PROSPERITY ACADEMY

A2 PHYSCIS 9702

Crash Course

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ELECTROMAGNETIC INDUCTION

COMPLETE NOTES

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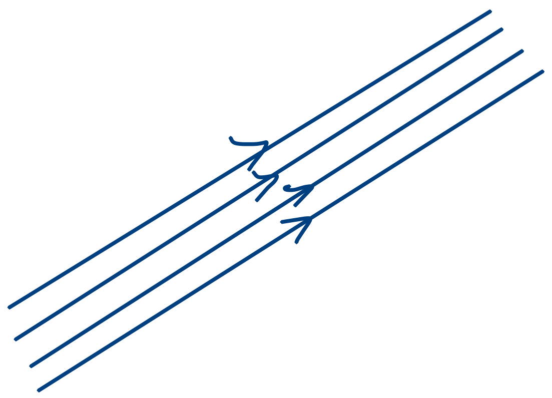
Electromagnetic Induction :-

Magnetic flux :- Collection of field lines



magnetic flux

Magnetic flux linkage:- (CAIE regards this as magnetic flux) [Scalar measured in Webers (Wb)]

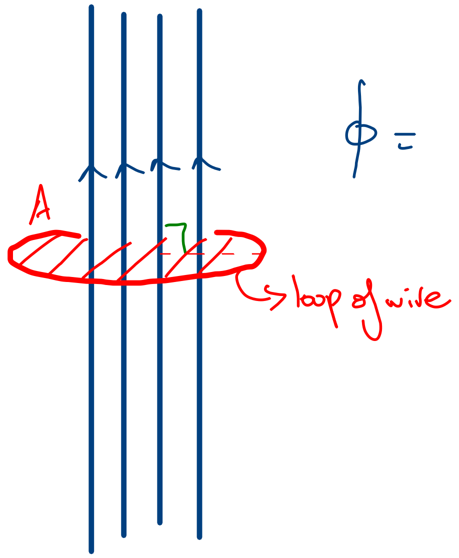
Defined as the product of :-

1) The magnetic field strength x <u>Perpendicular</u> cross sectional area of a loop of wire in that magnetic field.

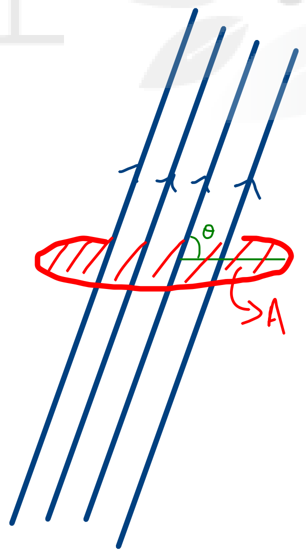
$$\phi = B \times A$$

2) The perpendicular component of magnetic field strength x cross sectional area of a loop of wire in that magnetic field.

