- ***Candidates should be able to*** :
  - ***Define magnetic flux.***
  - ***Define the weber (Wb).***
  - ***Select*** *and* ***use*** *the equation for magnetic flux :*

    $\Phi = BA\cos\theta$

  - ***State*** *and* ***use Faraday's law of electromagnetic induction.***
  - ***State*** *and* ***use Lenz's law.***
  - ***Select*** *and* ***use*** *the equation :*

    Induced e.m.f. = -rate of change of magnetic flux linkage

  - ***Describe*** *the function of a* ***simple ac generator.***
  - ***Describe*** *the function of a* ***simple transformer.***
  - ***Select*** *and* ***use*** *the* ***turns-ratio equation for a transformer.***
  - ***Describe*** *the function of* ***step-up*** *and* ***step-down*** *transformers.*

MAGNETIC FLUX (Φ)

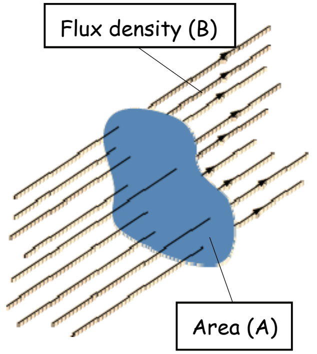
- *As we have already stated, a magnetic field is a region around a magnet in which magnetic forces are exerted. It was once thought that there must be something* ***'flowing'*** *from N-pole to S-pole through this magnetic field region.*
- *The flowing quantity was given the name,* ***MAGNETIC FLUX*** *and although it does not exist, the concept is very useful when describing magnetic fields.*

  The strength of a magnetic field can be visualised as ***the amount of flux passing through unit cross-sectional area*** *(i.e. a measure of the concentration of flux).*

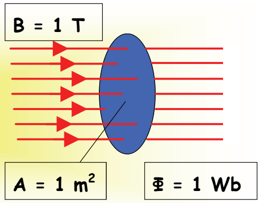
- *If a uniform magnetic field of* ***strength (B)*** *acts perpendicular to an* ***area (A)***, *the* ***MAGNETIC FLUX (Φ)*** *passing through the area is given by :*

$$\Phi = BA$$

(Wb) (T) (m^2)



1 WEBER (Wb) is the amount of magnetic flux flowing **perpendicularly** through an area of **1 m^2** in a magnetic field of flux density **1 T**.

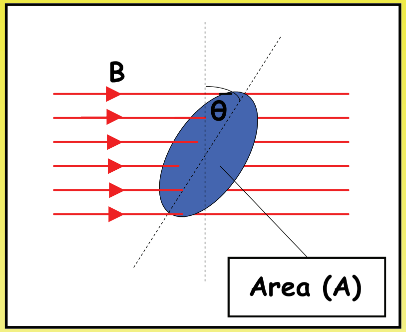


Since ***B = Φ/A, magnetic field strength*** *can be re-defined as* ***MAGNETIC FLUX DENSITY.***

MAGNETIC FLUX DENSITY (B) at a point in a magnetic field is the magnetic flux (Φ) perpendicular to unit area (A).

- *If the area **(A)** has turned through an angle **(θ)** from its original position, less magnetic flux now passes through it and the **magnetic flux (Φ)** is given by :*

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



- *When area **(A)** is **perpendicular** to the flux :*
  θ = 0°, and cos θ = cos 0° = 1

  So : $\Phi = BA$

- *When area **(A)** is **parallel** to the flux :*
  θ = 90°, and cos θ = cos 90° = 0

  So : $\Phi = 0$

MAGNETIC FLUX LINKAGE

- *The coils used in motors and generators have many turns of wire, so we need to know the amount of flux which **passes through** and so **'links with'** all the turns.*

*Consider a coil of **(N) turns** and **area (A)** which is perpendicular to a uniform magnetic field of **flux density (B)**.*

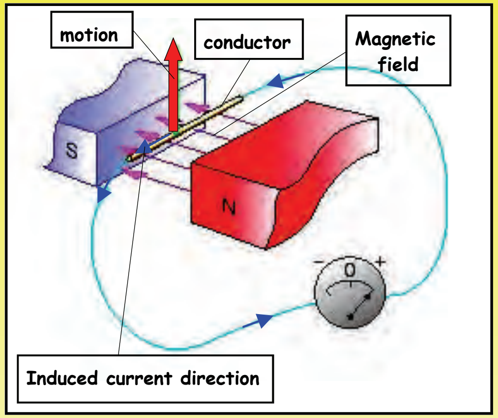
*The magnetic flux which links with the coil is called the **MAGNETIC FLUX LINKAGE (NΦ)** and is given by :*

$$N\Phi = BAN$$

(Wb) (T) (m^2)

