Chapter 22 Electromagnetic Induction

(a) deduce from Faraday's experiments on electromagnetic induction or other appropriate experiments:
  (i) that a changing magnetic field can induce an e.m.f. in a circuit
  (ii) that the direction of the induced e.m.f. opposes the change producing it
  (iii) the factors affecting the magnitude of the induced e.m.f.

(b) describe a simple form of a.c. generator (rotating coil or rotating magnet) and the use of slip rings (where needed)

(c) sketch a graph of voltage output against time for a simple a.c. generator

(d) describe the use of a cathode-ray oscilloscope (c.r.o.) to display waveforms and to measure potential differences and short intervals of time (detailed circuits, structure and operation of the c.r.o. are not required)

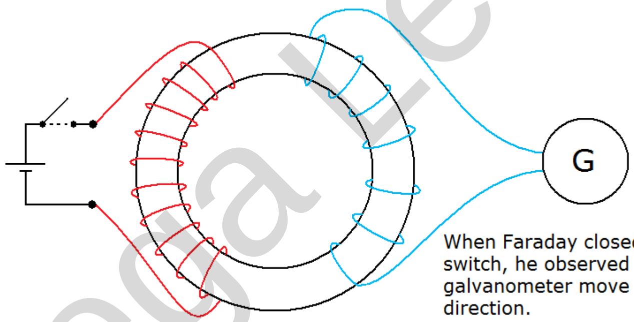
(e) interpret c.r.o. displays of waveforms, potential differences and time intervals to solve related problems

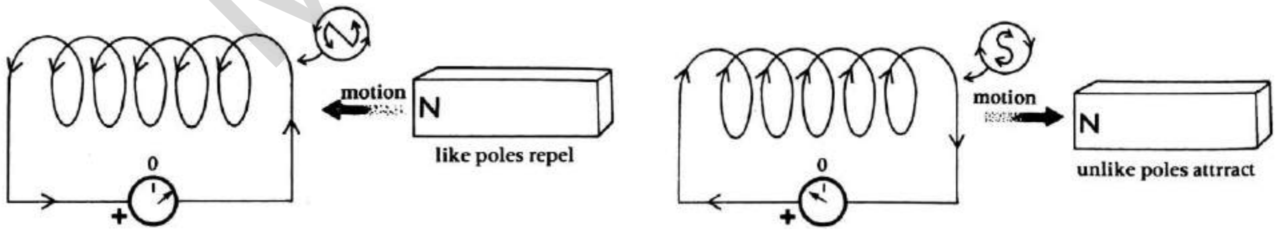
(f) describe the structure and principle of operation of a simple iron-cored transformer as used for voltage transformations

(g) recall and apply the equations $V_P / V_S = N_P / N_S$ and $V_P I_P = V_S I_S$ to new situations or to solve related problems (for an ideal transformer)

(h) describe the energy loss in cables and deduce the advantages of high voltage transmission

(a) Faraday's experiments and electromagnetic induction



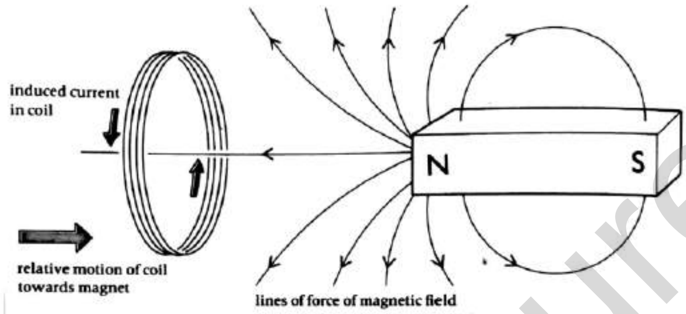


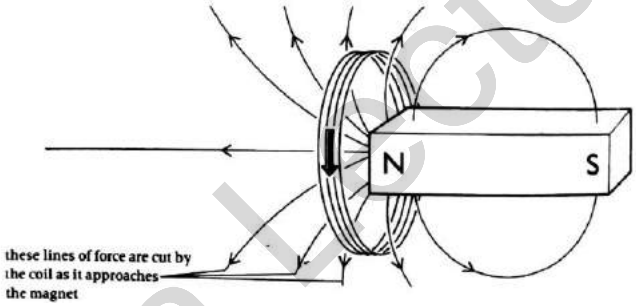
- The galvanometer needle deflects in one direction when the N pole moves towards the solenoid
- The galvanometer needle deflects in the opposite direction when the N pole moves away
- This shows that an **emf is induced** across the solenoid when there is **relative movement** between a conductor and a magnetic field
- When the **magnet is stationary relative to the solenoid**, **no emf** is produced and the galvanometer needle shows no deflection

Conclusions

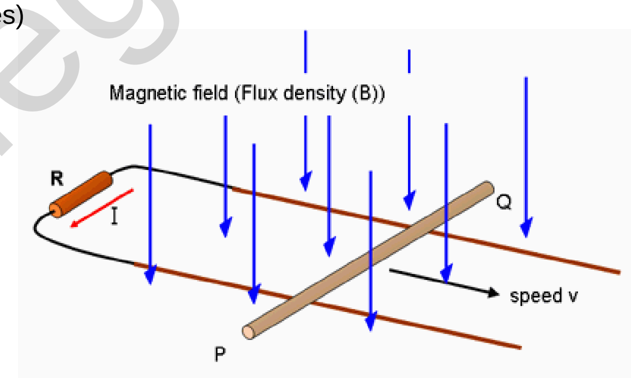
1 **Changing magnetic field induces (gives rise to) an emf in a circuit**

