AREA OF STUDY 1: Electric power

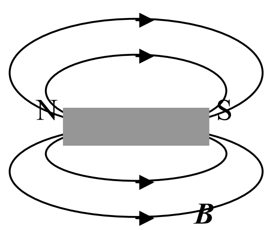
This area of study mainly concerns with the generation, transmission, distribution and use of electricity.

Magnetic fields

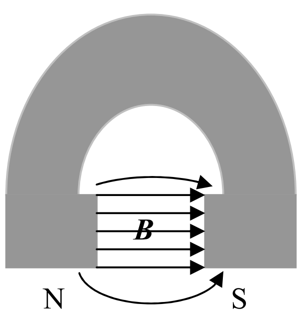
Magnetic field, **B**, in the region surrounding a magnet is a quantity used to describe the magnetic effect due to the presence of the magnet. It is a vector quantity.

To give a visual picture, lines (curves) are drawn on paper to represent the existence of a magnetic field. These lines are called **magnetic field lines**.

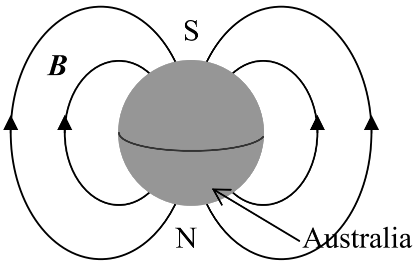
Example 1 *A bar magnet* When the bar magnet is suspended with a thread the end attracted towards the north pole of the earth is labelled as N (north). The other end is S (south).



Example 2 *A horse-shoe magnet*



Example 3 *The earth*

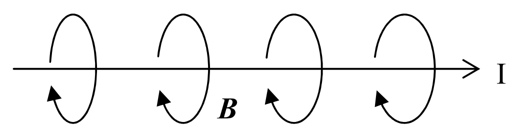


By convention, magnetic field lines always point away from N, the **north magnetic pole,** towards S, the **south magnetic pole**. The north magnetic pole (sometimes called the north seeking pole) of a compass points in the same direction as the magnetic field lines. A stronger magnetic field is indicated by closer magnetic field lines. The lines do not cross each other because the magnetic field cannot be pointing in more than one direction at any location.

Electromagnetism

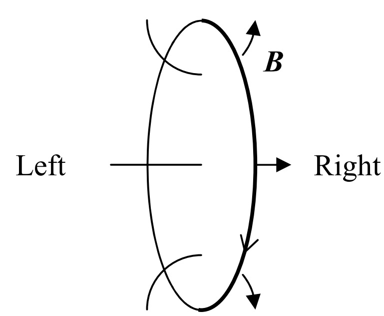
A device that uses electric current to generate magnetic field is called an **electromagnet**. The examples in the previous section are called **permanent magnets**.

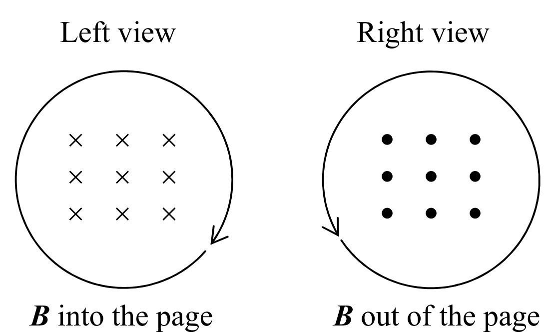
Magnetic field of a current-carrying wire



The direction of the magnetic field can be determined by the **right-hand-grip rule**.

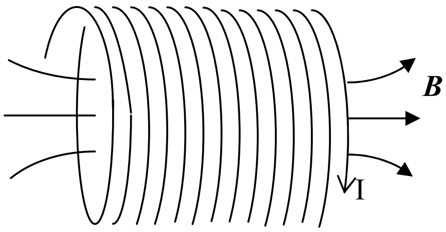
Magnetic field of a current-carrying loop





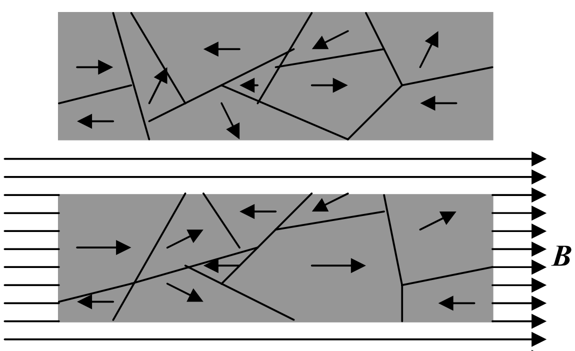
Magnetic field of a solenoid

A solenoid is a continuous coil of insulated wire with the radius of the coil much less than the length.



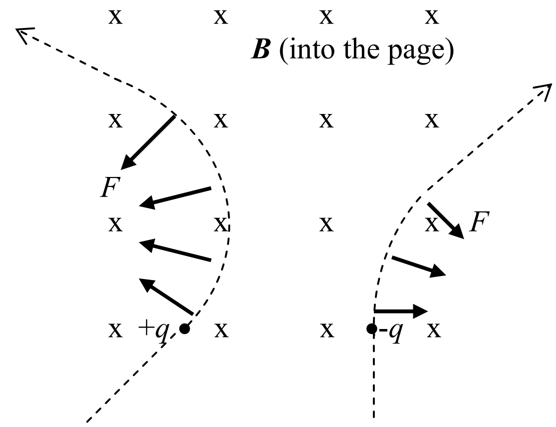
The magnetic field inside the solenoid is uniform.

A piece of iron is normally unmagnetised and made up of **domains** (regions that behave like tiny magnets) that are randomly arranged. When it is placed in a magnetic field those domains whose magnetic orientation is parallel to the external magnetic field grow larger at the expense of the others, and the piece of iron becomes magnetised. By placing a soft iron rod inside a solenoid its magnetic field can be greatly enhanced.