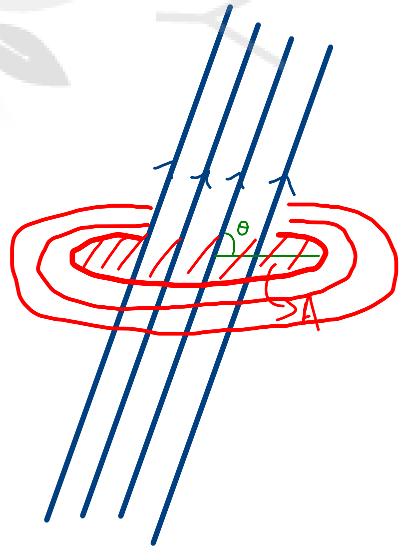
$$\phi = B\sin\theta \times A$$



$$\phi = B \times A$$



$$\phi = B\sin\theta \times A$$



$$\phi_N = N \times \phi_1$$

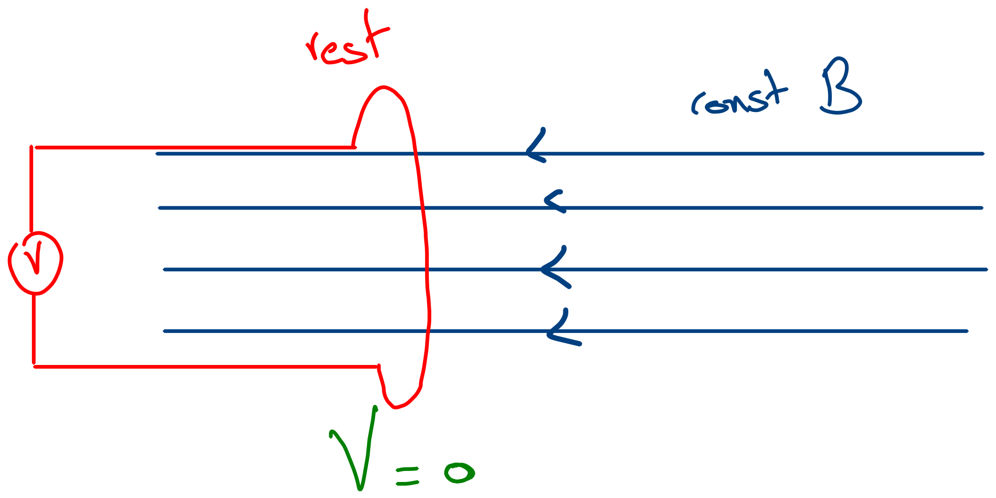
$$\phi_N = N \times B \times A \times \sin\theta$$