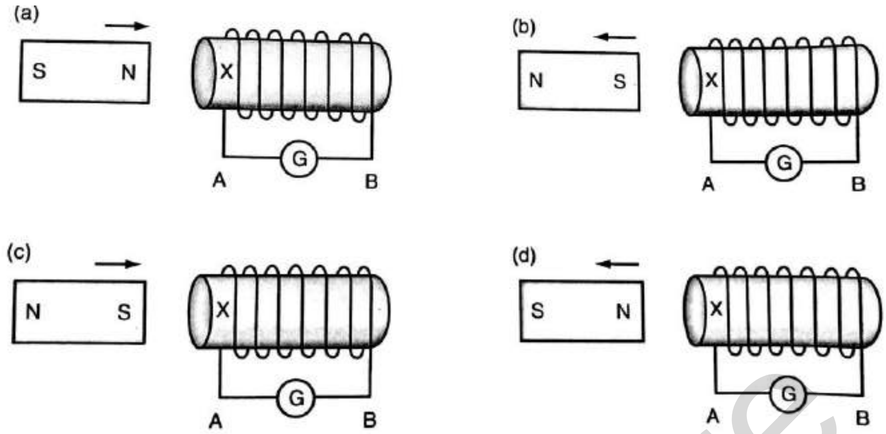
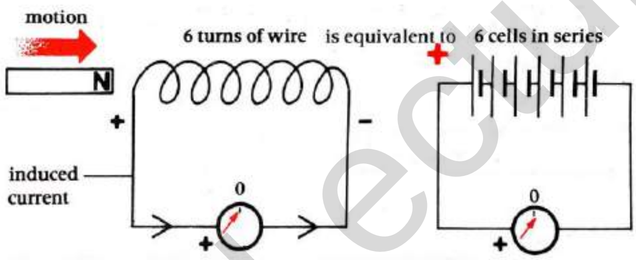
- A **change** in the magnetic field lines **linking** or '**cutting**' the coil results in an **emf** being induced across the ends of the coil (or an induced current flows in the coil)
- The magnetic field lines (magnetic flux) linking the turns in the coil increases from 0 to a maximum value or decrease from a maximum to 0.
- As the **rate of magnetic flux linkage increases**, the magnitude of the **emf increases**. Once the flux linkage reaches a **maximum** value and stops increasing, the induced emf decreases to zero. The reverse is also true. If the flux linkage decreases at an increasing rate, the magnitude of the emf also increases.





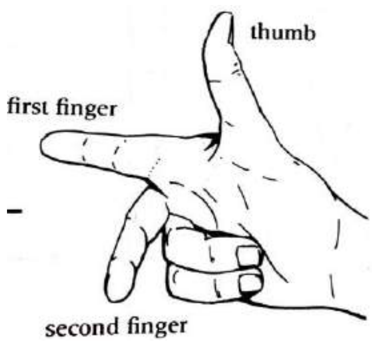
- **Faraday's law** states that the magnitude of the induced emf across the ends of the wire is directly proportional to the **rate** at which the magnetic lines of force cuts the wire (rate at which magnetic flux linking the wire changes)



2	**Lenz's Law: The direction of the induced emf is such that it always opposes the change that caused it** Determine the polarity of X in each example and the direction of the induced current (Right hand grip rule) 
3	The induced emf can be increased by moving the magnet **more quickly** or **increasing** the number of **turns** per unit length on the coil 

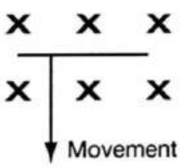
Fleming's Right hand dynamo (generator) rule

When a force acts on a conductor causing it to move in a direction which is **perpendicular** to a magnetic field, an induced current or emf is produced.

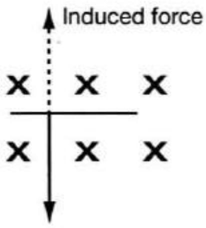


Lenz's law: Law of conservation of energy

- When the conductor moves through a magnetic field, an emf **is induced** in the conductor which results in a current flow. (Use **Fleming's right hand rule** to determine direction of induced current)

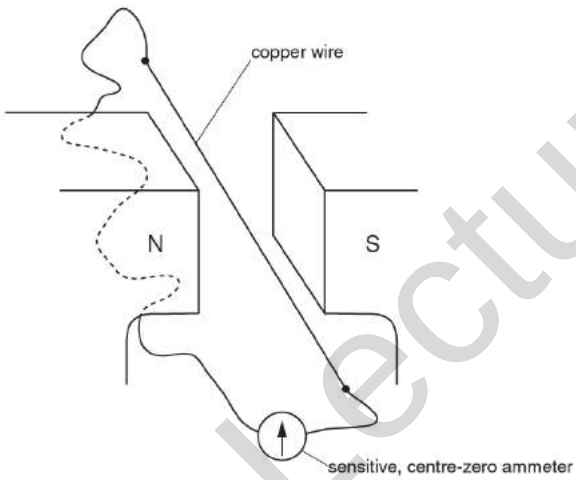


- A **second magnetic field** associated with this induced current will also be induced.
- The interaction between this second magnetic field and the original magnetic field produces a **force** on the conductor. (use **Fleming's left hand rule** to determine direction of force)



- By the **law of conservation of energy**, the direction of this induced force must be opposite to the motion of the conductor. (otherwise the conductor would move forever which goes against the law that **energy cannot be created**)

Question 1
A straight length of copper wire lies horizontally between the poles of a U shaped magnet. The figure shows the two ends of the wire connected to a very sensitive, centre-zero ammeter.



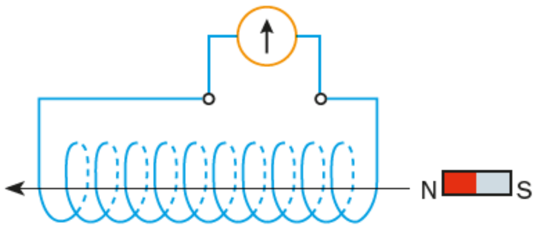
The copper wire is moved upwards slowly between the two magnetic poles. The needle on the ammeter deflects to the right.