Example 1 Explain how a magnet can pick up unmagnetised iron nails and paper clips.

Magnetic force on a moving charge in a magnetic field



Use the **right-hand slap rule** to determine the direction of the magnetic force on the moving positive charge in the magnetic field. The magnetic force is always perpendicular to both the magnetic field and the direction of motion of the charge. If the positive charge is replaced by a negative charge, the force is in the opposite direction.

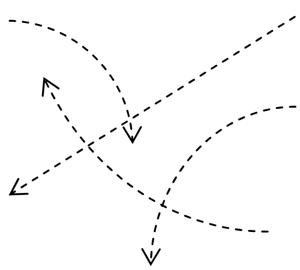
Example 1 The $\alpha, \beta, and, \gamma$ radiations emitted from a radioactive substance can be separated by means of a magnetic field across the path of the radiations.

Example 2 Charged cosmic ray particles (e.g. electrons) from outside the earth tend to strike the earth more frequently near the poles than at other places. Explain.

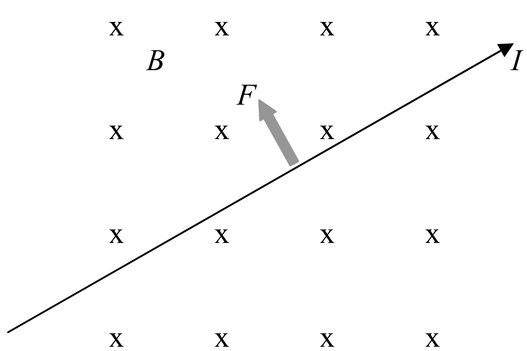
Example 3 Bringing a magnet close to a television screen will distort the picture. Why?

Example 4 An aeroplane is flying west in level flight near the south pole, where the earth's magnetic field is directed close to upward and in a northerly direction. As a result of the magnetic force on the free electrons in its wings, which wingtip will have more electrons than the other? Which wingtip will have more electrons if the plane is flying east?

Example 5 Four particles follow the paths shown below as they pass through a magnetic field which is directed into the page. Label each particle as positive, negative or neutral.



Magnetic force on a current-carrying wire placed in a magnetic field



Again the direction of the magnetic force on the wire can be determined by using the right-hand slap rule. The magnetic force is always perpendicular to both the magnetic field and the current.

The magnetic force F is directly proportional to the magnetic field B, the length L (in m) of the section of the wire inside B and the electric current I (in amperes, A) in the wire.

$$F \propto B$$
$$F \propto I$$
$$F \propto L$$
$$\therefore F \propto BIL$$

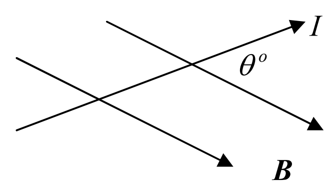
The force is at its maximum when the wire is perpendicular to B and is given by

$$F = BIL$$

If the wire is at an angle θ^o other than 90^o with the magnetic field B, the magnetic force on the wire is

$$F = BIL\sin\theta^o .$$

The angle θ^o is defined as shown below.



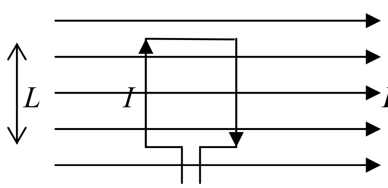
When the wire is parallel to B,
i.e. $\theta^o = 0^o \, or \, \theta^o = 180^o$, $F = 0$.

Example 1 Determine the direction of the magnetic force between two parallel wires carrying electric current in (a) the same direction and (b) opposite directions.

Example 2 A horizontal conductor in a power line carries a current of 5000A from east to west. The earth's magnetic field has a magnitude of 40.0 μT horizontally and is directed toward the north. Find the magnitude and direction of the magnetic force on 100m of the conductor due to the earth's magnetic field.

Magnetic force on a current-carrying loop in a magnetic field

To simplify the situation, consider a rectangular loop placed in a magnetic field.

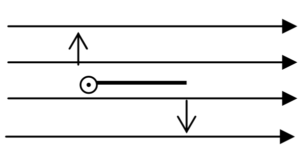


The force on the upper and the lower sides of the loop is zero. The force on the left side is $F = BIL$ into the page, while the force on the right side is $F = BIL$ out of the page. These two forces form a **force couple** and has a turning effect (**torque**) on the loop.

In translational motion, a force changes the velocity of an object. In rotation, a torque changes the **angular** (rotation) speed of an object.

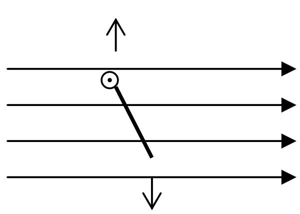
Now look at the top view of the loop in the magnetic field at different stages of its rotation.

1)



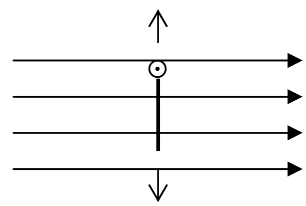
The force couple exerts a clockwise torque on the loop causing it to speed up the rotation.

2)



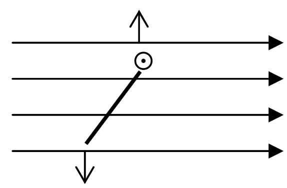
The two forces remain the same but the separation of the two forces is reduced resulting in a smaller clockwise torque. A smaller torque gives rise to a smaller rate of increase in the speed of rotation.

3)



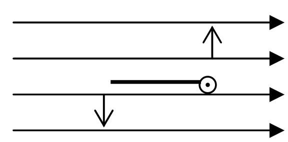
The two forces are still the same but at this stage, the torque is zero. However, the loop continues with its clockwise motion because of its angular momentum.

4)



Now the force couple exerts an anticlockwise torque on the loop causing it to slow down its clockwise rotation.

