SENIOR SIX TERM 2

TOPIC 4/5: ELECTROMAGNETIC INDUCTION

Competency: The learner evaluates how magnetism and current are linked and how this principle is applied in the operation of transformers and generators.

Magnetic induction

This is the process by which a magnetic substance acquires magnetic properties temporarily due to the presence of a magnet close to it. For instance when a magnet is placed close to an iron piece without touching it, the iron piece behaves like a magnet.

Types of electromagnetic induction

Motional induction is the generation of an electromotive force (emf) in a conductor when it moves through a magnetic field.

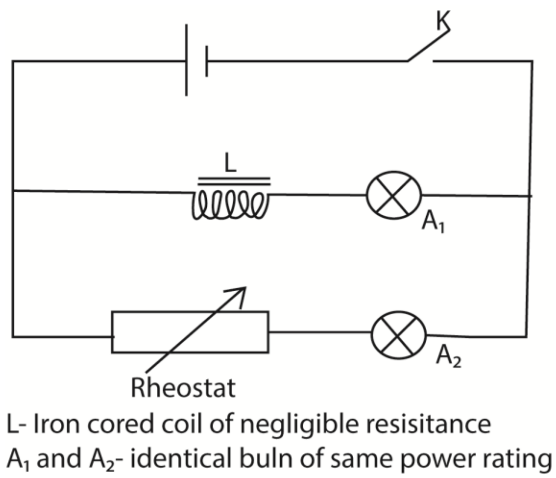
Transformer induction involves the transfer of energy between two or more coils through changing magnetic field.

Self-induction

It is a process by which an e.m.f is induced in a coil or circuit when the magnetic flux linking it changes due to the current flowing in the same circuit/coil.

Experiment to demonstrate self-induction

The circuit is arranged as shown below.



Procedure

- Switch K first closed and the rheostat adjusted until the two bulbs indicate the same brightness.
- When the switch is opened and closed again, bulb A_2 is observed to attain maximum brightness almost instantly while bulb A_1 take some time to attain maximum brightness.

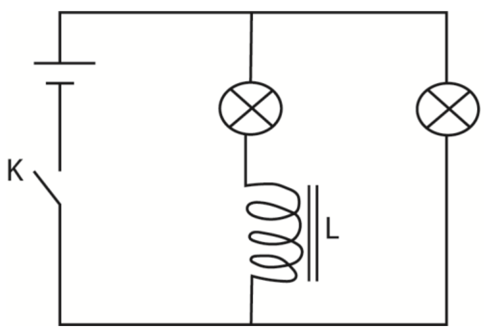
Explanation

The current in A_1 takes some time to attain a steady value due to back e.m.f induced in the coil as a result of change in the current flowing (due to self-induction) in the coil when the switch is closed.

The back e.m.f gradually decay to zero as current establishes a steady value and hence the current in the coil rises slowly to its maximum when the back e.m.f is zero for there is no change in magnetic flux linking it.

Example 1

In the figure below, A and B are identical bulbs and L is an iron cored coil.



(i) Explain what will be observed when switch K is closed and then opened

When K is closed, bulb A light s dimly and slowly becomes brighter while B becomes bright almost instantly and later the two bulbs acquire the same brightness.

When K is closed, the current begins to flow around the closed circuit and gradually increases to its steady value or maximum. The sudden change or increase in the current creates an increase in the magnetic flux around the coil and large back e.m.f is induced into the coil due to self-induction. This greatly oppose the flow of current in bulb A, causing most of the current to flow in bulb B, hence bulb A lights dimly and B brighter initially but latter the back e.m.f decay to zero and bulbs A and B now light to the same brightness.

When the switch is opened, bulbs A and B dim out gradually before going off. This is because opening switch will cause the currents and hence the magnetic flux around the coil to decay to zero. This cause back e.m.f in the opposite direction which tries to maintain the current in the circuit and hence the bulbs dim out gradually

(ii) Explain what you would observe when a battery is replaced by a.c voltage source and K is closed.

Bulb A may not light while B lights brightly because a.c causes a higher constant rate of change in magnetic flux around the soft iron cored coil and hence back e.m.f is constantly induced in the coil which greatly opposes the flow of current in A. The current in A may not rise to a value enough to lit it.

Secondary observation

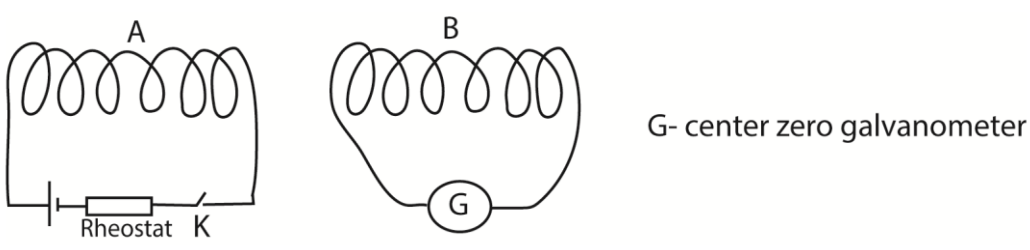
The iron core become warm

- The higher constant rate of change in magnetic flux induces eddy currents in the core which generate heat by I^2R mechanism.
- The a.c causes the direction of the magnetic domain in iron core to change according to the changing flux. This requires energy (hysteresis) which is later converted into heat energy in the core

Mutual induction

It is a process by which an e.m.f is induced in a coil when the magnetic flux linking it changes as a result of a change in the current flowing in nearby coil.