ELECTROMAGNETIC INDUCTION - EXPERIMENTAL PHENOMENA

STATIONARY FIELD MOVING CONDUCTOR



- *A voltage is induced in a conductor when it is moved through a magnetic field.*
  The same effect can also be produced by holding the wire stationary and moving the magnet.

  The induced voltage will produce an induced current if the conductor is part of a complete circuit.

The **size of the induced voltage or current** is **increased** by increasing :

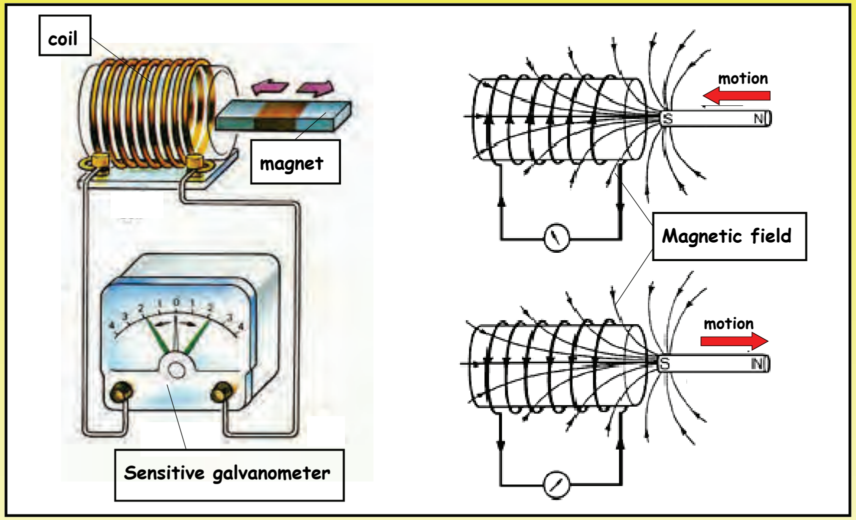
- The **magnetic field strength (B)**.
- The **speed (v)** of motion of the conductor.
- The **length (L)** of the conductor in the magnetic field.

The **direction** of the induced voltage or current is **reversed** by reversing :

- The **direction of motion** of the conductor.
- The **direction of the magnetic field**.

No voltage or current is induced if the wire is **held stationary** within the magnetic field (i.e. **no motion - no induced current**).

STATIONARY CONDUCTOR MOVING FIELD



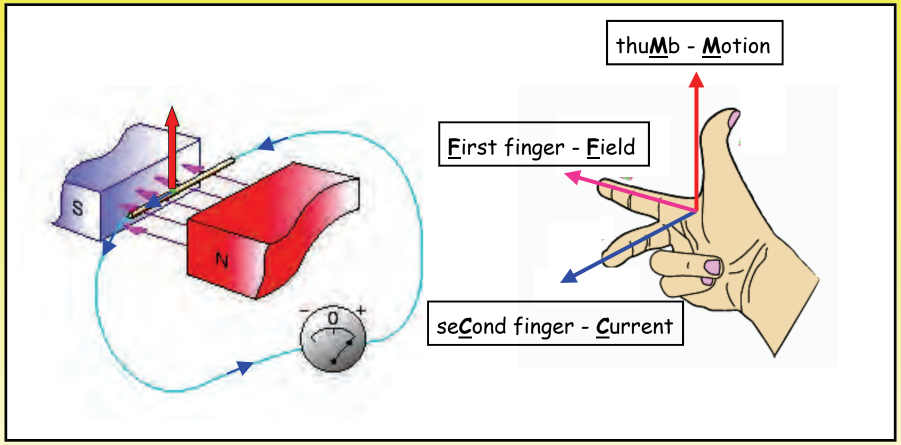
- *Moving a magnet into or out of a coil causes a current to be induced in the coil. The diagrams above show that when the magnet's S-pole is plunged into the coil, the galvanometer deflects one way and when the S-pole is pulled out of the coil, the deflection is reversed.*
  *The **faster** the magnet is moved, the **greater** is the deflection and there is **no deflection** when the magnet is held **stationary** inside the coil. The deflection is also **increased** by using a coil with a **greater** number of turns of wire.*

A **voltage (and current)** is induced in the coil whenever there is **relative motion** between the magnet and the coil. This is because the motion causes a change in the amount of **magnetic flux linking with the coil**.