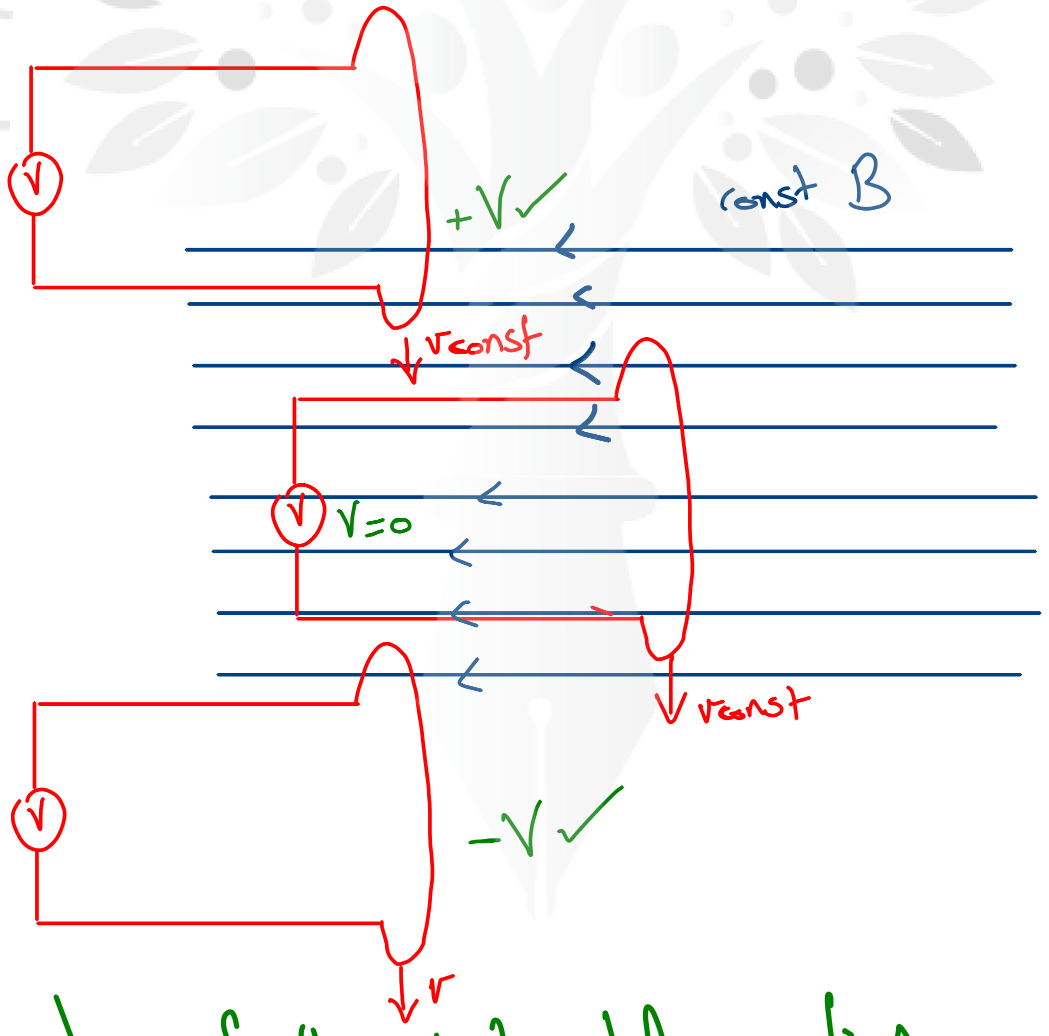
Faraday's law of Induction :-

The rate of change of magnetic flux linkage of a conductor is directly proportional to the e.m.f induced across the ends of that conductor.