(a) Explain why the needle on the ammeter deflects.

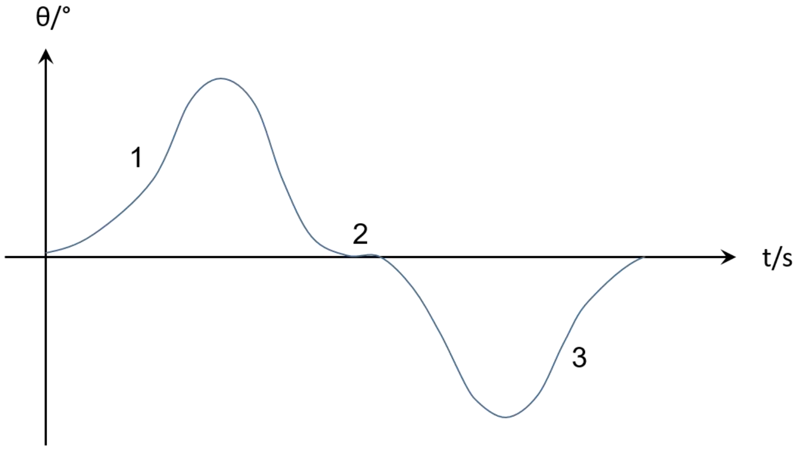
(b) The wire is moved downwards very quickly between the two magnetic poles. State what happens to the needle on the ammeter.

(c) State what happens to the needle on the ammeter when the copper wire is moved horizontally between the two poles.

Question 2



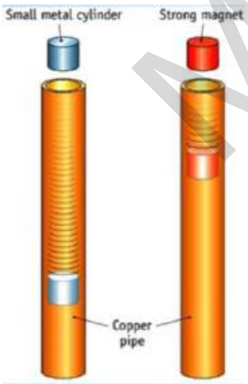
In the figure shown, a short bar magnet passes through a long solenoid. A galvanometer is connected across the solenoid. A graph of the angle of deflection is plotted against time and the result is shown. Using the principles of electromagnetic induction, explain the shape of the graph, focusing on the three regions labelled.



1	• As the north pole of the bar magnet enters the solenoid, there is a change in the number of magnetic field lines linking the solenoid (magnetic flux linkage in the solenoid changes). • The change in the magnetic flux linking the coils of the solenoid results in an induced emf in the circuit. • Faraday's law states that the **magnitude** of the induced emf is **proportional** to the rate at which the magnetic flux linkage changes. This emf drives an induced current through the closed circuit. • The induced current produces a galvanometer needle deflection θ. • By Lenz' law, the induced current creates a north pole at the right end of the solenoid to oppose the incoming north pole. Thus the galvanometer needle is deflected momentarily to one side.
2	At the instant when the bar magnet travels past the mid length point of the solenoid, there is no change in the magnetic linking the solenoid. (magnetic flux linkage is maximum, hence rate of change is now zero) There is no induced emf and hence no induced current to cause a deflection in the galvanometer.
3	As the south pole of the magnet exits the solenoid, there is again a change in the magnetic flux linking the solenoid (decrease in flux linkage) By Lenz's law, the induced current creates a north pole at the left end of the solenoid to oppose the outgoing south pole. Thus the galvanometer needle deflects momentarily in the **opposite** direction.

Question 3

A metal cylinder and a cylindrical magnet of the same weight are released from the top of a hollow copper tube.



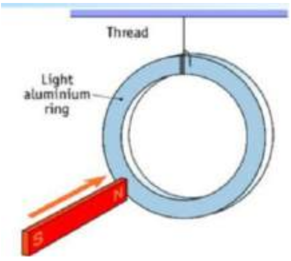
An induced emf is produced in the copper tube when the magnet falls through it.

(a) Sketch a graph to show how the induced emf in the copper tube varies with time.

(b) Explain why the magnet takes a longer time to reach the bottom of the tube compared to the metal cylinder.

As the **magnet** falls through the copper pipe, its magnetic field linking the copper tube changes, inducing a current in the pipe. By Lenz's law, the induced current flows in a direction which opposes the change causing it. The induced current causes a **repulsive force** to act on the falling magnet which slows it down. The metal cylinder does not experience any magnetic force therefore it does not slow down.

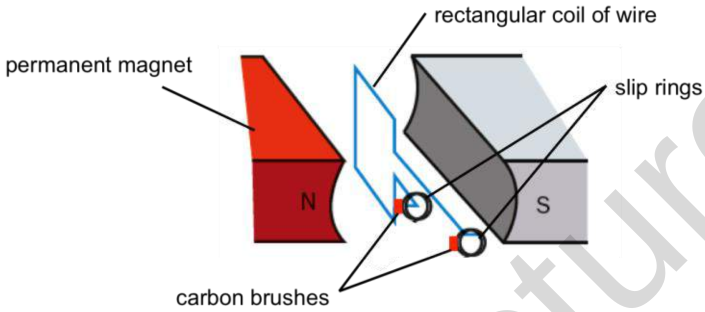
Question 4



Why does the light aluminium ring move away as the magnet is moved towards it?