The **direction** of the induced voltage and current depends on the **magnet pole being moved** and its **direction of motion**.

The **size of the induced voltage and current** is increased by increasing :
- The **speed of motion** of the magnet.
- The **number of turns** of the coil.

FLEMING'S RIGHT-HAND RULE



- *The **direction of the induced current** can be predicted using **FLEMING'S RIGHT-HAND RULE** as illustrated in the diagrams above.*

The thumb, first and second fingers of the right hand are held at **right angles** to each other. If the thuMb indicates the direction of **MOTION** of the conductor and the First finger the magnetic **FIELD** direction, then the seCond finger gives the induced **CURRENT** direction.

- **PRACTICE QUESTIONS (1)**

1 In the British Isles, the vertical component of the Earth's magnetic field has a flux density of **5.0×10^{-5} T**.

Calculate the **magnetic Flux (Φ)** which passes through the British Isles if its area is **2.9×10^{11} m^2**.

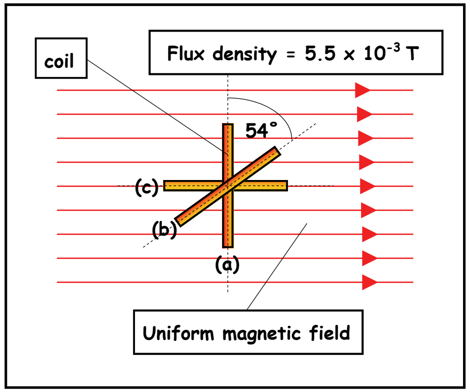
2 A bar magnet produces a magnetic flux density of **2.0×10^{-2} T** at the surface of each of its poles. How much **magnetic flux** passes through each pole if their dimensions are **0.8 cm x 1.4 cm?**

3 A cylindrical coil of **560** turns of wire has a diameter of **8.0 cm**. Calculate the **magnetic flux linkage** when the coil is placed with its end at **right angles** to a uniform magnetic field of flux density **1.6×10^{-4} T**.

4 A coil of **170** turns and area **0.12 m^2** is placed at **90°** to a uniform magnetic field whose flux density increases from **0.05 T** to **1.30 T**. Calculate the **change** in **magnetic flux linkage** of the coil.

5 A rectangular coil of **600** turns has dimensions of **10 cm x 7 cm.**

It is initially positioned so as to be **perpendicular, position (a),** to a uniform magnetic Field of flux density **5.5×10^{-3} T,** as shown in the diagram.



It is then rotated, first to **position (b) at 54°** to its initial position and then to **position (c)** in which it is **parallel** to the field.

Calculate the **flux linkage** of the coil in each of the three positions.

LAWS OF ELECTROMAGNETIC INDUCTION

- *Electromagnetic induction occurs whenever there is relative motion between a conductor (or a set of conductors) and a magnetic field.*
- *The **magnitude** of the **induced voltage (or current)** depends on the rate at which magnetic flux is **'cut'** or **'linked'**.*

FARADAY'S LAW OF ELECTROMAGNETIC INDUCTION

The magnitude of the induced emf or voltage in a circuit is equal to the rate of change of magnetic flux linkage through the circuit.

$$\textbf{Induced emf, } E = N\frac{\Delta\Phi}{\Delta t}$$

(Wb) (V) (s)

Michael Faraday

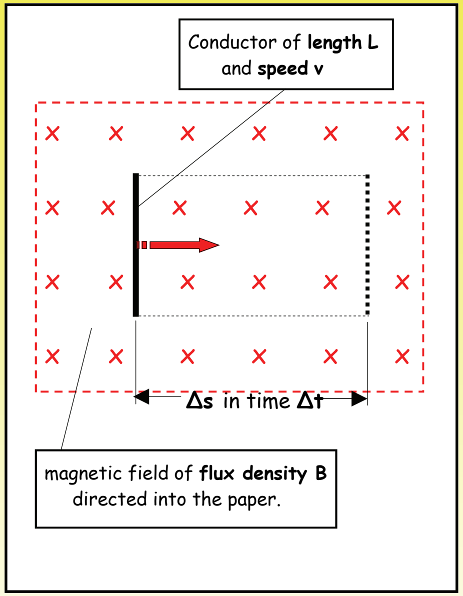
- N = number of turns of wire linking the magnetic flux.
- $N\,\Delta\Phi/\Delta t$ is the change of flux linkage per second.