when there is no change in magnetic flux linkage, there will be no e.m.f

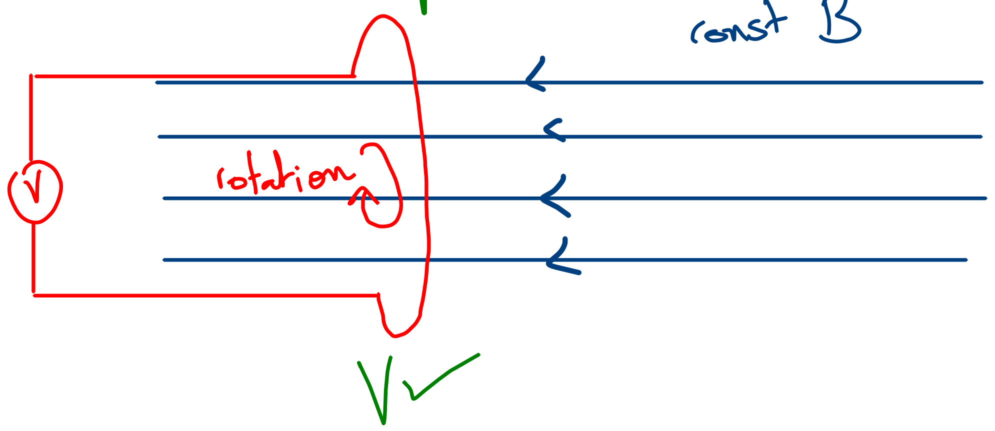
$$E \propto \frac{d\phi}{dt}$$





1) e.m.f through translatory motion

2) E.m.f through rotatory motion



3) You can also vary B

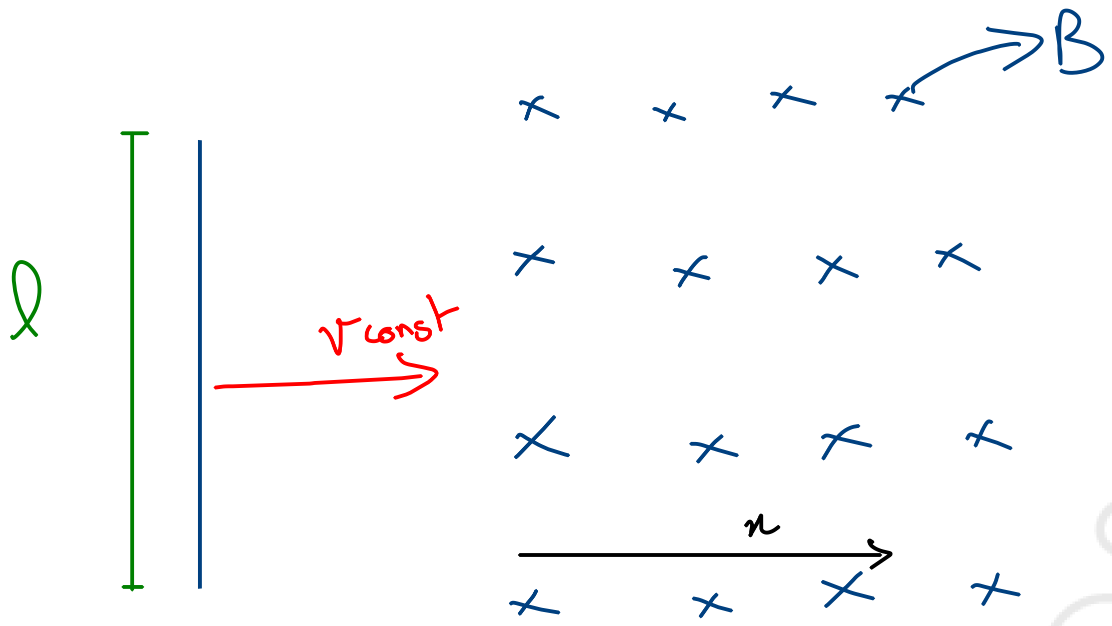
Lenz's law:-

The e.m.f induced in a conductor is such that it opposes the change producing it.

$$E = -\frac{d\phi}{dt}$$

Right Hand Flemming Rule (Used when current is being produced)

1) thumb → motion
2) pointer → magnetic field
3) middle finger → Induced current



$$\mathcal{E} = \frac{-d\phi}{dt} \Rightarrow \frac{-d(B \times A)}{dt} \Rightarrow B \times \frac{-dA}{dt} = B \times \frac{-d(x \times l)}{dt} = Bl \times \frac{-dx}{dt} = \boxed{\text{Magnitude of E.m.f} = Blv}$$

5 The poles of a horseshoe magnet measure 5.0 cm × 2.4 cm, as shown in Fig. 5.1.

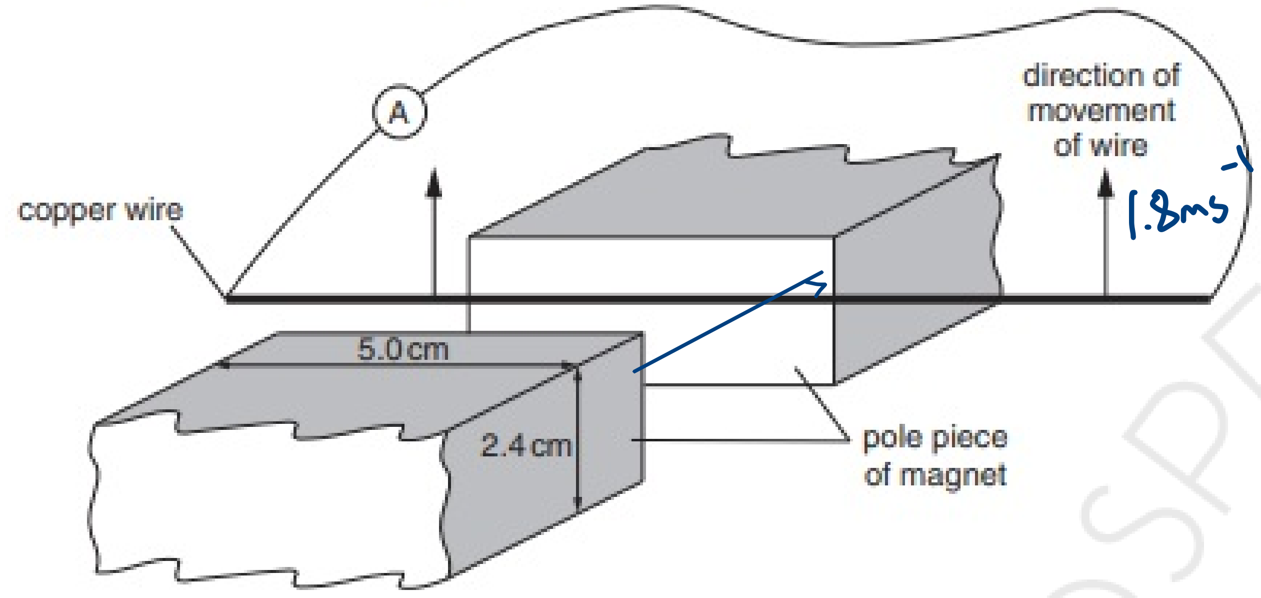


Fig. 5.1

The uniform magnetic flux density between the poles of the magnet is 89 mT. Outside the region of the poles, the magnetic flux density is zero.