Experiment to demonstrate mutual induction



- The setup is shown above
- When the switch K is closed, the galvanometer deflects indicating induction of e.m.f in the coil B, hence mutual induction.

Self-inductance

This is the tendency of a coil to resist changes in current itself. Whenever current changes through a coil, they induce an emf, E which is proportional to the rate of change through the coil.

E = $L\frac{dI}{dt}$ =>L= $\frac{E}{\frac{dI}{dt}}$

It can also be defined as the ratio of the magnitude of the back e.m.f induced in a coil or circuit to the rate of change of current flowing in the coil or circuit.

Or

$$E = L\frac{dI}{dt}$$

When$\frac{dI}{dt} = 1As^{-1}$;

E = L

Thus self-inductance can also be defined as the magnitude of the back e.m.f induced in a coil or circuit when rate of change of current flowing in the coil is $1As^{-1}$.

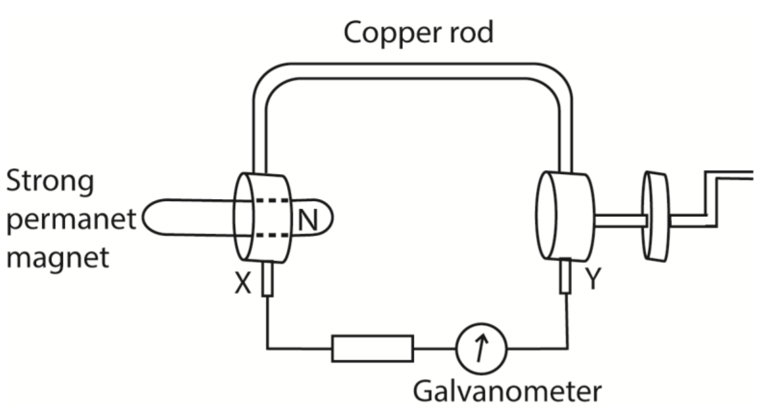
Laws of electromagnetic induction

(i) **Faraday's law** states that the magnitude of the e.m.f induced in a circuit is directly proportional to the rate of change of magnetic flux linked with the circuit.

(ii) **Lenz's Laws** states that induced current flows always in such a direction as to oppose the change which is giving rise to it.

An experiment to demonstrate Faraday's law of electromagnetic induction.

Verification setup



X and Y are brush contact.

A copper rod which can rotate round the north pole of permanent magnet is connected as shown above.

The wheel is turned steadily until the deflection of the galvanometer is constant.

The time, t, for N rotations is measured and the number of revolution (n) per second is determined from n = $\frac{N}{t}$. The deflection θ of the galvanometer is also noted.

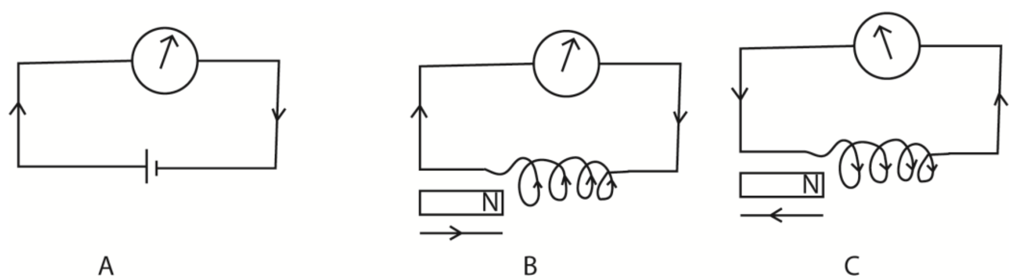
The experiment is repeated at different speed of rotation of the wheel and values of n and θ tabulated.

A graph of θ against n is plotted.

A straight line graph is obtained implying that θ ∝ n

Since θ ∝ e.m.f induced and n ∝ speed of rotation of the rod, then the induced e.m.f is proportional to the rate of change of flux linkage.

An experiment to illustrate Lenz's law of electromagnetic induction



- The galvanometer is first connected in series with a battery and the direction for a given direction of current is determined.
- The battery is disconnected and is replaced by a coil of known winds.
- A strong permanent magnet is brought towards the coil with N-pole facing the coil, the galvanometer deflects in a direction for which the side of the coil facing the magnet is N-pole.
- When the magnet is move away from the coil, the galvanometer deflects in opposite direction, implying that the pole near the coil is an S-pole.
- In the first case, the pole due to the induced current was repelling the approaching magnet, while in the second case, the pole was attracting the receding magnet.
- The induced current therefore is in such as to oppose the change causing it, which is Lenz's law.