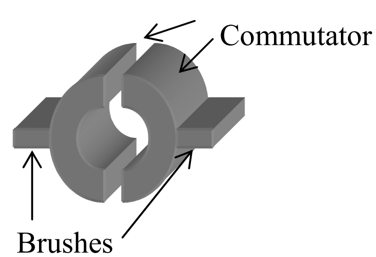
5)



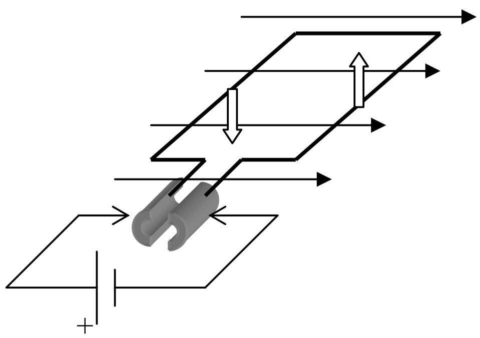
The anticlockwise torque causes the loop to come to a stop momentarily at this position and reverse its rotation, and the whole process repeats itself in the reverse direction.

Instead of reversing its rotation, the loop can maintain its clockwise motion if the electric current is switched around when the loop reaches and passes the position shown in 3), resulting in a reversal of direction of the two forces. Now the torque is in the clockwise direction and the loop continues its rotation.

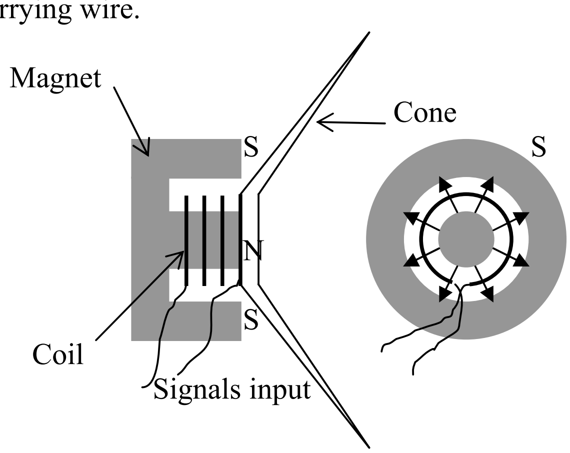
The simple device that is used to switch the current around is called a **split-ring commutator**.



A loop with a commutator placed in a magnetic field forms a simple **DC motor**.



Example 1 A loudspeaker also works on the principle that a magnet exerts a force on a current-carrying wire.



Example 2 In analog voltmeters and ammeters, the reading is displayed by means of the deflection of a pointer over a scale. They work by measuring the turning effect exerted by a magnetic field on a current loop. The figure below shows the basic **galvanometer**, on which both analog ammeters and voltmeters are based. Because of the arrangement, the net magnetic field through the coil is perpendicular to the sides of the loop and the force on each side is BIL newtons.

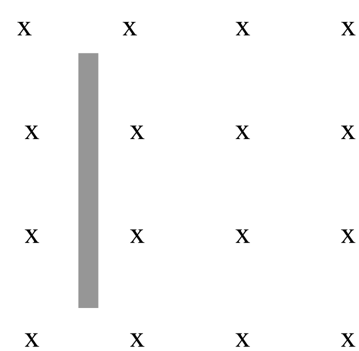
Example 3 In example 2, the coil is 2.1cm long and 1.2cm wide. It has 250 turns and the magnetic field is 0.23 T. If a current of 100 μA, calculate the force on each side of the loop.

Electromagnetic induction

The generation of electricity by means of magnetism is known as **electromagnetic induction**.

The current generated is called **induced current** and the voltage **induced emf**, ξ.

A simple generator of electricity

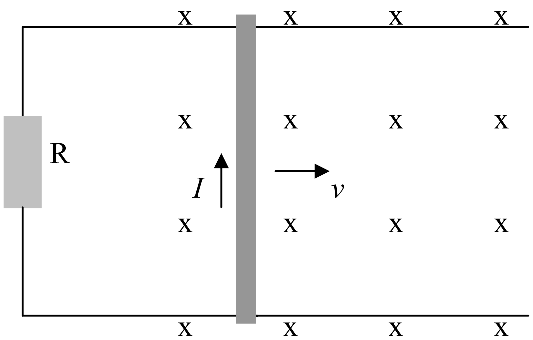


The conductor is pushed to move across the magnetic field. It carries the charges within to move in the same direction. When charges move in a magnetic field, they experience a magnetic force. For the electrons, some are forced to one end of the conductor. Thus one end will have more electrons than protons and become negatively charged. The other end will have less electrons than protons and become positively charged. This separation of positive and negative charges establishes an electrical potential (induced emf, ξ).

While the conductor is pushed, a (conventional) current flows in it and the conductor experiences a magnetic force opposite to the push. The current drops to zero when the desired induced emf is reached. At this point, the magnetic force becomes zero and the conductor continues its motion without being pushed.

This demonstrates the concept of **work** and energy. The electrical potential energy stored in the conductor is coming from the work done by the force in pushing the conductor.

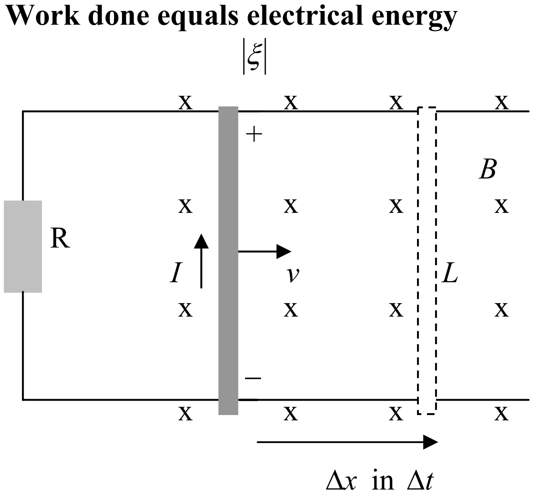
Using the electrical potential energy



An external circuit of resistance R is connected to the conductor by two conducting rails on which the conductor slides along. A current I flows and a magnetic force opposes the motion. The conductor slows down to a stop when the generated electrical potential energy is expended.