INDUCED EMF = RATE OF CHANGE OF MAGNETIC FLUX LINKAGE

EXAMPLES OF THE USE OF FARADAY'S LAW

CONDUCTOR MOVING AT 90° TO A MAGNETIC FIELD

*Consider a conductor of **length (l)** moving at a **constant speed (v)** (such that it covers **distance Δs** in **time Δt**) at **90°** to a magnetic field of **flux density (B)**.*



$E = \Delta\Phi/\Delta t = \Delta(BA)/\Delta t$

$E = BL\Delta s/\Delta t =$ **BLv**

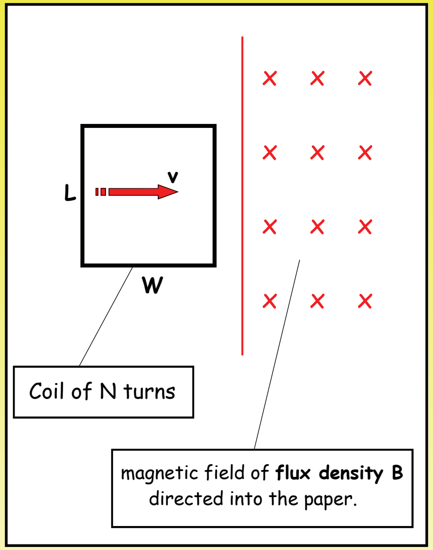
INDUCED EMF,

$$E = BLv$$

(V) (T) (m) ($m\ s^{-1}$)

RECTANGULAR COIL MOVING INTO A UNIFORM MAGNETIC FIELD

*Consider a rectangular coil of **(N)** turns, **length (L)** and **width (W)** moving into a uniform magneticfield of **flux density (B)** at **constant speed (v)**.*



Time for coil to completely enter the field = W/v

In this time, flux linkage NΦ increases from 0 to BNLW.

Induced emf, E = change of flux linkage per sec

$E = N\Delta\Phi/\Delta t$

$E = \dfrac{BNLW}{W/v} =$ **BlvN**

INDUCED EMF,

$$E = BLvN$$

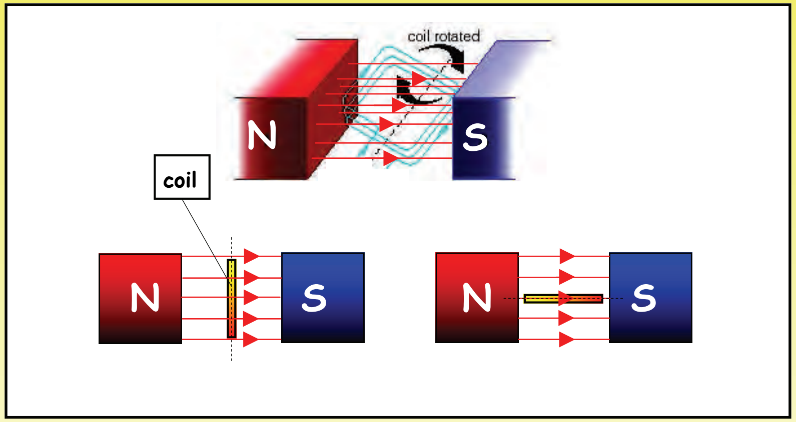
(V) (T) (m) ($m\ s^{-1}$)

- *Once the coil is completely inside the field, there is **no change in the flux linkage**, so the **induced emf = 0**.*

COIL ROTATING IN A UNIFORM MAGNETIC FIELD

Another way in which a change in magnetic flux linkage can be produced is by rotating a coil in a magnetic field.

The ***maximum flux linkage*** *occurs when the plane of the coil is* ***at right angles*** *to the field and when the plane of the coil is* ***parallel*** *to the field, the flux linkage is reduced to* ***zero.*** *This is illustrated in the diagram shown below.*



WORKED EXAMPLE

A circular coil of **20 turns** and radius **10 cm** is situated with its plane **perpendicular** to a magnetic field of flux density **0.50 T**. Calculate the **e.m.f. induced** in the coil if it is rotated through **90°** in a time of **50 ms**.