A stiff copper wire is connected to a sensitive ammeter of resistance 0.12 Ω. A student moves the wire at a constant speed of $1.8\,\mathrm{m\,s^{-1}}$ between the poles in a direction parallel to the faces of the poles.

B

(a) Calculate the magnetic flux between the poles of the magnet.

ϕ

$$\phi = B \times A$$
$$= (89\times10^{-3}) \times [(5\times10^{-2}) \times (2.4\times10^{-2})]$$
$$= 1.068\times10^{-4}$$

magnetic flux = 1.1×10^{-4} Wb [2]

(b) **(i)** Use your answer in **(a)** to determine, for the wire moving between the poles of the magnet, the e.m.f. induced in the wire.

$$E = -\frac{d\phi}{dt} \Rightarrow \frac{\phi_f - \phi_i}{\Delta t} = \frac{(1.1\times10^{-4} - 0)}{\left(\frac{2.4\times10^{-2}}{1.8}\right)}$$
$$= 8.0\times10^{-3}\ \mathrm{V}$$

$$v = \frac{d}{t}$$
$$t = \frac{d}{v}$$
$$\Delta t = \frac{2.4\times10^{-2}}{1.8}$$

(ii) Show that the reading on the ammeter is approximately 70 mA.

$$E = IR$$
$$8\times10^{-3} = I \times (0.12)$$
$$I = 70\,\mathrm{mA}\ \text{shown}$$

[1]

(c) By reference to Lenz's law, a force acts on the wire to oppose the motion of the wire. The student who moved the wire between the poles of the magnet claims not to have felt this force.

Explain quantitatively a reason for this claim.

$$F = BIl$$
$$F = (89\times10^{-3}) \times (70\times10^{-3}) \times (5\times10^{-2}) \simeq 3\times10^{-4}\ \mathrm{N}$$

A force of 3×10^{-4} N is way too less to be felt

[3]

7 A solenoid is connected in series with a battery and a switch. A Hall probe is placed close to one end of the solenoid, as illustrated in Fig. 7.1.

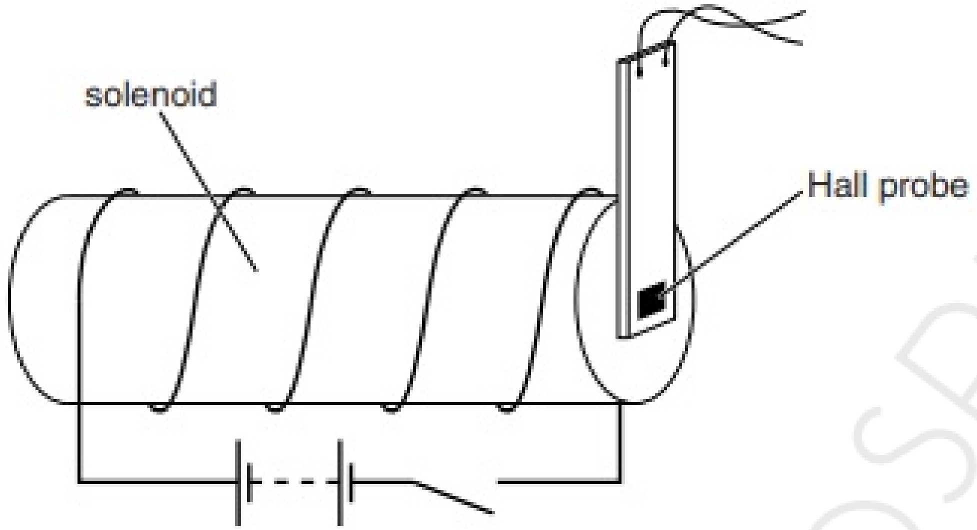


Fig. 7.1

The current in the solenoid is switched on. The Hall probe is adjusted in position to give the maximum reading. The current is then switched off.

(a) The current in the solenoid is now switched on again. Several seconds later, it is switched off. The Hall probe is not moved.

On the axes of Fig. 7.2, sketch a graph to show the variation with time *t* of the Hall voltage V_H.