Example 2

Explain why Lenz's law is referred to as an example of energy conservation or

Why Lenz's law does not violet the principle of conservation of energy.

In order not to violet the principle of conservation of energy, the effects of induced current must oppose the motion of the magnet in such a way that work done by an external agent in moving the magnet is the one that is converted into electrical energy and hence there is just transformation of energy from one form to another (from mechanical energy to electrical energy) and hence Lenz's law is an example of energy conservation..

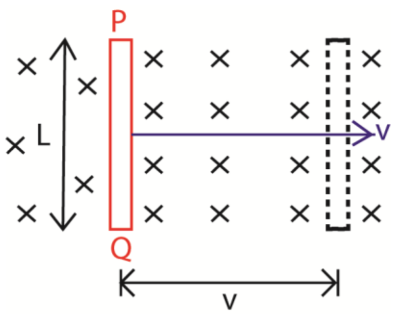
Magnitude of e.m.f induced in a coil depends on

- Number of turns N in the coil
- Rate of change in magnetic flux
- Strength of Magnetic flux
- Area of the coil

Derivation of e.m.f induced in a moving rod across a magnetic field

(a) Derivation of e.m.f induced in a moving rod by applying the laws of electromagnetic induction

Considering a rod of length L meters moving at right angles to a uniform magnetic field of flux density B tesla moving with uniform speed v ms^{-1} as shown in figure below:



From the laws of electromagnetic induction;

The induced e.m.f, E = $\frac{\Delta\phi}{\Delta t}$

But ϕ = BA

E = $-\frac{d(BA)}{dt}$

= $-B\frac{dA}{dt}$

But $\frac{dA}{dt}$ = -Lv

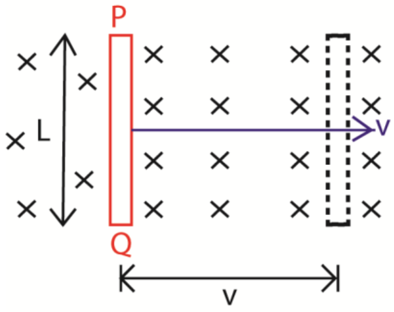
(negative because the area is decreasing, rate of decrease in area)

∴ E = -B x –Lv

= BLv

Derivation of e.m.f induced in a moving rod by considering the force extended on the electrons

By virtue of motion of the rod in the magnetic field, the electrons inside the rod experiences a magnetic force.



Applying Fleming's right Handle Rule, the induced e.m.f for current is directly from Q to P.

The electrons flow or drift from P to Q (by convention current and electrons flow in opposite directions) thus P acquires a positive charge and Q acquires a negative charge.

An electric field is thus setup which attracts electrons towards the positively charged end P.

Equilibrium is reached when upward electronic force is counterbalanced by the downward magnetic force.

At equilibrium, Ee = Bev

⇨ E = BV, where E is electric field intensity

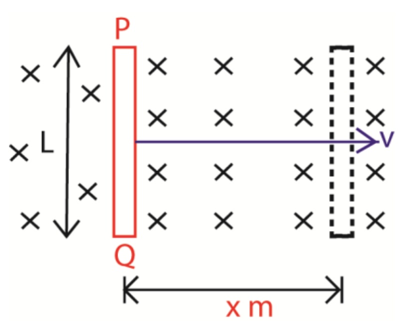
But E = $\frac{E'}{L}$ where E' is the induced e.m.f.

$\therefore \frac{E'}{L} = Bv$

$\therefore E' = BLv$ where v= speed of the rod, B= magnetic flux density, L = length of the rod.

Derivation of e.m.f induced in a moving rod by applying the principle of conservation of energy

Consider a rod PQ placed at right angles to a uniform magnetic field of flux density B Tesla as shown.



Suppose the rod is moved through of x meters in time t seconds; from the principle of conservation of energy, work done by the external agent in moving the rod is what is conserved into electrical energy.

Therefore, electrical energy = work done in moving the rod.

If E is the induced e.m.f in the rod, then

EIt = Force x distance

But force = BIL, I is the induced current in the rod

⇨ EIt = BILx

$E = \frac{BLx}{t}$

Since $\frac{x}{t} = v$ (speed of the body)

∴ $E = BLv$

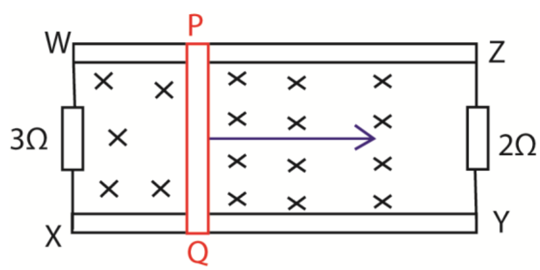
Example 3

A rod PQ, 1.2m long moves at right angles to a magnetic field of flux density 0.4T and at a speed of $4ms^{-1}$. Find the e.m.f induced in the rod.