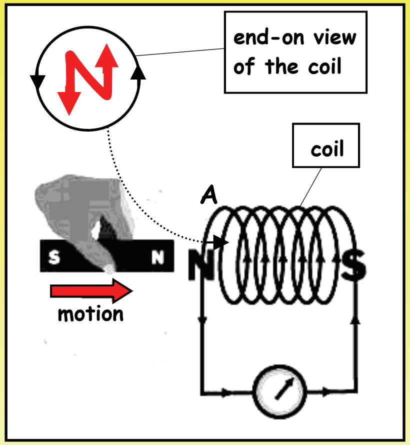
- Coil area, $A = \pi r^2 = \pi \times 0.10^2 = 0.0314\ m^2$.

- Magnetic flux linkage when coil is perpendicular to the field, $N\Phi = BAN = 0.50 \times 0.0314 \times 20 = 0.314$ Wb.
  Magnetic flux linkage when coil is parallel to the field, $N\Phi = 0$ Wb.
  So, change in magnetic flux linkage, $N\Delta\Phi = 0.314$ Wb.

- Induced e.m.f., $E = \dfrac{N\Delta\Phi}{\Delta t} = \dfrac{0.314}{50 \times 10^{-3}} =$ **6.28 V**

LENZ'S LAW

- *Consider the N-pole of a magnet being pushed into a coil as shown in the diagram opposite.*



The direction of the induced current in the coil is such that the magnetic field which it produces gives end ***A*** *of the coil a N-polarity. In this way* ***the induced current direction is such that it opposes the change that produces it*** *(The* ***N-pole*** *at end* ***A*** *of the coil* ***repels*** *the magnet's* ***N-pole****).*

So work has to be done in order to push the magnet into the coil against the repulsive force. The energy resulting from the work done is transferred to the electrical energy of the current.

NOTE

If the induced current were in the opposite direction, **end A** of the coil would have been a **S-pole** the magnet would then have been accelerated into the coil by the **attraction** force. This would mean an **increase** in the induced current, which would in turn mean a **bigger attraction force** and so on......

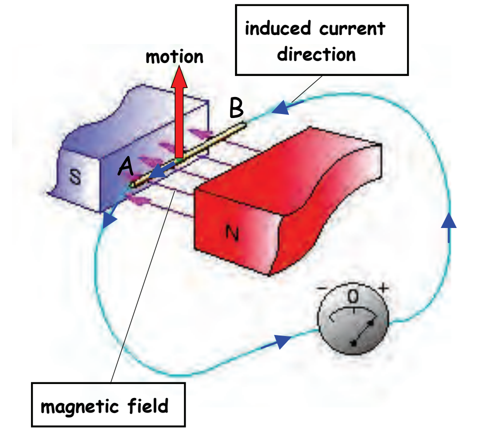
Therefore, even though no work was being done, the magnet would be continuously increasing its kinetic energy and the induced current would also carry on increasing. This contravenes **the Principle of Conservation of Energy** and it is therefore impossible.

- *If the magnet* ***N-pole*** *were* ***pulled out*** *of the coil instead of being pushed into it, the induced current direction would be such as to give a* ***S-polarity*** *at end* ***A****.*

Once again, the induced current direction is such that ***it opposes the change or motion that produces it.*** *Work has to be done against the* ***attraction*** *force in order to pull the magnet N-pole out of the coil.*

- *Consider a wire AB moved **upwards** through a horizontal magnetic field as shown opposite.*
  ***Fleming's right-hand rule** shows that the direction of the induced current is **B to A**.*

  A force acts on a current-carrying wire in a magnetic field.
  *Applying **Fleming's left-hand rule** in this case tells us that an **Downward** force acts on the wire.*



Therefore, work has to be done to move the wire upwards and so generate electricity.

NOTE

If the induced current direction were **A to B**, there would be a **upward** force on the wire and this would mean that we would be getting kinetic and electrical energy without doing any work. This contravenes the **Principle of Conservation of energy** and so cannot be correct.

LENZ'S LAW

The direction of the induced current is always such as to oppose the change which causes the current.