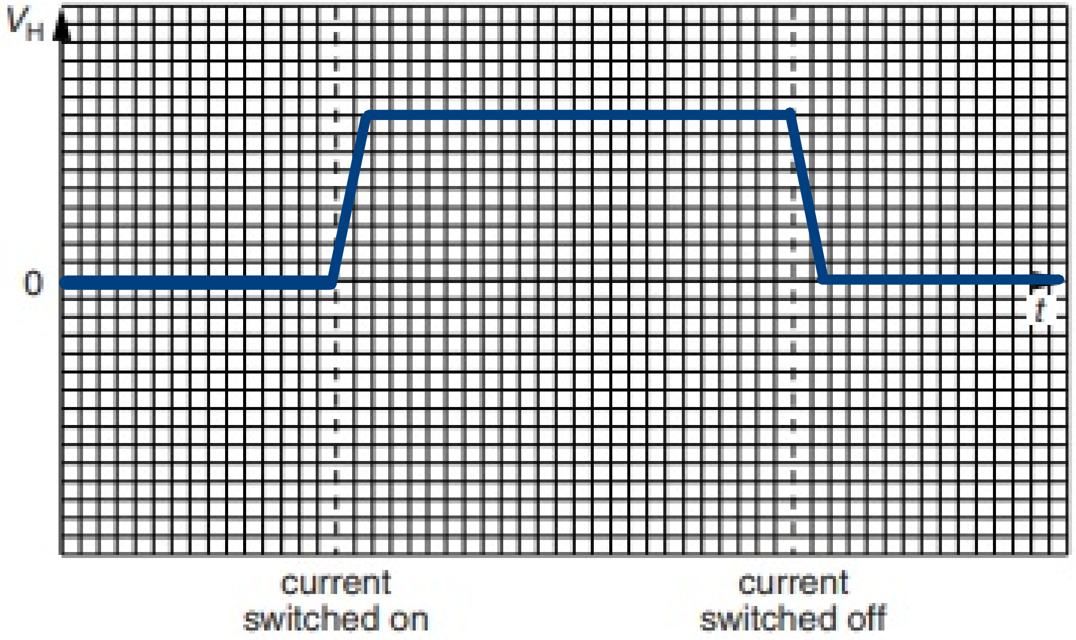


Fig. 7.2

[3]

(b) The Hall probe is now replaced by a small coil. The plane of the coil is parallel to the end of the solenoid.

(i) State Faraday's law of electromagnetic induction.

The e.m.f produced across the ends of a conductor placed in a magnetic field is directly proportional to the rate of change of magnetic flux linkage through it. [2]

(ii) On the axes of Fig. 7.3, sketch a graph to show the variation with time *t* of the e.m.f. *E* induced in the coil when the current in the solenoid is switched on and then switched off.