To keep the current flowing and more electrical energy dissipating in the external circuit, more work must be done by the applied force to overcome the opposing magnetic force (resulting in zero net force) in order to maintain the motion of the conductor.

Work done equals electrical energy



Electrical energy dissipated in R = Work done by the applied force.

$|\xi| I\Delta t = BIL\Delta x \quad \therefore \; |\xi|\Delta t = BL\Delta x$

Hence $|\xi| = \dfrac{BL\Delta x}{\Delta t}$ (a) i.e. $|\xi| = BLv$ (b)

Equation (b) shows that emf ξ is directly proportional to the strength of magnetic field B, the length of the conductor (inside the magnetic field) L and the speed v of the conductor.

Equation (a) suggests that there are other ways to induce emf besides the method just discussed.

In equation (a) $L\Delta x$ represents the change in area ΔA where the magnetic field passes through, and $B\Delta A$ represents the **change in magnetic flux** $\Delta\Phi$,

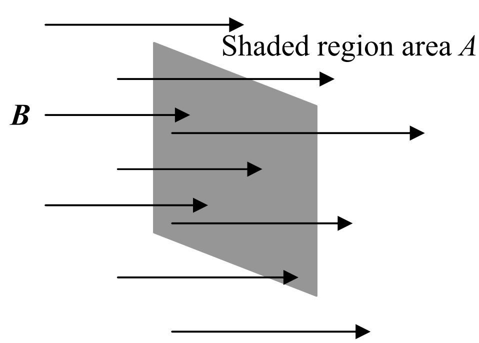
$$\therefore |\xi| = \frac{\Delta\Phi}{\Delta t}.$$

In fact, $\xi_{av} = -\dfrac{\Delta\Phi}{\Delta t}$ and $\xi_{av} = -n\dfrac{\Delta\Phi}{\Delta t}$ if there are n turns of wire. (Note: $\xi = -n\dfrac{d\Phi}{dt}$).

Magnetic flux Φ

Magnetic field ***B*** is often called **magnetic flux density**, i.e. magnetic flux per unit area. Magnetic flux Φ can be pictured as the number of magnetic field lines passing perpendicularly through a region of area A.

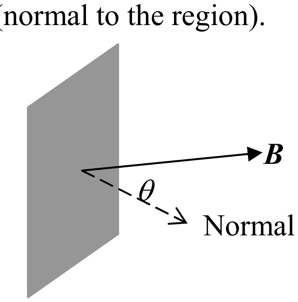
$$B = \frac{\Phi}{A}, \text{ or } \Phi = BA.$$



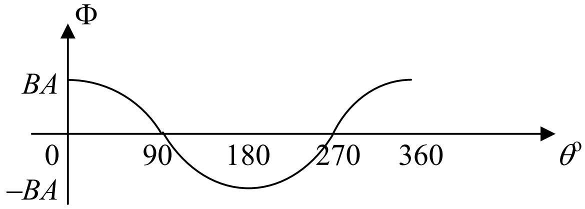
If ***B*** is not perpendicular to the region, then the magnetic flux is

$$\Phi = BA\cos\theta$$

where θ is the angle between ***B*** and the direction that the region facing (normal to the region).



As θ increases from 0^o, Φ decreases. Φ is maximum ($= BA$) when $\theta = 0^o$, $\Phi = 0$ when $\theta = 90^o$.



Magnetic field is measured in tesla (T), magnetic flux is in weber (wb) and area in m^2.

$$1 \text{ T} = 1 \text{ wbm}^{-2}$$

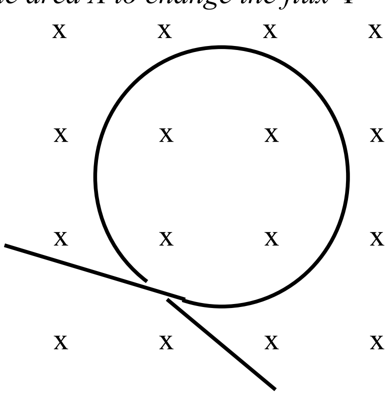
At the surface of the earth $B \approx 10^{-4}$ T.

Example 1 A circular loop (radius = 10 cm) of copper wire is placed inside a uniform magnetic field of 0.10T. Calculate the magnetic flux enclosed by the loop if the magnetic field is (a) perpendicular, (b) parallel, to the plane of the loop.

Ways to change the magnetic flux Φ

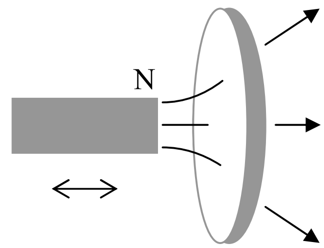
According to $\Phi = BA\cos\theta$ magnetic flux can be changed by changing B, A or θ.

Change the area A to change the flux Φ
e.g.



Pulling or pushing the two ends decreases or increases the area enclosed by the loop.

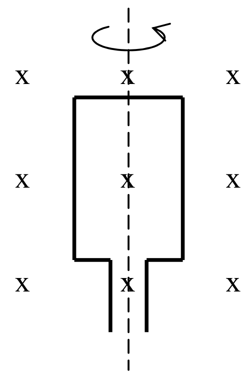
Change the magnetic field to change the flux Φ
e.g.



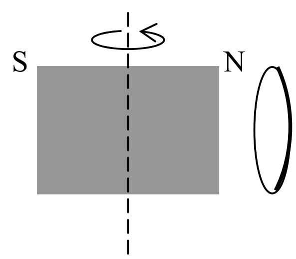
Moving the magnet closer to (or away from) the loop increases (or decreases) the magnetic field through the loop.