Solution

Induced e.m.f, E = BLv = 0.4 x 1.2 x 4 = 1.92V

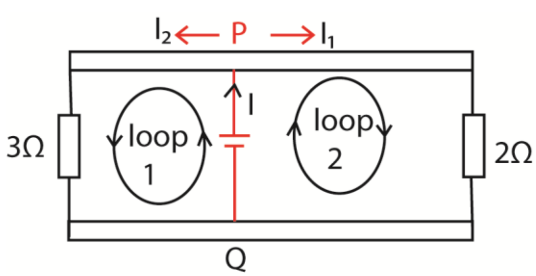
Example 4



In the figure above, a rod PQ 1.2m long is moved in a perpendicular magnetic field of flux density 0.4T at a speed of 4m/s along a frictionless rails XY and WZ. Find the power generated by the rod.

Solution

Applying Fleming's Right Hand rule, the induced current flows from Q to P, this gives the polarity of induced e.m.f with a positive terminal on the side P.



E = BLv = 0.4 x 1.2 x 4 = 1.92V

At the junction, $I = I_1 + I_2$

From $I = \frac{V}{R}$

Considering loop 1;

$I_1 = \frac{1.92}{3} = 0.64A$

Considering loop 1;

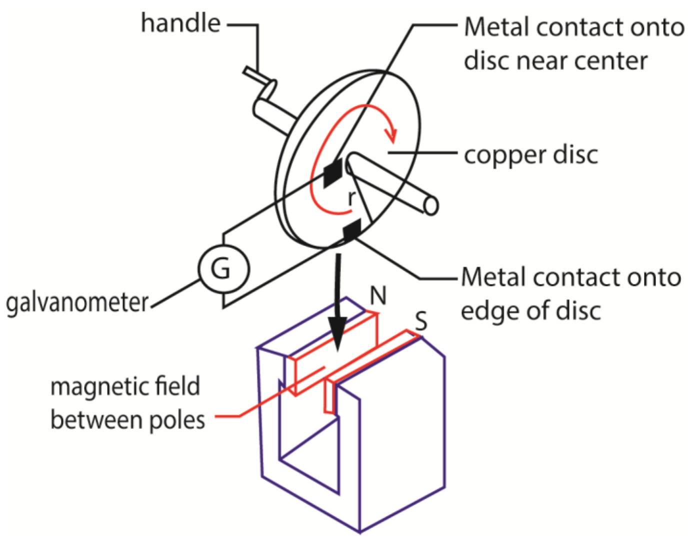
$I_2 = \frac{1.92}{2} = 0.96A$

$I = I_1 + I_2 = 0.64 + 0.96 = 1.6A$

Power = EI = 1.92 x 1.6 = 3.1W

E.m.f induced in a circular disc (disc dynamo)

A disc is an arrangement of obtaining electrical energy from mechanical energy by rotating a circular metal disc in a perpendicular magnetic field abut an axle passing through its center.



The disc is rotated at uniform angular velocity, ω, and the e.m.f induced in the disc is tapped by connecting a wire between the center of the disc axle and the rim of the disc.

The induced e.m.f is due to the motion of linear conductor of length = radius r.

From the e.m.f induced in a moving rod

E = BLv ……………………………………(i)

Where v is the average velocity,

$v = \frac{0+r\omega}{2} = \frac{r\omega}{2}$ …………………………… (ii)

(i) and (ii)

$E = \frac{Br\ x\ r\omega}{2} = \frac{Br^2\omega}{2}$

But ω =2πf, where f is the frequency of rotation per second

$E = \frac{B\ x\ 2\pi r^2 f}{2} = B\pi r^2 f$

E = BAf

Example 5

A circular metal disc of radius 8cm is rotated at right angle to a uniform magnetic field of flux density 0.4T at 80 revolution per minute. Find the e.m.f induced in the disc.

Solution

Induced e.m.f, E = BAf, $E = \pi r^2 = 3.14 \times 0.08^2$, $f = \frac{80}{60}\ rev/s$

$E = 0.4 \times 3.14 \times 0.08^2 \times \frac{80}{60} = 0.011V$

Example 6

A circular metal disc of radius 12cm is rotated in a perpendicular magnetic field of flux density 0.4T about an axle of radius 6cm at 52rev/min. Calculate the e.m.f generated

Solution

Induced e.m.f, E = BAf

$= B(\pi(R^2 - r^2)f$

$= 0.4\pi(0.12^2 - 0.06^2) \times \frac{52}{60}$

$= 0.0117V$

Example 7

A conducting disc of radius 0.05m with its plane perpendicular to uniform magnetic field of flux density 0.25T, rotates at 15 revolution per second about an axis through its center and perpendicular to its plane.