The mathematical statement of **Faraday's Law** incorporates **Lenz's Law** by the inclusion of a **minus sign** (which represents the fact that **the induced emf acts in such a direction as to oppose the change that causes it**).

$$E = -N\frac{\Delta\Phi}{\Delta t}$$

- **PRACTICE QUESTIONS (2)**

1 A square coil of **100 turns** of wire has sides of length **5 cm**. It is placed in a magnetic field of flux density **20 mT**, so that the flux is **perpendicular** to the plane of the coil.

(a) Calculate the **magnetic flux linkage** with the coil.

(b) The coil is now pulled out of the field in a time of **0.10 s**. Calculate the **average e.m.f.** induced in the coil.

2 A straight wire of length **0.20 m** moves at **right angles** to a magnetic field of flux density **0.15 T**, at a constant speed of **5.0 m s^{-1}**.

Calculate the **average e.m.f.** induced across the ends of the wire.

3 An aircraft having a wing span of **36 m** flies **horizontally** at a constant speed of **300 m s^{-1}**, in an area where the vertical component of the Earth's magnetic field is **5.0 x 10^{-5} T**.

Calculate the magnitude of the **e.m.f.** generated across the aircraft's wing tips.

4 A small wire coil of area **1.5 cm^2** and having **2000 turns** is placed between the poles of a powerful magnet.

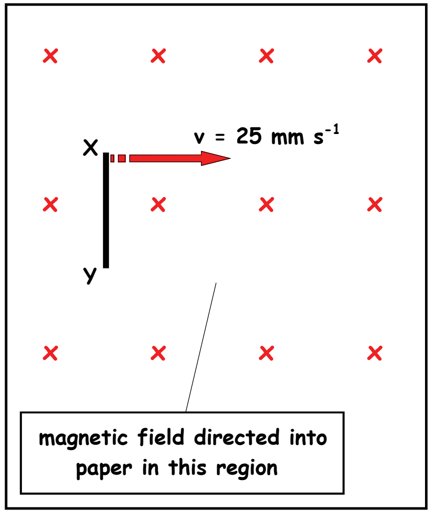
The ends of the coil are connected to a voltmeter. The coil is then pulled out of the magnetic field and the voltmeter records an average e.m.f. of **0.44 V** over a time interval of **0.25 s**.

Calculate the **flux density** between the magnet poles.

5 (a) A straight metal rod **XY** of length **0.15 m** moves through a uniform magnetic field with a velocity of **25 mm s^{-1}**.
When the rod was moving at **right angles** to the field, the induced e.m.f. was found to be **0.85 mV**. Calculate :

(i) The **flux** Cut by the rod in **5.0 s**.

(ii) The **magnetic flux density.**



(b) In (a), the field direction was **vertically downwards** and the rod was **horizontal** as shown in the diagram.

(i) State the **polarity** of each end of the rod.

(ii) If the rod was part of a complete circuit, **state** and **explain** the direction in which the induced current would pass through it.

6 (a) A bar magnet was positioned near a coil connected to a centre-zero reading meter. When the magnet was **pushed into** the coil, the meter's pointer deflected **briefly to the right.**

(i) **Explain** why the pointer only defected **briefly.**

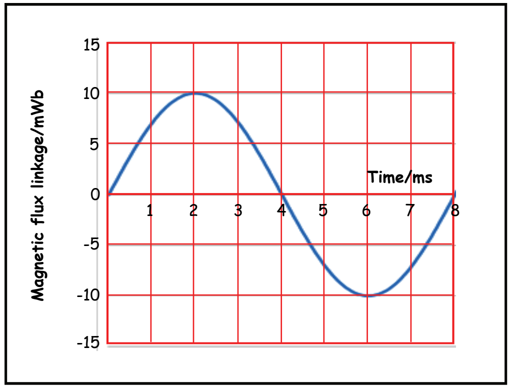
(ii) **State** and **explain** what is observed when the magnet is **withdrawn from the coil.**

(b) In (a) the flux density of the magnet was **25 mT** and the area Of the **30 turn** coil was **4.0 x 10^{-4} m^2**. The magnet was pushed into the coil in **0.20 s**. Calculate : *8*

(i) The **magnetic flux linkage** through the coil.

(ii) The **average e.m.f.** induced in the coil.

7 The diagram opposite shows how the flux linking **one turn** of a wire coil varies with time.



(a) Use the graph to calculate the **peak value of the e.m.f.** induced across the **single turn** of the coil.

(b) Sketch a graph with **labelled axes** to show how the **e.m.f. induced** across the single turn varies over the same time interval.