Change the angle θ *to change the flux* Φ
This is done by either rotating a loop in a magnetic field or rotating a magnet near a loop.

e.g.

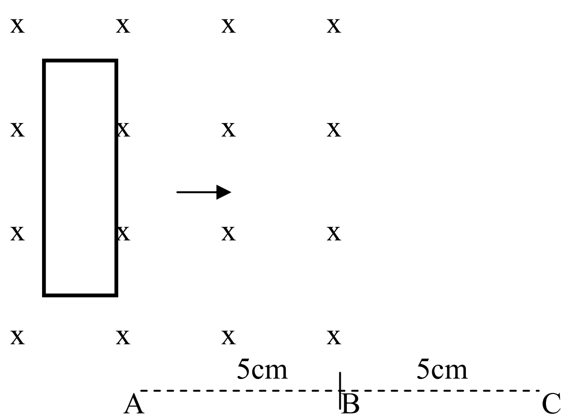


or



Example 1 A 250 turns rectangular coil makes a 90^0 rotation from a position of zero flux in 0.25s. The coil has dimensions 8cm by 6cm and it is placed in a uniform magnetic field of 100μT. Find the magnitude of the average induced emf during the interval.

Example 2 A 8cm by 2cm rectangular loop is pulled out of a magnetic field of 100μT at a constant velocity of $1.0ms^{-1}$.



Draw a graph showing the magnetic flux as a function of time from A to C. The loop is at A in the above diagram at t = 0.

Draw a graph of the induced emf as a function of time.

The loop has a resistance of 0.5Ω. Draw a graph showing the magnitude of the induced current in the loop as a function of time.

Draw a graph of power vs time.

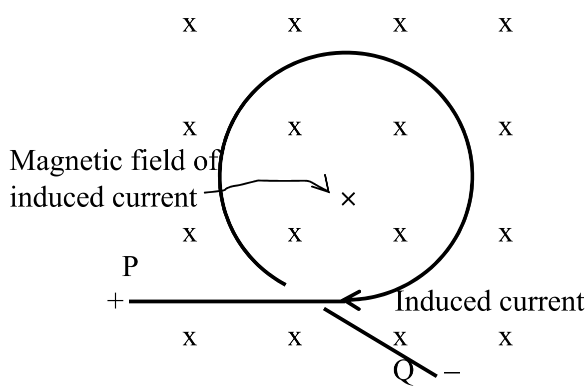
How much electrical energy is changed to heat?

Direction of induced current and polarity of the output terminals of a generator–Lenz's law

An induced current in a closed conducting loop will flow in such a direction that it *opposes* (the negative sign in $\xi_{av} = -\frac{\Delta\Phi}{\Delta t}$) the change in magnetic flux that produces it. This is known as **Lenz's law** and it is used to determine the direction of the induced current in a closed conducting loop if there is a change in magnetic flux.

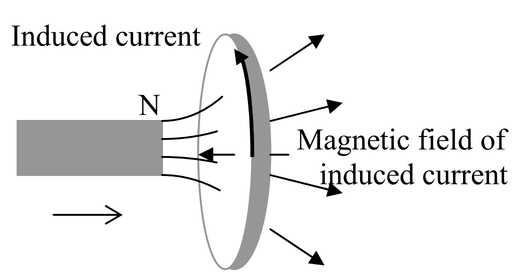
For an open loop, use Lenz's law to find the direction of the induced current and then determine the polarity of the terminals of the loop.

Example 1 A loop with enclosed area changing in a constant magnetic field.
e.g. decreasing area



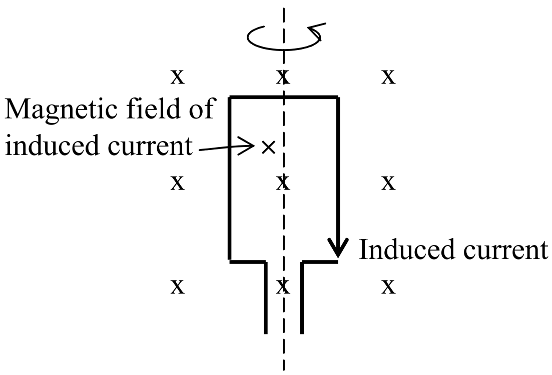
When the enclosed area decreases the magnetic flux through the loop into the page decreases. According to Lenz's law, the induced current generates magnetic field (hence flux) through the loop into the page to make up for (to *oppose*) the decrease in flux. To achieve this the induced current flows clockwise (i.e. electrons flow anticlockwise and accumulate at terminal Q making it negatively charged) making terminal P positively charged.

Example 2 A loop in a changing magnetic field.
e.g. moving the magnet towards the loop



Magnetic field increases as the magnet moves towards the loop resulting in more flux to the right through the loop. The induced current *opposes* the flux increase by generating magnetic field to the left inside the loop. To achieve this the induced current flows anticlockwise (view from the magnet side).

Example 3 A rotating loop in a uniform magnetic field.
e.g. loop rotates clockwise (view from below)

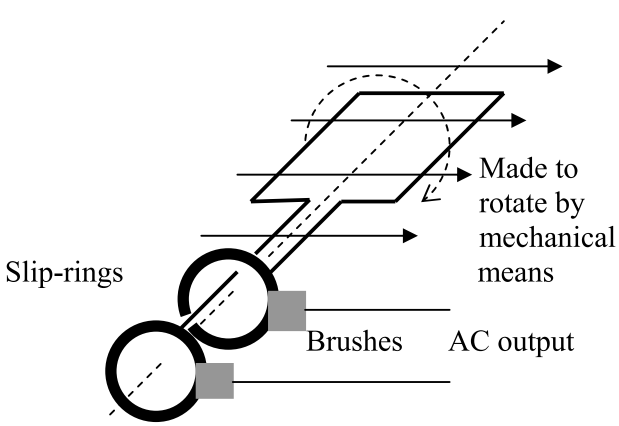


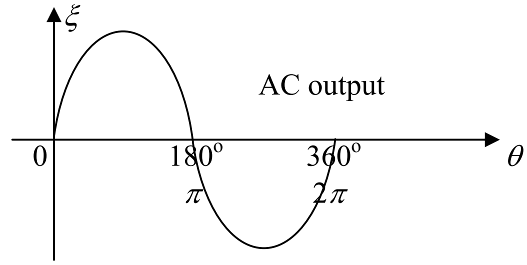
As the loop rotates from the orientation shown above the flux decreases because there are less magnetic field lines passing through the loop into the page. To *oppose* this the induced current flows clockwise (viewing the page) in order to generate more magnetic field into the page through the loop.