Calculate

(i) Magnetic flux threading the disc at any time (03marks)

Magnetic flux, $\phi = BA$ but $A = \pi r^2$

- $\phi = B\pi r^2$

$= 0.25 \times 3.14 \times (0.05)^2 = 1.96 \times 10^{-3}Wb$

(ii) E.m.f generated between the center of the disc and any point on its rim.

or $\varepsilon = \phi f = 1.96 \times 10^{-3} \times 15 = 2.9 \times 10^{-2}V$

Example 8

An airplane of wing span 30m flies horizontally at a speed of $1000kmh^{-1}$.

What is the p.d across the tips of its wings, if the horizontal component of the earth's magnetic field is 1.46×10^{-4}T? (Angle of dip at the place is 70^0) (03marks)

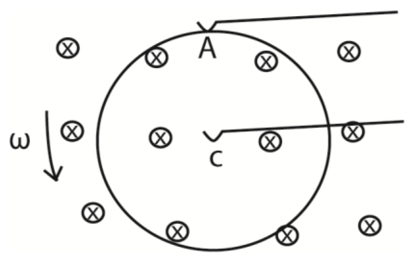
$E = B_V Lv$; but $Bv = B_H \tan 70^0$

$E = B_H \tan 70^0 Lv$

$= 1.46 \times 10^{-4} \times \tan 70^0 \times 30 \times \frac{1000 \ x\ 1000}{1 \ x\ 60 \ x\ 60} = 3.34V$

Example 9

A circular metal disc of radius R. rotates in an anticlockwise direction at angular velocity, ω, in a uniform magnetic field of flux density, B, directed into paper as shown in the figure below



A and C are contact points
Derive an expression for e.m.f induced between A and C.

Le r = radius of the disc
Thus AC cuts the magnetic flux continuously.
The average velocity V of AC = $\frac{0+r\omega}{2} = \frac{r\omega}{2}$
∴ Induced e.m.f in Ac = E = BLV

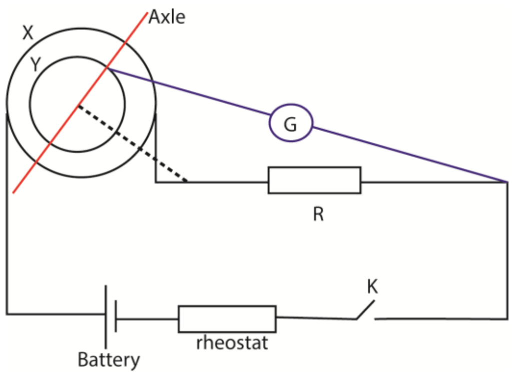
$= \frac{Br.r\omega}{2}$

$= \frac{1}{2} Br^2\omega$

Absolute method of measurement of resistance (Lorentz method)

The e.m.f induced in a moving rod is used in the absolute measurement.

A circular metal disc is placed inside a solenoid X of known number of turns, N and length, L meters in series with a battery, unknown resistance R, a rheostat and a switch K



Switch K is closed and the disc of diameter, r, is rotated about an axle passing through its center at such a speed until the e.m.f induced between the center and the rim is counter balanced by the potential difference across the resistor when the galvanometer shows no deflection

At this stage, the number of revolutions n in a given time t (s) are noted.

f $= \frac{n}{t}$ revolution per second

area A of the disc = πr^2

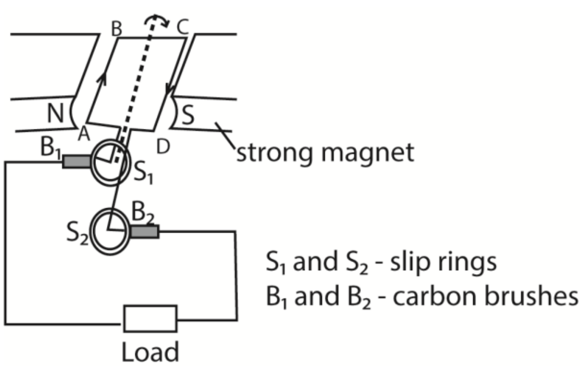
At no deflection the induced e.m.f in the disc, BAf = IR, where I is the current flowing through the coil

But B = $\frac{\mu_0 NI}{L}$

$\therefore IR = \frac{\mu_0 NIAf}{L}$

R = $\frac{\mu_0 NAf}{L}$

The simple a.c generator



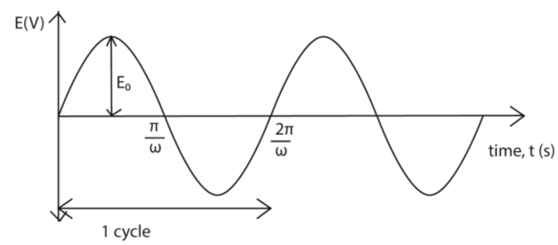
It consists of a rectangular coil of wire pivoted between opposite curved poles of a strong magnet and free to rotate about its axis with uniform angular velocity.

The ends of the coil are connected to two slip rings which press slightly against the carbon brushes connected to the load.