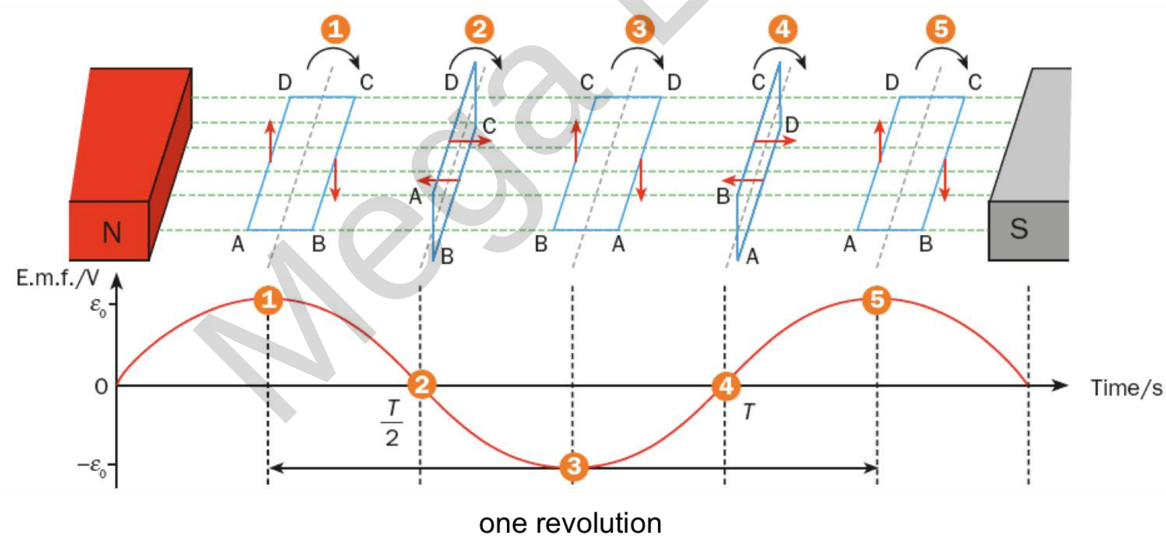
(b) Structure of an AC Generator

Rotating coil generator (O level syllabus)



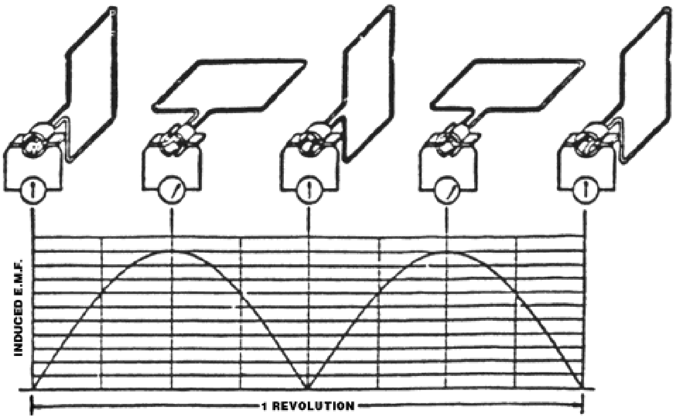
Slip rings – Ensures that the alternating output voltage of the rotating coil is transferred to an external circuit (If a split ring commutator is used, it reverses the direction of the output emf to the external circuit every half cycle such that a DC output is obtained)

(c) Graph of **voltage against time** for a simple a.c. generator

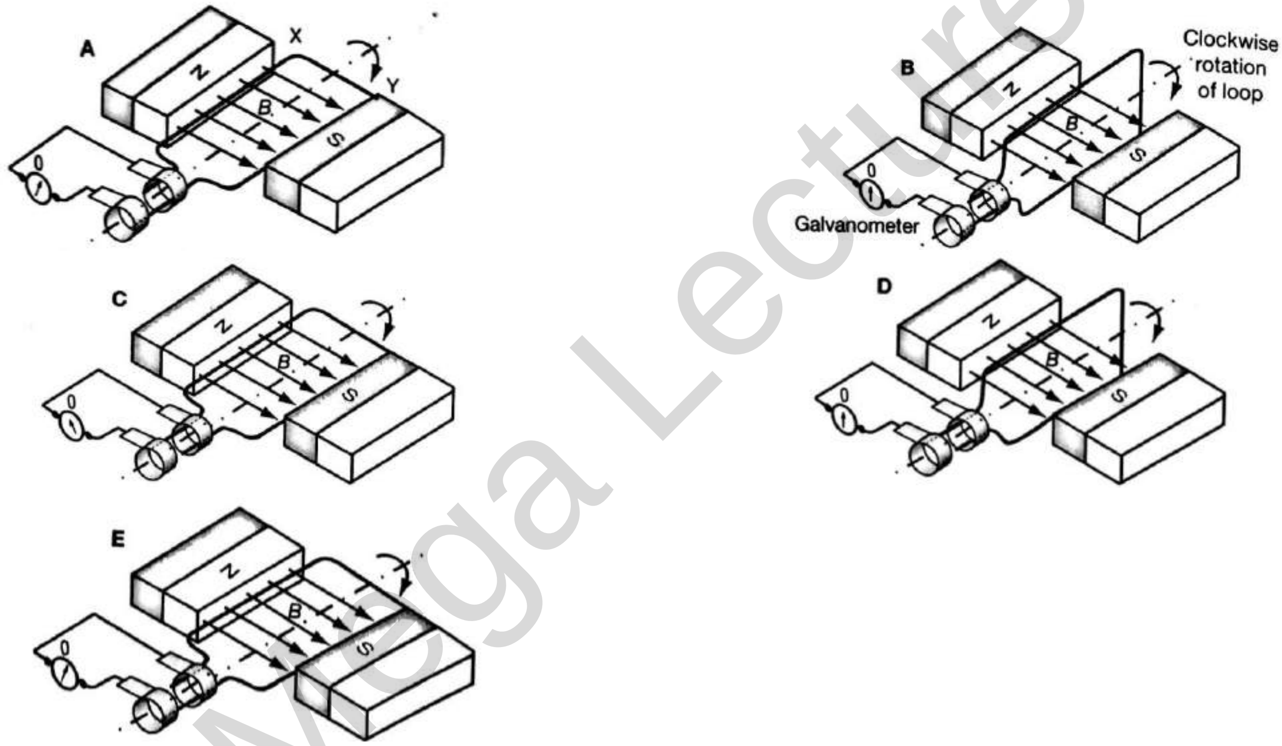


How does the magnetic flux linkage vary with time?

