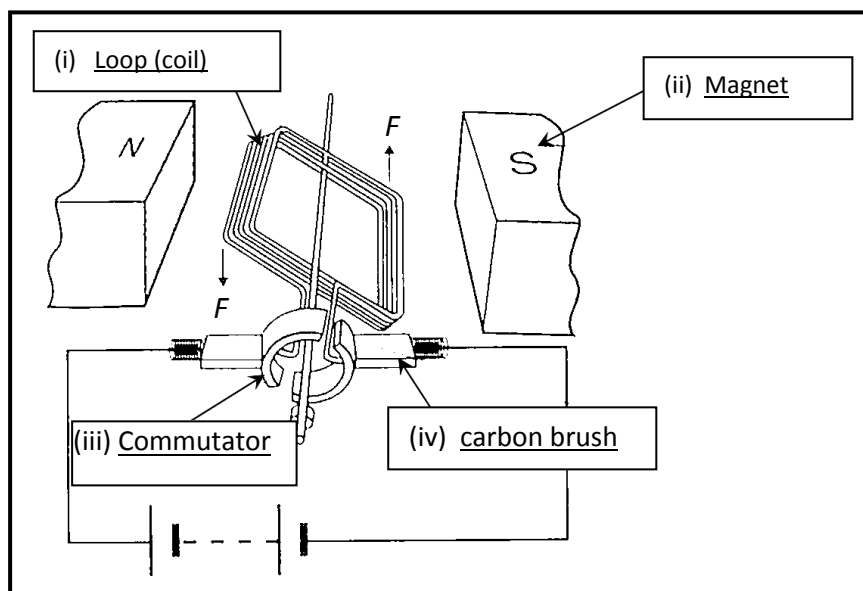


3. The commutator reverses the direction of the current in the coil whenever the commutator changes contact from one brush to another. The carbon brushes conduct the current into the coil and out of the coil.

Learning Activity 6

- Both motors are connected to a power supply. The main difference between the two motors is that, a DC motor uses a split-ring (commutator) while an AC motor uses slip rings for its operation.

2.



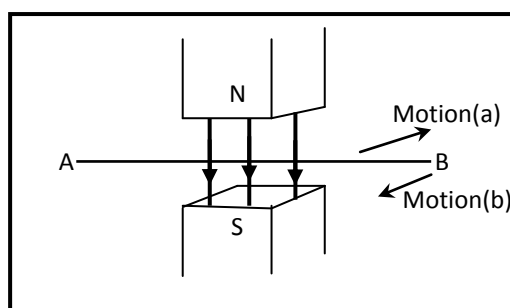
- The motor is a DC motor. Using the conventional current direction and the FLHR on the left side of the coil, the coil will rotate in the clockwise direction.

Learning Activity 7

- Answer C

- Use a bigger and stronger magnet.
 - Speed of the relative motion of the magnet or coil.
 - Increase the number of the turns in the coil.

2. a)



A conductor in a magnetic field



- b) i) into the page:
The induced current direction will be from B to A.
- ii) out of the page:
The induced current direction will be from A to B.
-

Learning Activity 8

1. A DC dynamo has a coil which is rotated by the magnetic field. The coil is usually known as the armature winding. The armature is connected to the commutator, which contains two half rings. The commutator reverses the connections of the coil with the external circuit every time the coil passes the vertical position. This will allow the current to pass through in one direction only.
 2. An AC dynamo produces current that changes directions as the coil rotates. The current is maximum when the coil is horizontal. It changes direction, when the coil is vertical. The coil is fixed to two slip rings which rotate it. The current passes to the external circuit via a carbon brush which rests against the slip rings.
-

Learning Activity 9

1. $N_s : N_p = 9 : 240 = 3 : 80$

2. $V_p I_p = V_s I_s$

$$240 \times I_p = 3 \times 0.3$$

$$I_p = 0.00375 \text{ A}$$

3. Power Output = 48W

$$\text{Efficiency} = \frac{\text{Power Output}}{\text{Power Input}} \times 100\%$$

$$80\% = \frac{48}{240 \times I_p} \times 100\%$$

$$\text{Therefore } I_p = 0.25 \text{ A}$$



$$4. \quad a) \quad P = \frac{V^2}{R} \rightarrow 4.5 = \frac{V^2}{2} \rightarrow 9 = V^2$$