How it works

- The coil ABCD is rotated in a magnetic field, the magnetic field linked with it changes and hence e.m.f is led away by means of slip rings which press slightly against the carbon brushes.
- Applying Fleming's right hand rule, the induced current enters the coil AB and leaves the coil via CD.
- Starting with the coil in the vertical position, the magnetic flux linking it is maximum and hence no induced e.m.f.
- The induced e.m.f increases with the position of the coil in the magnetic field until it becomes maximum with the coil in horizontal position and then decrease to zero as the coil rotates to the vertical position
- The force acting on the sides of the coil change as the coil passes over the position and hence he current flowing in the coil reverses. Hence an alternating e.m.f or current flows through the load.

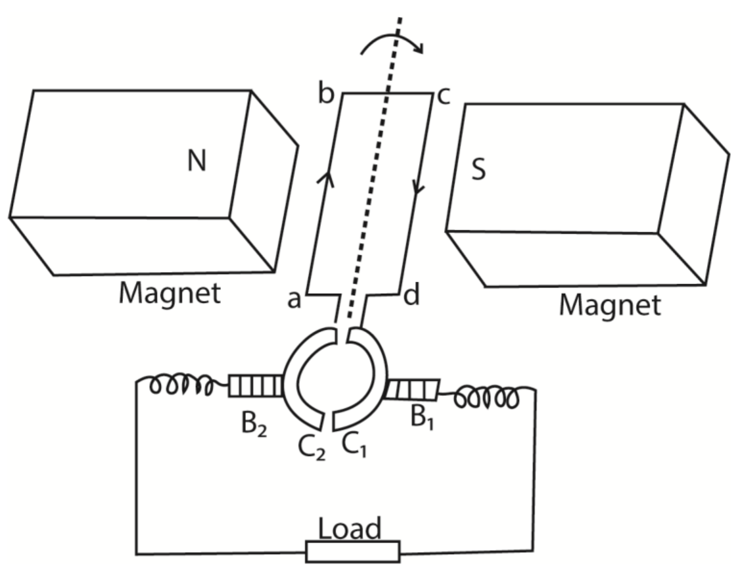
A graph of induced e.m.f against time in an a.c generator



The main energy losses in an a.c. generator and how they are minimized

- Eddy current loss are minimized by laminating the armature
- I^2R losses are minimized by use of low resistance winding wires
- loss due to friction minimized by lubricating the rubbing parts

d.c. generator



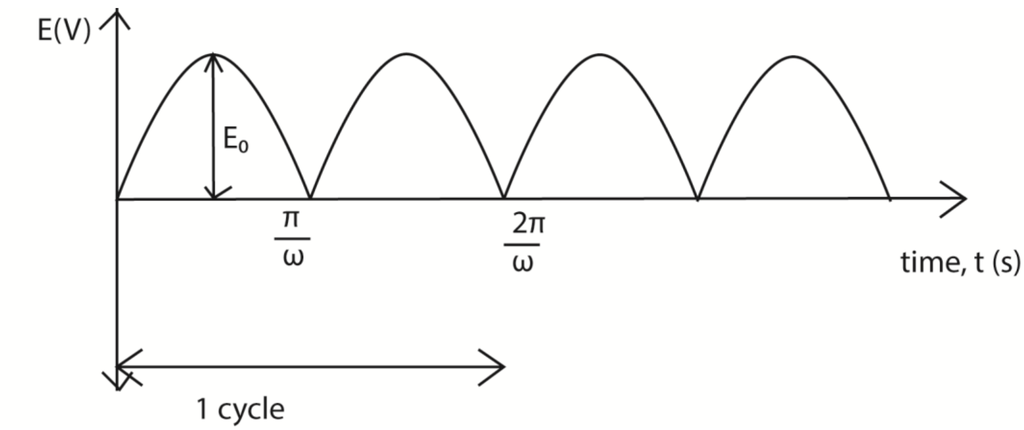
It consists of a rectangular coil abcd of wire pivoted between curved poles of a strong magnet and free to rotate about its axis with a uniform velocity.

The ends of the coil are connected to two halves of split ring (commutators) which press lightly against the carbon brushes connected to the load.

Mode of action

When the coil rotates at uniform velocity in magnetic field, e.m.f is induced in it. When the coil is in vertical position, the commutators change brushes C_1 to B_2 and C_2 to B_1. E.m.f reverses direction but the current does not change direction. Hence current flows in the same direction in a resistor.