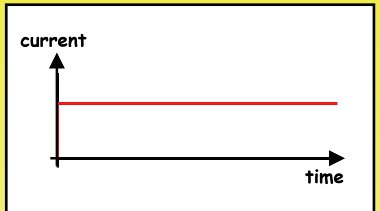
(c) The coil consists of **200 turns** of wire. Assuming that the flux links all the turns, calculate the **peak e.m.f.** across the whole coil.

(d) Suggest a way of **increasing the e.m.f. induced** across the coil without altering the coil itself.

THE SIMPLE A.C. GENERATOR

- ***DIRECT CURRENT* (d.c.)** *is the **unidirectional** flow of electric charge in a conductor.*

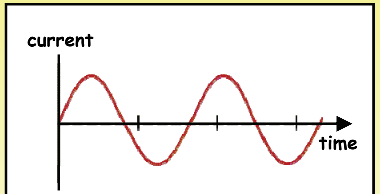
  *When d.c. (e.g. from a battery) passes along a wire the flowing electrons which constitute the current **drift slowly along the wire in a constant direction.***



Graphical representation of a DIRECT CURRENT

- *In **ALTERNATING CURRENT (a.c.)** the movement of the electric charge **periodically changes direction.***

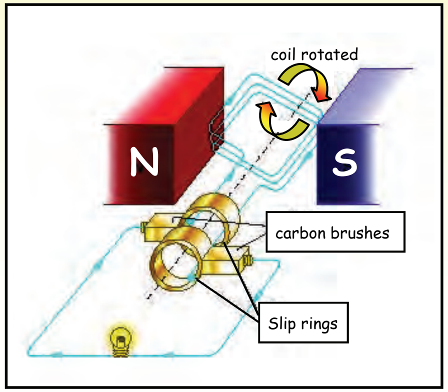
  *When a.c. (e.g. from the mains) passes along a wire, the electrons **oscillate back and forth about their mean positions** and do not drift along the wire as they do in the case of a direct current.*

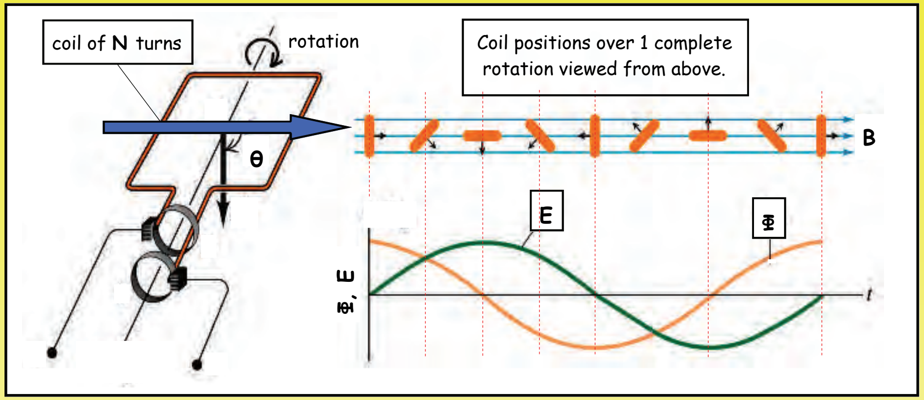


Graphical representation of an ALTERNATING CURRENT

- *Alternating current can be generated by rotating a coil in a magnetic field.*

  The simple a.c. generator shown in the diagram opposite consists of a coil which is free to rotate on an axle and whose ends are connected to two conducting slip rings which turn with the coil.
  The current induced in the coil when it is rotated between the magnet poles passes to the external circuit via stationary carbon brushes which press against the slip-rings.





- *When the coil rotates at a steady rate the **flux linkage** and hence the **e.m.f. induced** changes continuously.*

- *For a coil of area **(A)**, having **(N)** turns and rotating through a uniform magnetic field of flux density **(B)**, the flux **(Φ)** linking the coil at any instant is given by :*

$$\Phi = BAN\cos\theta$$

*Where **θ** is the angle between the plane of the coil and the magnetic flux lines.*

- *When the plane of the coil is **perpendicular** to the field, **θ = 0°**, **cosθ = 1** and so the **flux linkage is a maximum (Φ = BAN).***
- *When the plane of the coil is **parallel** to the field, **θ = 90°**, **cosθ = 0** and so the **flux linkage is zero (Φ = 0).***