DC Generator output (not in syllabus)



Question 5

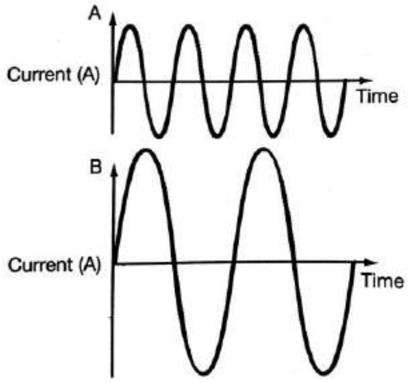


(a) Deduce the direction of the induced current in each of the coils from the point of view of an observer in front of the slip ring (clockwise, anticlockwise or zero current)

(b) State if the magnetic flux linkage and induced emf in each of the positions is maximum or zero.

Position	Direction of induced current (clockwise/anticlockwise/zero)	Magnetic flux linkage (maximum or minimum)	Size of induced current (maximum or minimum)
A			
B			
C			
D			
E			

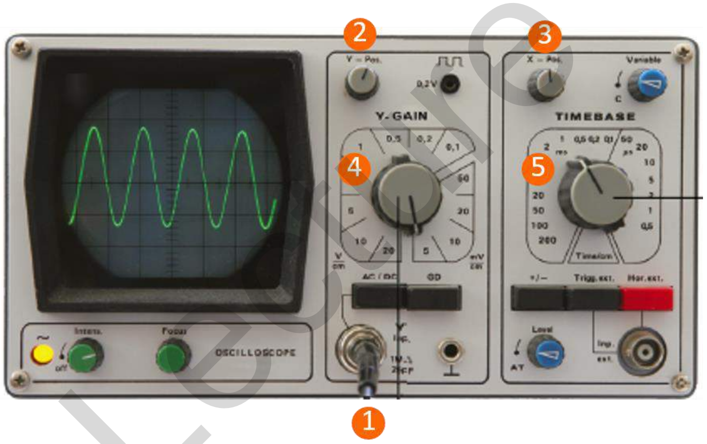
Question 6
The figure shows the current produced by two different generators.



(a)	Compare these graphs in terms of magnitude of current and frequency.
(b)	Explain, in terms of possible structural differences between the two generators, why these graphs are different.

(d) Cathode Ray Oscilloscope (CRO)

1. Input voltage
2. Y-shift or Y-offset – shifts entire trace **vertically** up or down
3. X-shift – shifts entire trace **horizontally** left or right
4. Y-gain control – amplifies height of electron beam
5. Time base control – controls speed at which electron beam sweeps across the screen



Y gain (Volts/division on the y-axis)

- Determines height of trace

Time base (milliseconds/division on the x-axis)

- Varying voltage connected to X-deflection plates.
- Causes one plate to become steadily more positive so that the electron beam moves at constant speed across the screen

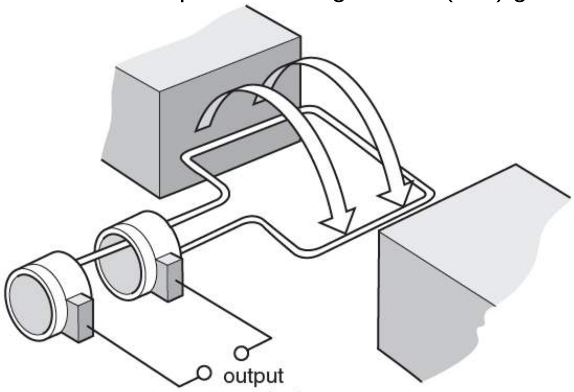
Time base frequency (Hz)

- Number of times the spot travels across the screen from left to right in one second
- e.g. timebase frequency 25 Hz → spot sweeps across the screen 25 times in 1 second

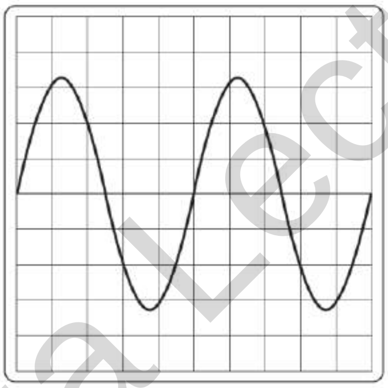
Given that the input voltage has a frequency of 50 Hz – in one second, the direction of the voltage alternates 50 times.
If the time base frequency is 25 Hz – in one second, the electron beam sweeps across the screen 25 times.

The number of complete waves that will be observed on the CRO screen is 50/25 = 2

Question 7
The figure below shows the structure of a simple alternating current (a.c.) generator.



(a) On the figure, label (i) the coil of the generator with the letter C, (ii) a slip ring with the letter S, (iii) a carbon brush with the letter B.
(b) The a.c. generator is operating and the arrows on the figure show the direction of rotation. Explain why there is an electromotive force between the two output terminals.
(c) The output terminals of the a.c. generator are connected to a cathode-ray oscilloscope. (c.r.o.) The figure below shows the trace on the screen of the c.r.o.