A graph of induced e.m.f against time in a d.c generator



The peak value of induced e.m.f increases with increase in

- The number of turns in the coil
- The area of the coil
- The strength of the magnetic field
- The frequency of rotation of the coil

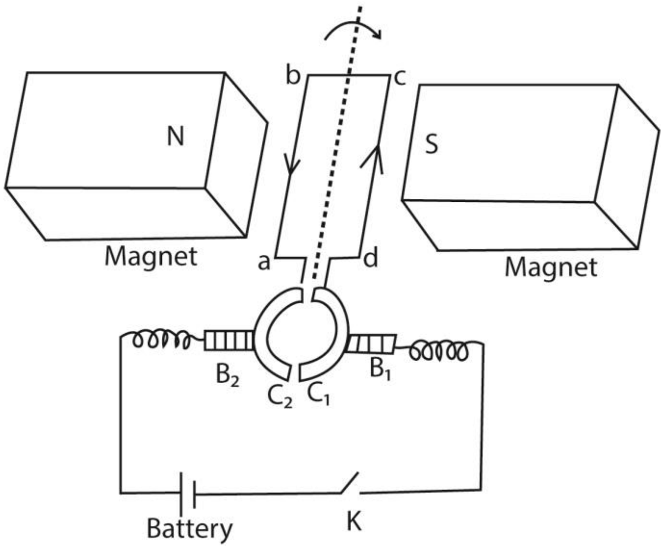
How to convert a d.c. generator be converted into an a.c. generator.

To convert a d.c. generator to an a.c. generator, the ends of the rectangular coil are connected to a pair of slip rings instead of the commutators.

How to convert an a.c. generator be converted into d.c. generator

To convert an a.c. generator to d.c. generator, the ends of the rectangular coil are connected to a pair of commutators instead of the slip rings.

A d.c motor



It consists of a rectangular coil abcd of wire pivoted between curved poles of a strong magnet and free to rotate about its axis with a uniform velocity.

The ends of the coil are connected to two halves of sprit ring (commutators) which press lightly against the carbon brushes.

Mode of operation

The switch K is closed and current flows in the coil in the direction shown

Applying Fleming's left hand rule, ab experiences an upward force and side cd a downward force. the two forces constitute a couple which rotates the coil in a clockwise direction.

When the coil passes over the vertical position, the commutators change contact with the carbon brushes and current in the coil is immediately reversed. The forces acting on the sides thus change and the coil continues to rotate in the same direction.

Because the conductors cut the magnetic field, an e.m.f that oppose the supply voltage is induced in it called back e.m.f

If Vis the supply voltage and E is the back e.m.f, then then the current Ia is given by

Ia = $\frac{V-E}{R_a}$ where Ra is the armature resistance

Back e.m.f and efficiency of the motor

When the armature coil of a motor rotates in magnetic field, an, e.m.f is induced in the coil. The induced e.m.f opposes the applied p.d. and is therefore a back e.m.f.

If V, E and r are applied p.d, induced e.m.f and resistance to the armature coil respectively, then the current flowing in the coil is given by

I = $\frac{V-E}{r}$

=> V- E = Ir

Multiplying through by I

VI = EI + I^2r

Since I^2r is the power dissipated as heat in the armature, EI is the mechanical power output and VI is the power supplied.

Efficiency of the motor, η = $\frac{EI}{VI}\ x\ 100\%$

= $\frac{E}{V}\ x\ 100\%$

Example 10

A motor whose armature resistance is 2Ω is operated on 240V mains supply. If the back e.m.f in the motor is 220V, calculate the armature current. (03marks)

I = $\frac{V-E}{r}$ = $\frac{240-220}{2}$ = 10A

Example 11

A transformer has 2000 turns in the primary coil. The primary coil is connected to a 240V mains. A 12 V, 36W lap is connected to the secondary coil. If the efficiency of the transformer is 90%, determine the

(i) number of turns in the secondary coil (02marks)

$N_S = \frac{V_S}{V_P}\ x\ N_P$ = $\frac{12}{240}\ x$2000 = 100

(ii) current flowing in the primary coil (03marks)

IsVs = 0.9IpVp

Ip = $\frac{I_S V_S}{0.9V_p}$ = $\frac{36}{0.9\ x\ 240}$ = 0.167A

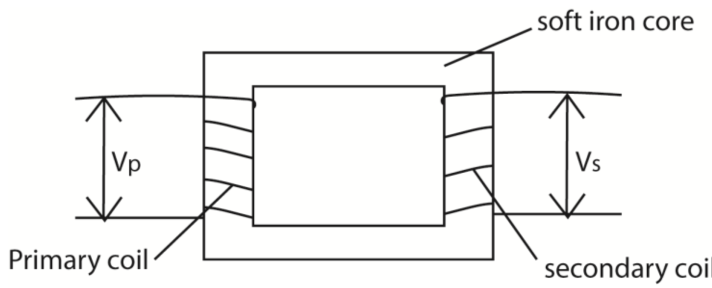
Example 12

Explain the significance of back e.m.f. in the operation of a d.c. motor (02marks)

The back e.m.f in a d.c. motor provides the useful power of the motor.

The back e.m.f also reduces the heating effect in motor by reducing the current, since I = $\frac{V-E_b}{r}$ where Eb = back e.m.f

The structure and action of a.c transformer.