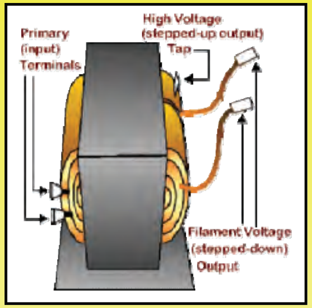
- *The **e.m.f. induced** in the coil is the **rate of change of flux linkage** with the coil and this is a **maximum** when the flux linkage is **zero** and **zero** when the flux linkage has its **maximum** value. In the diagram above, the **induced e.m.f. (E)** is given by **the gradient of the flux linkage (Φ) graph.***

  *So, when the sides of the coil are **at right angles** to the field, **E is a maximum.** because the rate at which the coil sides cut through the flux is a **maximum.***

  *And when the sides of the coil are **parallel** to the field, **E is zero** because **no flux** is being cut by the coil sides.*

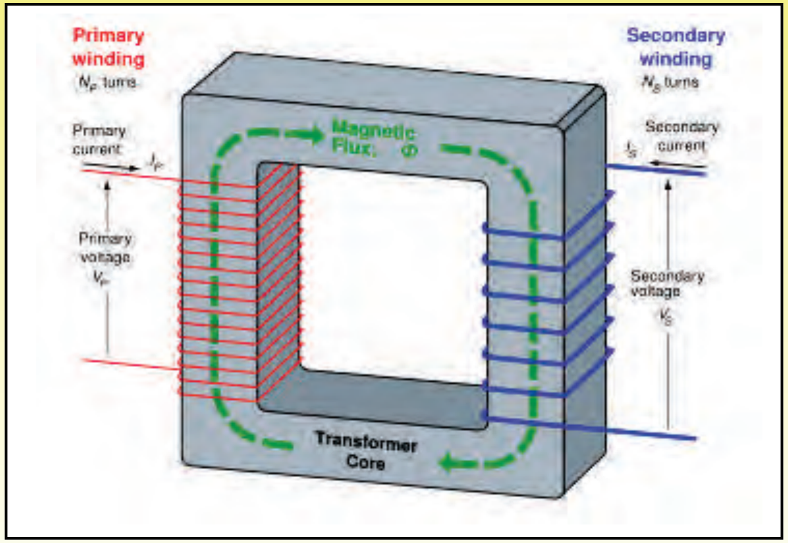
- *The direction of the induced e.m.f. and hence the induced current reverses every half-cycle of the rotation and that is why the generator produces **ALTERNATING CURRENT (a.c.).***

THE TRANSFORMER



- *Transformers are very efficient devices which use the phenomenon of **electromagnetic induction** to change **alternating p.ds (voltages)** from one value to another.*

- *In its simplest form the transformer consists of two coils - the **PRIMARY COIL** and the **SECONDARY COIL** - wound onto a laminated, soft iron core.*



- *An **alternating voltage** applied to the primary coil produces an **alternating current** which gives rise to an **alternating Magnetic field** in the core. This varying magnetic flux then links up with the turns of the secondary coil and so induces an **alternating e.m.f. (or voltage)** across it.*

- *Transformers are designed to minimise energy losses. The windings, for example, are made of very low resistance copper so as keep energy loss due to heat being produced in the coils to a minimum. The core shape and material also ensures that virtually all the magnetic flux produced by the primary coil will link with the turns of the secondary.*

- *For an **IDEAL TRANSFORMER** (i.e. one which is **100%** efficient), the relationship between the primary and secondary voltages **(V_p, V_s)** and the number of turns on each coil **(N_p, N_s)** can be shown to be :*

$$\frac{\text{secondary voltage}}{\text{primary voltage}} = \text{turns ratio} = \frac{\text{number of turns on the secondary}}{\text{number of turns on the primary}}$$

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

- A <u>**STEP-UP**</u> transformer has **more** turns on the **secondary** coil than on the **primary** coil, so the **secondary** voltage is **GREATER** than the **primary** voltage.

$$N_s > N_p \quad \text{so} \quad V_s > V_p$$

- A <u>**STEP-DOWN**</u> transformer has **less** turns on the **secondary** coil than on the **primary** coil, so the **secondary** voltage is **LESS** than the **primary** voltage.

$$N_s < N_p \quad \text{so} \quad V_s < V_p$$