Slip-rings and split-ring commutators

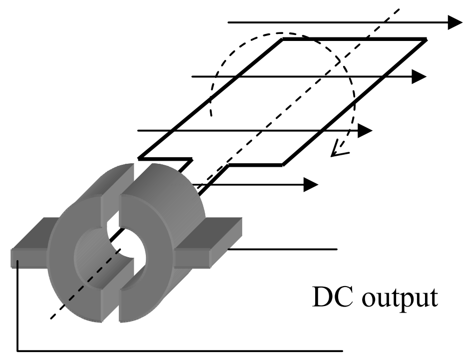
Alternating emf induced in a rotating conducting loop placed in a magnetic field is made accessible by means of **slip-rings**. Each ring is connected to one end of the loop and electrically connected by a metal brush to the rest of the electric circuit.

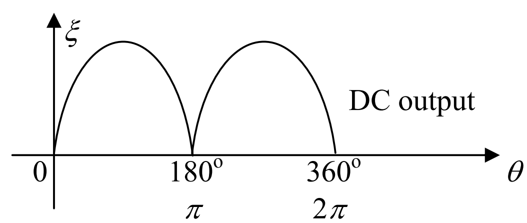
The loop, the magnetic field (either from a permanent magnet or an electromagnet), the slip-rings and the metal brushes form an **AC generator**.





If a set of split-ring commutators is employed instead of slip-rings, the device is a **DC generator**.



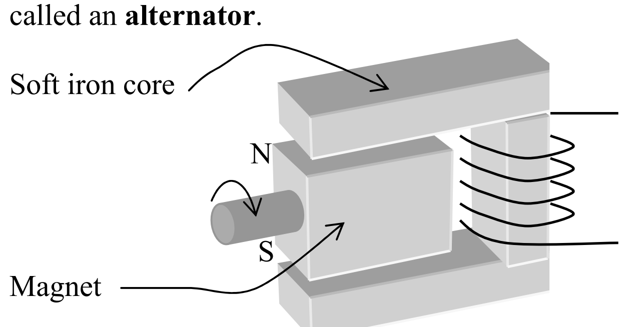


DC motors and DC generators

The DC generator above has the same construction as the DC motor discussed previously. They are in fact the same device. The device is a generator when mechanical energy is used to turn the loop and changed to electrical energy. It is a motor when electrical energy is used to rotate the loop and becomes mechanical (kinetic) energy.

Alternators

Alternating emf can also be induced by rotating a permanent magnet or electromagnet close to a fixed coil. External circuit is connected to the terminals of the coil, and no slip rings are required. This device is called an **alternator**.

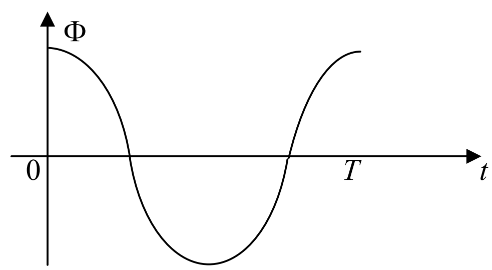


Sinusoidal AC voltages

When a loop of area A rotates uniformly in a constant magnetic field B, the resulting emf is a sinusoidal voltage.

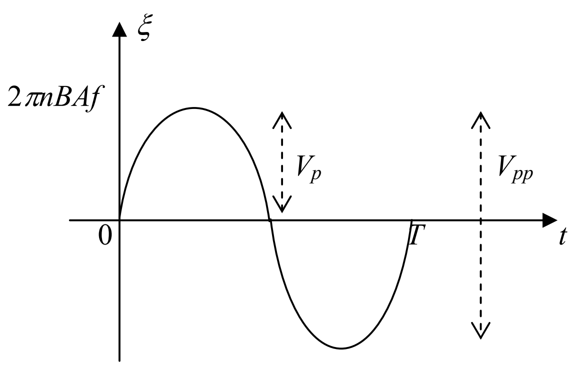
Uniform rotation means that the loop rotates at constant angular speed (radians per second) $\omega = 2\pi f$, where f is the frequency of rotation (number of revolutions per second) and $f = \frac{1}{T}$, T is the period of rotation.

$\therefore \theta = \omega t$ and $\Phi = BA\cos\omega t$.



Note: $T = \frac{2\pi}{\omega}$ and $f = \frac{\omega}{2\pi}$.

Since $\xi = -n\frac{d\Phi}{dt}$, therefore $\xi = nBA\omega\sin\omega t$ or $\xi = 2\pi nBAf\sin 2\pi ft$.