Vp= primary voltage, Vs = secondary voltage

- Transformer consists of two coil of insulated wire, the primary and secondary wound on laminated soft iron core.
- When alternating voltage, V_p is connected to primary coil, it drives alternating current in the primary coil.
- The alternating current produces a varying magnetic flux ϕ_p that link the primary coils inducing a back e.m.f E_B in the primary.
- The varying magnetic flux, ϕ_s links the secondary coil by mutual induction/inducing alternating voltage, V_s in the secondary

  $V_p = N_p\frac{d\phi_p}{dt}$ ………………………. (i)

  $V_s = N_s\frac{d\phi_p}{dt}$……………………….(ii)

  Eqn (i) ÷Eqn (ii)

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

When $N_s > N_p$ the transformer is a step up

$N_s < N_p$ the transformer is a step down

Example 13

Explain why the voltage at a generating power station must be stepped up to very high value for long distance transmission (03marks)

Transmission is at high voltage to reduce power loss

Note that

Power supplied, P =IV

$I = \frac{P}{V}$

Hence when V is high, I is small. From power loss, $P' = I^2R$, when I is small power loss is reduced.

Example 14

A transformer connected to a.c supply of peak voltage 240V is to supply a peak voltage of 9.0V to a mini-lighting system of resistance 5Ω. Calculate the

(i) r.m.s current supplied to the lighting system (02marks)

$$V_{r.m.s} = \frac{V_0}{\sqrt{2}}$$

$$I_{r.m.s} = \frac{V_{r.m.s}}{R} = \frac{V_0}{\sqrt{2}R}$$

$$= \frac{9.0}{5\sqrt{2}} = 1.27A$$

(ii) average power delivered to the lighting system. (02marks)

$P = I^2R$

$= I_{r.m.s}^2 R$

$= (1.27)^2 \times 5$

$= 8.1W$

Example 15

Explain why the current in the primary coil of a transformer increases when the secondary is connected to the load.

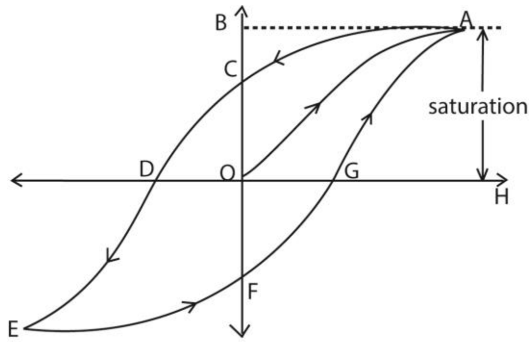
When load is connected to the secondary winding, a current flows in it. The current flows in such a direction as to reduce the back e.m.f in primary coil, hence the current increase

Energy losses in a transformer

- Heat dissipated in the windings by I^2R mechanism. This is minimized by use low resistance thick copper wires.
- Energy loss resulting from loss of flux or flux leakage. This is minimized by winding secondary coil on primary coil
- Eddy currents are minimized by laminating the core.
- loss due to friction minimized by lubricating the rubbing parts
- losses. When an alternating current is passes through the coil, wound on the core, the magnetic domain dipoles are forced to change directions according to changing magnetic flux created as a result of a.c. These changes of the domain dipoles require energy which is lost from the system. This energy loss is called hysteresis loss.

  Hysteresis loss is minimized by using a core made of self-magnetic substance which requires very little energy to create magnetic reversal e.g. soft iron below the hysteresis curve of a ferromagnetic substance

  A graph, explain the hysteresis curve for ferromagnetic material



- When a magnetic field is applied to a ferromagnetic material, the magnetic domains tend to align with the applied field. The magnetic flux density increases along OA until saturation. When the magnetizing field is reduced to zero, there is residue magnetization at C. This is due to failure of the dipoles to respond instantly. Energy is lost.
- To bring the dipoles to their original orientation, a magnetic field OD is applied in opposite direction. As the magnetic field is increased in this reversed direction, saturation is attained at E
- When reversed magnetic field is reduced to zero, state F is attained. Reversal of dipoles requires an increase of magnetic field in opposite direction to state EF. The cycle is then repeated on further increase of magnetic field
- The curve of B verses H is called a hysteresis curve

Uses of transformers

A transformer is used to step up or down voltage to suit the required appliance.

The appliances that may require a transformer include telephone, radios, loud speakers, x-ray machines. T.Vs and so on.

Eddy currents

If a block of metal is moved in a magnetic filed or kept in changing magnetic field, free electrons in the conductor experience a force and begin to circulate.

This gives rise to induced currents in a closed circular path known as edd currents.

These currents flow in such a direction so as to oppose the motion of a conductor in the field.

Eddy currents produce a large amounts of heat in the soft iron core of transformers, induction coils,electronics and thus reduce efficiency of electrical devices.

Uses of eddy currents

- Damp oscillations in a moving coil galvanometer preventing oscillation of the pointer and leading to accurate reading
- Eddy currents produce enough heat to melt metals in induction furnace.

- Electric brakes: the axle of a train is surrounded by a coaxial cylindrical drum. When the train is to be stopped, a strong magnetic field is applied to the rotating drum. This generates large eddy currents that oppose motion of axle.
- Speedometer, eddy current are used in speedometer

Thank you
Dr. Bbosa Science