Therefore, $V = 3V$

$$b) \quad \text{Efficiency} = \frac{\text{Power output}}{\text{Power input}} \times 100\%$$

$$90\% = \frac{4.5}{240 \times I_p} \times 100\%$$

Therefore $I_n = 0.021A$

Learning Activity 10

1. The advantage is to reduce power losses due to heating effects along transmission lines.
 2. The main advantage is because AC voltages can be changed easily and without much power loss by transformers.
 3. In domestic power transmission, transformers steps down voltages to the required amount.
-

If you have queries regarding the answers, then please visit your nearest FODE provincial centre and ask a distance tutor to assist you.



REFERENCES

Chew Charles, Fong Siew Chow and Tiong Boon Ho. (eds). GCE 'O' Level Physics Matters. Singapore: Marshall Cavendish, 2007.

Giancoli C. Douglas . (ed). Physics Principles with Applications. Virginia: Prentice – Hall International, 1985.

Lofts Greame , O' Keeffe Dan, Pentland Peter, Philip Ross, Bass Garry, NardelliDaniella, Robertson Pam, Tacon Jill and Pearce John. (eds). Jacaranda Physics . Queensland: John Wiley & Sons, 2004.

TeekSeng Foo, Tiek Cheng Yee, HinBeng Lee ChuanGeok Chong and Wong Jonathan. (eds). SUCCESS Physics. Selangor DarulEhsan: Oxford Fajar, 2010.

Wilkinson John. Essentials of Physics. South Yara: Macmillan Education Australia, 1993.

Young D. Hugh, Zemansky W. Mark and Sears W. Francis. (eds). University Physics, 8TH Eddition. Pittsburgh, Pennsylvania: Eddision – Wesley, 1991.

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FODE SUBJECTS AND COURSE PROGRAMMES

GRADE LEVELS	SUBJECTS/COURSES
Grades 7 and 8	1. English
	2. Mathematics
	3. Personal Development
	4. Social Science
	5. Science
	6. Making a Living
Grades 9 and 10	1. English
	2. Mathematics
	3. Personal Development
	4. Science
	5. Social Science
	6. Business Studies
	7. Design and Technology- Computing
Grades 11 and 12	1. English – Applied English/Language & Literature
	2. Mathematics - Mathematics A / Mathematics B
	3. Science – Biology/Chemistry/Physics
	4. Social Science – History/Geography/Economics
	5. Personal Development
	6. Business Studies
	7. Information & Communication Technology

REMEMBER:

- For Grades 7 and 8, you are required to do all six (6) subjects.
- For Grades 9 and 10, you must complete five (5) subjects and one (1) optional to be certified. Business Studies and Design & Technology – Computing are optional.
- For Grades 11 and 12, you are required to complete seven (7) out of thirteen (13) subjects to be certified. Your Provincial Coordinator or Supervisor will give you more information regarding each subject and course.

GRADES 11 & 12 COURSE PROGRAMMES

No	Science	Humanities	Business
1	Applied English	Language & Literature	Language & Literature/Applied English
2	Mathematics A/B	Mathematics A/B	Mathematics A/B
3	Personal Development	Personal Development	Personal Development
4	Biology	Biology/Physics/Chemistry	Biology/Physics/Chemistry
5	Chemistry/ Physics	Geography	Economics/Geography/History
6	Geography/History/Economics	History / Economics	Business Studies
7	ICT	ICT	ICT

Notes: You must seek advice from your Provincial Coordinator regarding the recommended courses in each stream. Options should be discussed carefully before choosing the stream when enrolling into Grade 11. FODE will certify for the successful completion of seven subjects in Grade 12.

CERTIFICATE IN MATRICULATION STUDIES

No	Compulsory Courses	Optional Courses
1	English 1	Science Stream: Biology, Chemistry, Physics
2	English 2	Social Science Stream: Geography, Intro to Economics and Asia and the Modern World
3	Mathematics 1	
4	Mathematics 2	
5	History of Science & Technology	

REMEMBER:

You must successfully complete 8 courses: 5 compulsory and 3 optional.