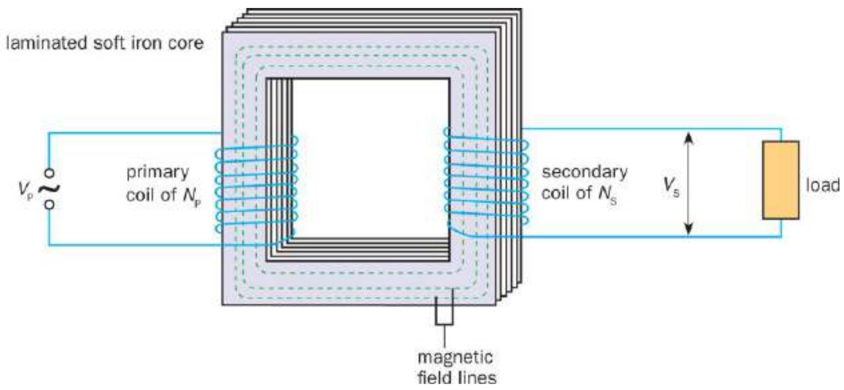


Describe how the trace and a setting on the c.r.o. are used to find the time for one revolution of the coil of the a.c. generator. You may draw on the figure.

Compare the **difference** in the **functions** of the parts in a **DC motor** and an **AC generator**

Part of motor	Function in motor	Function in generator
Armature	Rotates to convert electrical energy into kinetic energy	Rotates to transfer kinetic energy to electrical energy
Magnets	Provide field for interaction with a second field induced by current to produce a force and hence a turning effect on the coil	Provide field to induce current in rotating coil
Coil	Carries supply current	Movement of coil in magnetic field induces current
• Commutator in DC motor • Slip ring in AC generator	Changes direction of supply current every half rotation so moment produced is in a constant direction	Provide electrical contact between rotating coil and the external circuit and to allow for a.c. production
Brush	Provide electrical connection for supply current to coil	Provide electrical connection for output current

(f) Simple iron-cored transformer



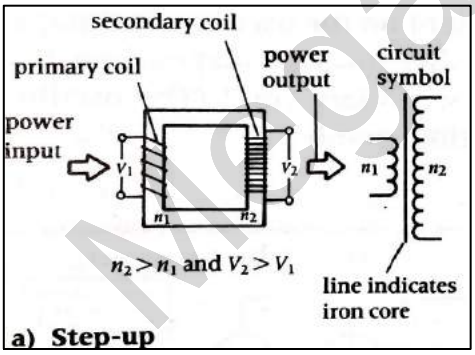
- The alternating voltage in the primary coil (V_p) causes an alternating magnetic field to be set up in the soft iron core.
- The alternating magnetic field lines in the iron core cut/link the secondary coil causing an emf (V_s) to be induced in the secondary coil.
- The frequency of the induced emf in the secondary is the same as the frequency of the a.c. in the primary coil.

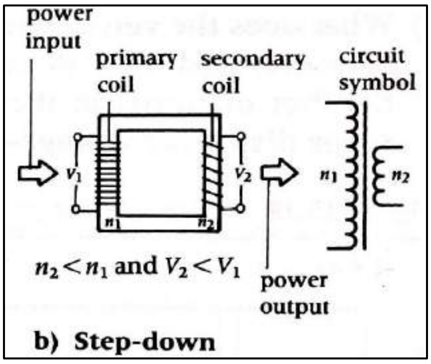
$$\frac{secondary\ voltage}{primary\ voltage} = \frac{secondary\ turns}{primary\ turns}$$