The amplitude of the sinusoidal voltage is called the peak voltage V_p,

$$V_p = 2\pi nBAf .$$

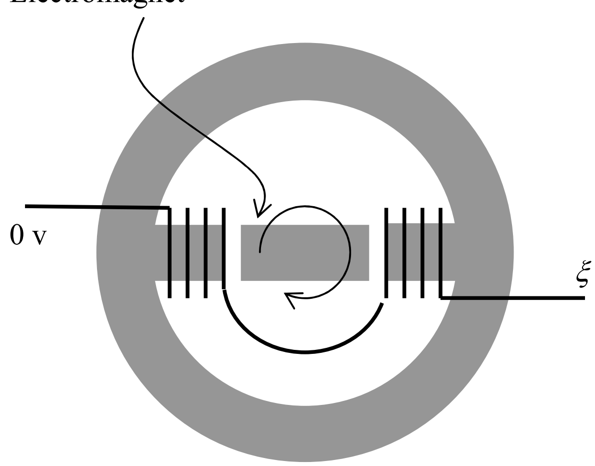
The peak voltage is directly proportional to the number n of loops in the coil, the magnetic field strength B, the size (area A) of each loop and the frequency f of rotation.

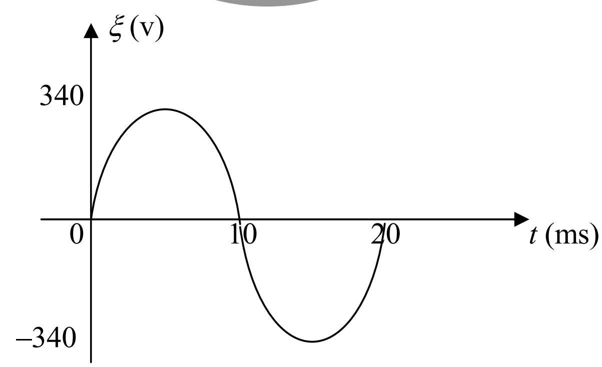
V_{pp} is called the peak-to-peak voltage.

Example 1 What are the effects of doubling the frequency of rotation of the coil on the induced emf?

AC power supply

The power delivered to homes are generated by rotating an electromagnet between two connected coils at f = 50Hz $\left(\therefore T = \frac{1}{f} = 0.02s = 20ms\right)$.





$V_p \approx$ 340v, $V_{pp} \approx$ 680v.

Example 1 In a power station, does the generator stop turning, slow down its rotation or keep on turning at the same frequency when there is no one using electricity?

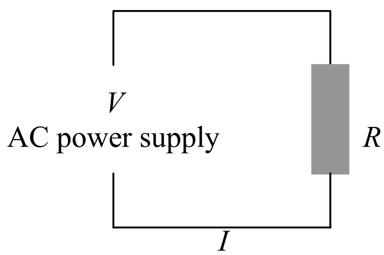
rms voltage and rms current

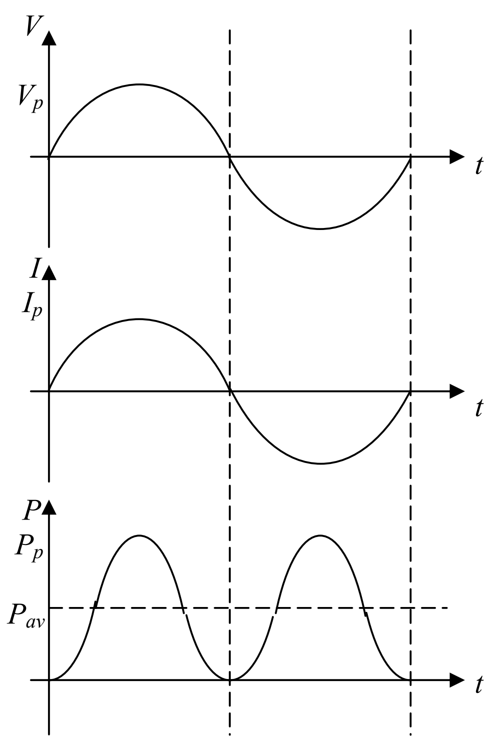
The two quantities, rms voltage V_{rms} and rms current I_{rms} are introduced to simplify the calculation of the average power P_{av} of an AC power supply.

$$P_{av} = V_{rms} I_{rms}$$

where $V_{rms} = \frac{V_p}{\sqrt{2}}$ and $I_{rms} = \frac{I_p}{\sqrt{2}}$ by definition.

Example 1 Explain why $P_{av} = V_{rms} I_{rms}$.





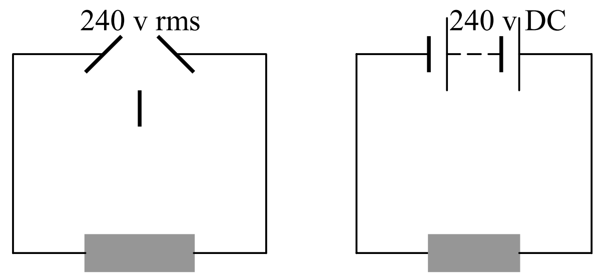
The area under the P vs t graph represents energy, and it is the same as $P_{av} \times t$.

Mathematically, $P_{av} = \frac{1}{2} P_p = \frac{1}{2} V_p I_p = \frac{V_p}{\sqrt{2}} \times \frac{I_p}{\sqrt{2}}$.

Therefore $P_{av} = V_{rms} I_{rms} = \frac{V_{rms}^2}{R} = I_{rms}^2 R$.

For our AC power supply, $V_{rms} = \frac{340}{\sqrt{2}} = 240$ v, and it is equal to the power supply of 240v DC.

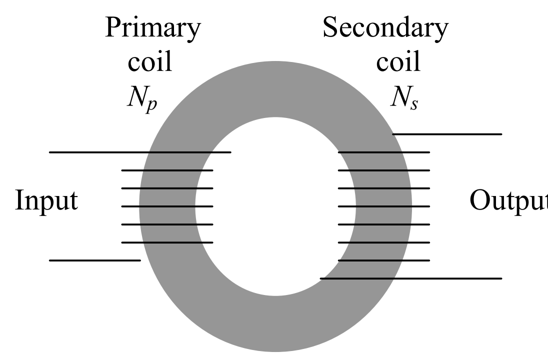
The following diagrams show the same electric heater connected to the two power supplies. The same amount of heat energy is generated if the heater is on for the same length of time.