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

(g) Power transfer in an ideal transformer

$$P_{in} = P_{out}$$
$$I_pV_p = I_sV_s$$

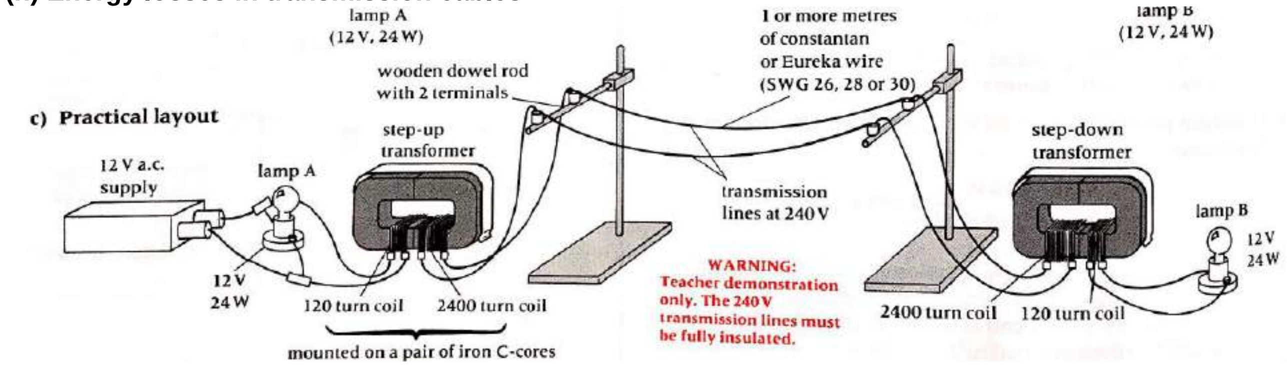


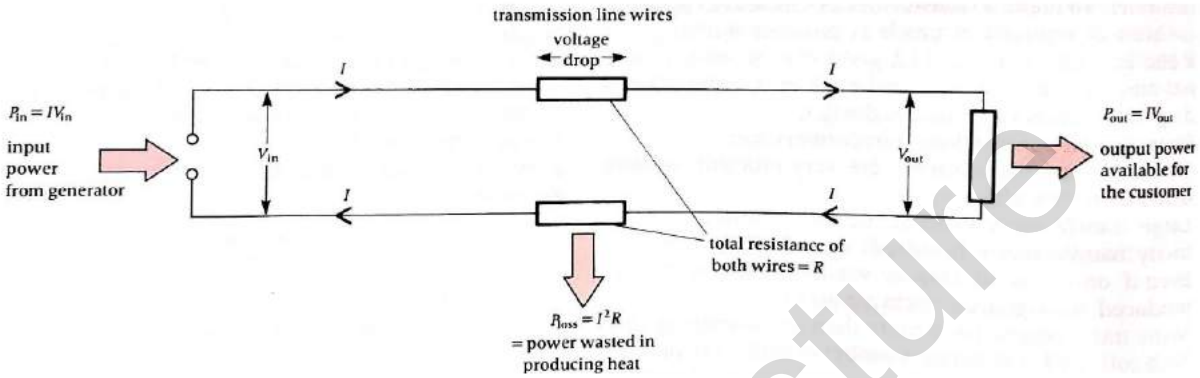


To reduce losses in a transformer

Type of loss	Method to reduce loss
Heating losses in copper wire	Thick copper wires with low resistance
Heating losses due to eddy currents in iron core (changing magnetic field induces current in core, current will in turn produce heat)	Laminated iron core reduces eddy currents
Incomplete linkage of magnetic field lines between primary and secondary coil	Wind secondary coil on top of primary coil
Energy used in magnetising iron core and reversing this magnetisation when current reverses	Iron core is made of soft iron which is easily magnetised and demagnetised

(h) Energy losses in transmission cables

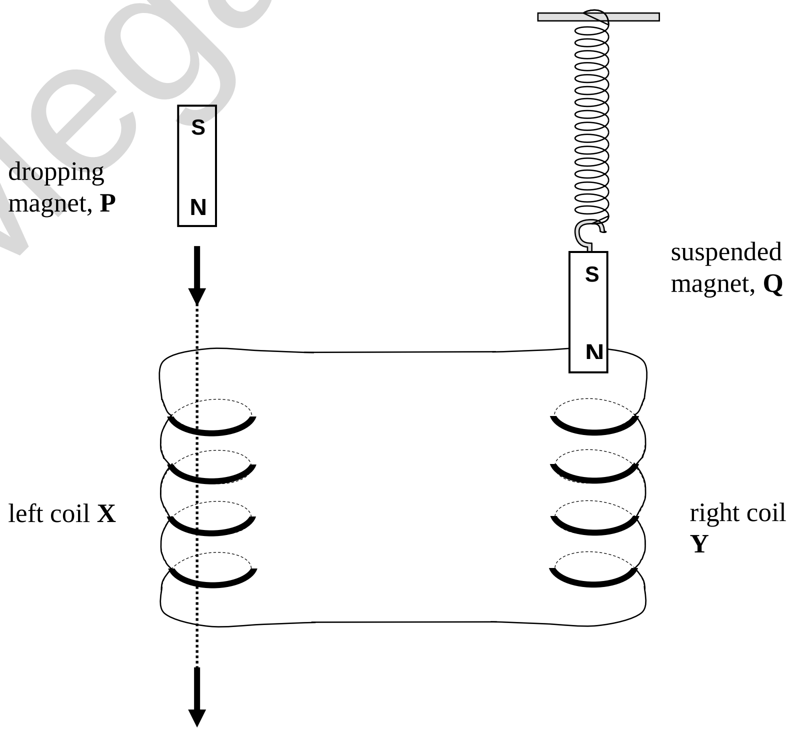




- Current in the transmission line is always the same but the voltage drops along the wire as power is lost in the form of heat so that V_{out} is less than V_{in}.
- Power loss is given by I^2R where R is the resistance of the wire in the transmission line.
- **High transmission voltage** keeps the **current** in the wires **low**
- Resistance is kept low by using **thick wires** with a large cross sectional area

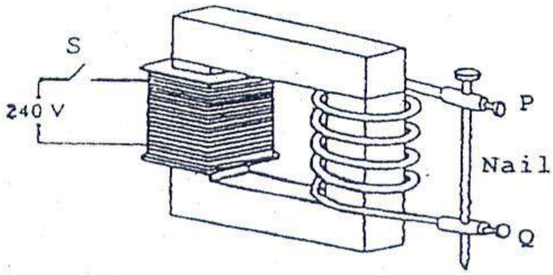
Question 8

The diagram shows two solenoids connected in series. A bar magnet, **P**, is dropped through the left coil, **X**.



(a) Describe and explain what happens to the suspended magnet, **Q** when the north pole of the falling magnet, **P**, approaches the top of the left coil, **X**. [4]

(b) A transformer in Fig. Q has a primary coil of 400 turns of insulated copper wire and a secondary coil of 5 turns of thick-walled copper tubing.



The primary coil is connected to the 240 V a.c. mains and a nail is connected across the secondary terminals.
When the switch **S** is closed, the nail glows.

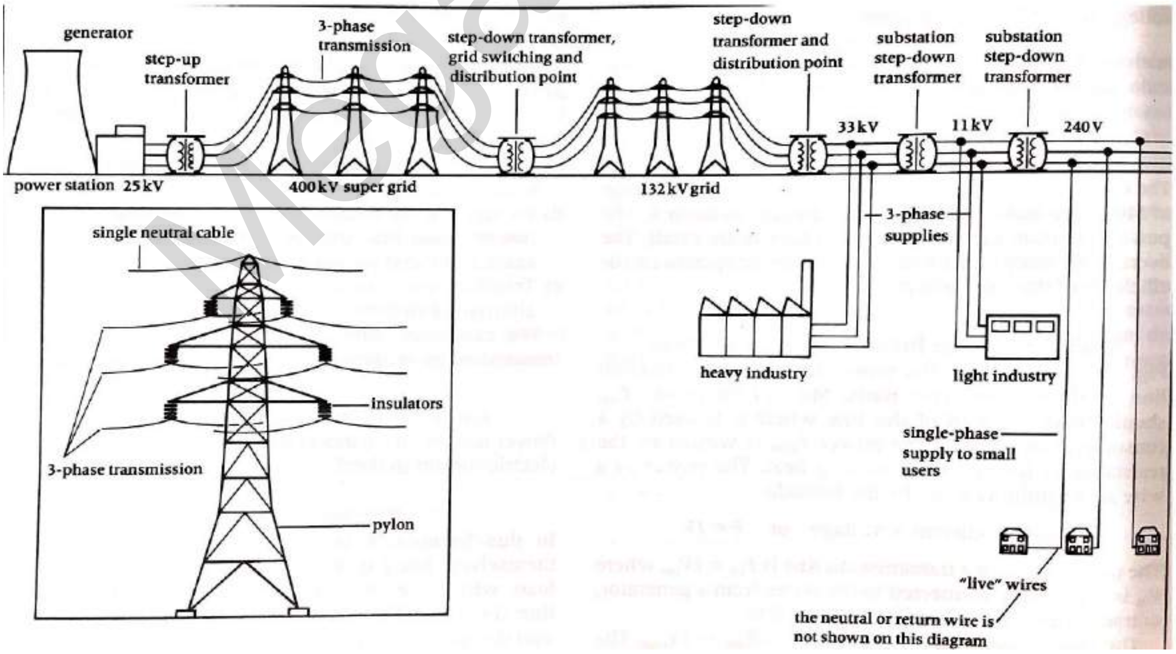
(i) Calculate the potential difference across the ends of the nails. [1]

(ii) Explain why the nail glows. [1]

(iii) Explain why an a.c. source is used in the primary coil of the transformer. [2]

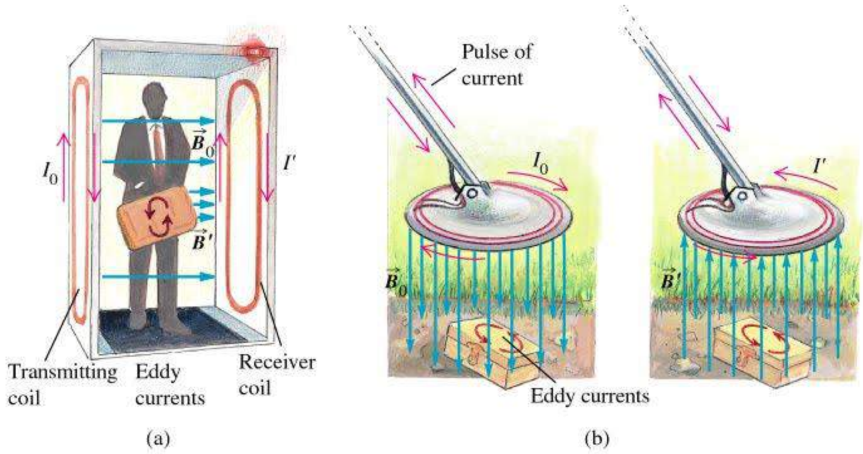
(iv) If the soft-iron core is removed before the switch is closed, the nail remains quite cool. Explain this observation. [2]

Transmission through the grid system

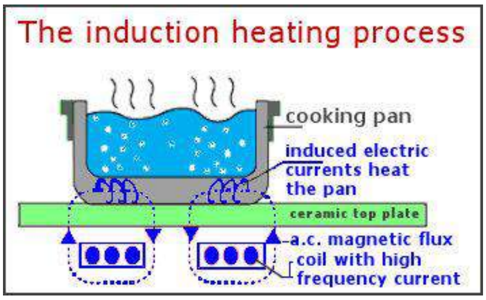


Other uses of induced emf

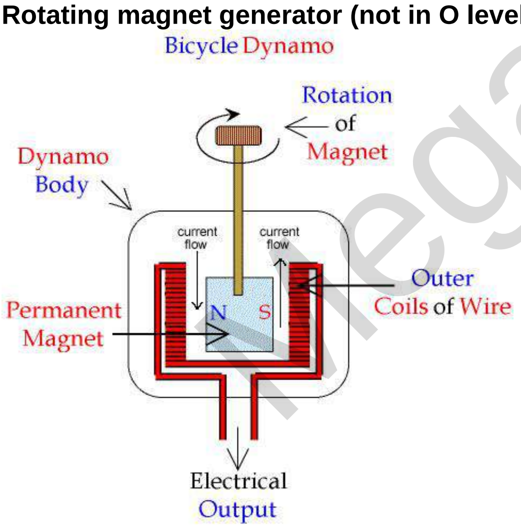
Metal detector



Induction cooker



Rotating magnet generator (not in O level syllabus)



8	**(a)**	one label correct <u>and</u> not contradicted	C1
		C, 1S and 1B all correct and clear <u>and</u> none contradicted	A1
	(b)	any **three** from: magnetic field (between poles) (coil / wire) cuts field / flux **or** field / flux cuts (coil / wire) **or** field / flux changes (electromagnetic) induction brushes rub against / in contact with rings	B3
	(c)	(half) distance across screen **or** count divisions of / measure wavelength **or** the wavelength corresponds to one rotation	B1
		half distance multiplied by time base setting	B1

3 (a) As the N pole of P approaches the coil, an emf is induced in the coil due to change in magnetic flux linking its coils. This causes a magnetic field to be set up in coil X. By Lenz's law, the polarity of the end facing the approaching N pole becomes an N pole while the end of coil Y facing the S pole of coil Q is an induced N pole. Therefore, Q will be repelled by coil Y since like poles repel.

(b) (i) Turns ratio = 400: 5 = 80: 1

Secondary emf = 240 ÷ 80 = 3 V

(ii) When voltage is stepped down, current increases. The high current through the nail causes it to heat up and glow.

(iii) An ac is needed to ensure that the magnetic flux linking the coils change continuously so that a continuous emf can be induced in the secondary coil

(iv) The induced emf is proportional to the rate of change of magnetic flux and the iron core's purpose is to increase the magnetic field strength, therefore if it is removed, the rate of flux change is reduced and the magnitude of the induced emf and current decreases hence the iron nail remains cool.