Transformers

A **transformer** is an electrical device which changes the voltage of a power supply without changing the amount of power (*VI*) to be delivered.

A simple transformer consists of two coils of insulated wire, with different numbers of turns, wound around a doughnut shape soft iron core.



The primary (input) winding, of N_p turns, is connected to an alternating emf generator. The secondary (output) winding, of N_s turns, is connected to a load resistance *R*.

How does a transformer work?

The alternating current at the primary winding gives rise to an alternating magnetic field inside the soft iron core. The secondary winding is linked to the primary through the core, a changing magnetic field in the core results in a changing magnetic flux in the secondary winding. According to **Faraday's law of electromagnetic induction**, $\xi = -n\frac{d\Phi}{dt}$, an emf is induced in the secondary winding.

If the voltage at the primary winding is constant, there is zero induced emf (i.e. 0 v) at the secondary winding.

Step-up and step-down transformers

In a **step-up transformer**, $N_s > N_p$ and output voltage is higher than input voltage. In a **step-down transformer**, $N_s < N_p$ and the output is lower.

For a transformer, $\frac{V_s}{V_p} = \frac{N_s}{N_p}$. This is known as the **transformer equation**.

For an ideal transformer (i.e. 100% efficiency), there is no power loss within the transformer and therefore, the output power equals the input power.

$$P_s = P_p$$
$$V_s I_s = V_p I_p .$$

Therefore, $$\frac{I_s}{I_p} = \frac{V_p}{V_s} = \frac{N_p}{N_s} .$$

A real transformer is typically 99% efficient, i.e.

$$P_s = 0.99 P_p .$$

In the above equations, V_s, V_p, I_s and I_p can be all rms values or all peak values.

Example 1 A transformer for a radio reduces 240v to 9.0v. The secondary contains 30turns and the radio draws 400mA. Calculate (a) the number of turns in the primary, (b) the current in the primary and (c) the power transformed.

Transmission of electric power and power loss in the transmission lines

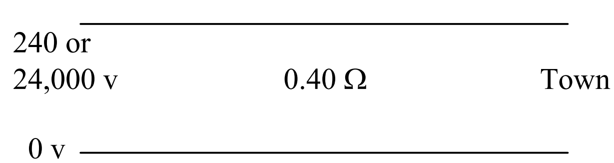
Power stations are often situated some distance from metropolitan areas and thus electricity is transmitted over long distances in the transmission lines. Transmission lines are made of very good conductors but they do have resistance. Heat will be generated and dissipated in the air. Amount of heat dissipated in unit time is known as **power loss**, P_{loss} , and is measured in Js^{-1} or w.

If there is a current *I* (amperes, A) and the total resistance of the transmission lines is *R* (ohms, Ω),

$$P_{loss} = I^2 R .$$

Since $P_{loss} \propto I^2$, the size of the current have a large effect on the power loss in the transmission lines. For example, if the current is ten times, the power loss is 100 times. If the current is reduced to one tenth, the power loss becomes one hundredth.

Example 1 An average of 120 kw of electric power is supplied to a country town from a power station 10km away. The transmission lines have a total resistance of 0.40 Ω. Calculate the power loss if the power is transmitted at (a) 240 v and (b) 24,000 v.

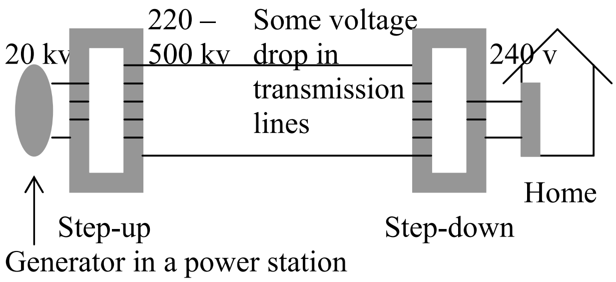


The above example shows that power loss can be minimised if the power is transmitted at high voltage input. The higher the voltage, the smaller the current for the same power input and lower power wasted as heat in the transmission lines. It is for this reason that power is usually transmitted at very high voltages, about 500kv.

A major reason alternating current (AC) is in nearly universal use, is that the voltage can easily be stepped up or down by a transformer.

The output voltage of the generator in the power station is stepped up before transmission. Upon arrival in a city, it is stepped down in stages at electric substations prior to distribution.

The following diagram shows an oversimplifying transmission circuit.



Voltage drops

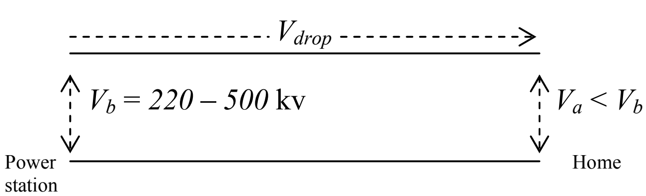
The voltage at the input end of the transmission lines is always higher than the voltage at the other end because of the power loss. The difference in voltages is the voltage drop. Voltage drop is given by

$V_{drop} = V_b - V_a$, where V_b and V_a are

voltages before and after transmission respectively,

or $V_{drop} = IR$ where I is the current in the

transmission lines and R the total resistance of the transmission lines.



Since $V_{drop} \propto I$, higher consumption of electric power in homes, offices and factories will result in larger current in the transmission lines and hence a lower voltage supply (slightly lower than 240 v) during peak periods.

Example 1 Refer to the previous example, calculate the voltage drop and the voltage at the receiving end in each case.

Example 2 The following diagram represents a load curve which shows the demand for electricity in Victoria over a 24-hour period in Winter.

(a) Estimate the electric energy consumption over the 24-hour period in Mwh and in MJ.

(b) At what time is the current in the transmission lines the highest? the lowest?

(c) At what time is the voltage at the power point the highest? the lowest?