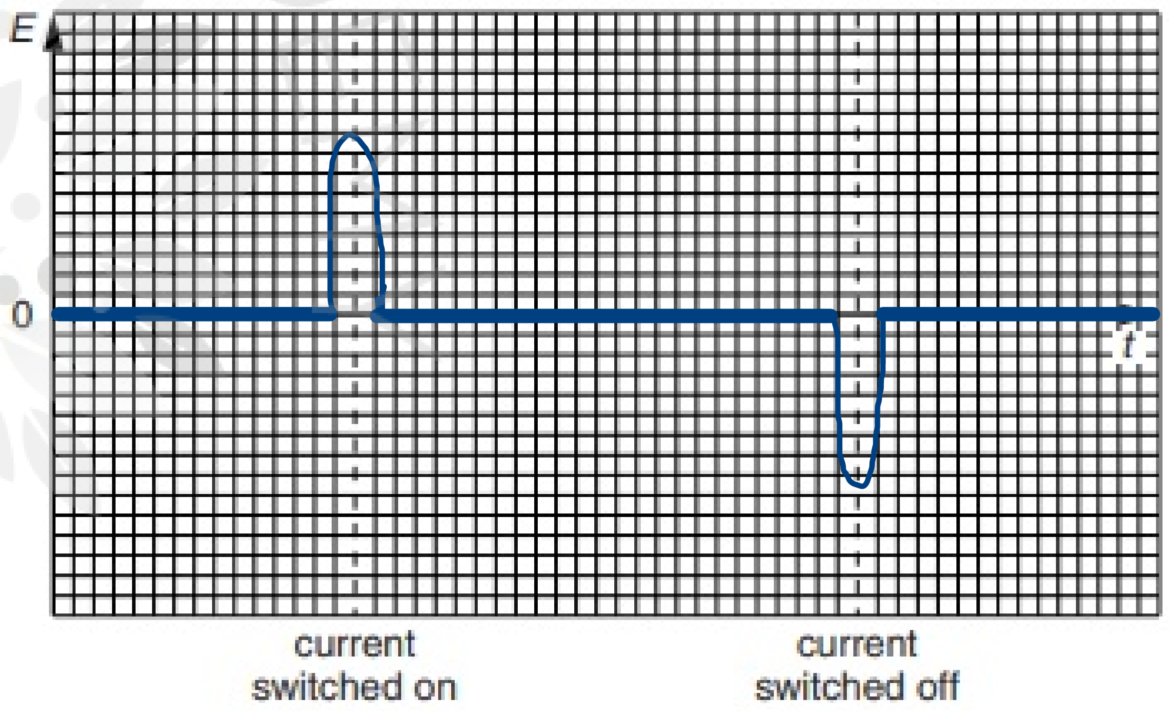


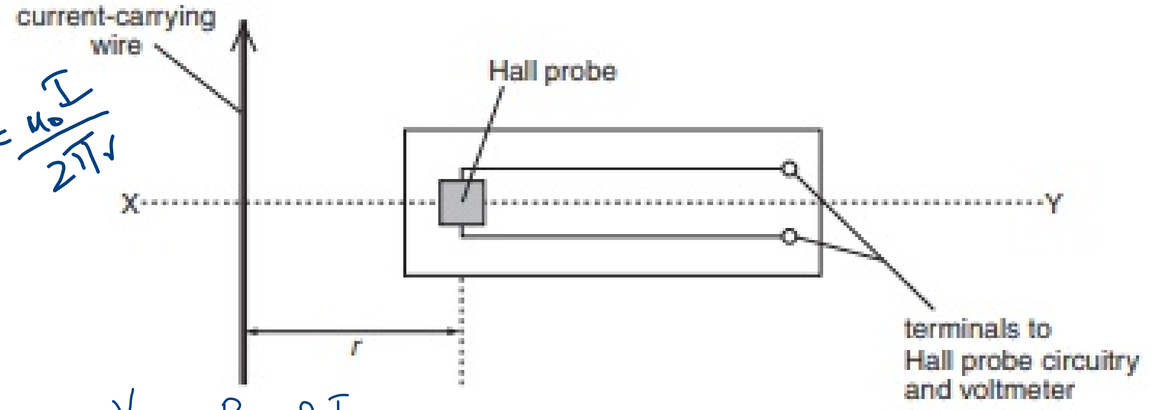
Fig. 7.3

$I \rightarrow B \rightarrow \phi$

[3]

5 (a) A constant current is maintained in a long straight vertical wire. A Hall probe is positioned a distance r from the centre of the wire, as shown in Fig. 5.1.

$B = \frac{\mu_0 I}{2\pi r}$



$V_H = \frac{B \sin\theta \, I}{ntq}$

Fig. 5.1

(i) Explain why, when the Hall probe is rotated about the horizontal axis XY, the Hall voltage varies between a maximum positive value and a maximum negative value.

V_H is maximum when the magnetic field s are perpendicular to the Hall probe. As the hall probe rotates, the angle with the magnetic field changes. [2]

(ii) The maximum Hall voltage V_H is measured at different distances r. Data for V_H and the corresponding values of r are shown in Fig. 5.2.

V_H / V	r / cm
0.290	1.0
0.190	1.5
0.140	2.0
0.097	3.0
0.073	4.0
0.060	5.0

Fig. 5.2

It is thought that V_H and r are related by an expression of the form

$$V_H = \frac{k}{r}$$

where k is a constant.

$0.290 = \frac{K}{1 \times 10^{-2}}$ $0.190 = \frac{K}{1.5 \times 10^{-2}}$ $0.140 = \frac{K}{2 \times 10^{-2}}$

$K = 2.9 \times 10^{-3}$ $K = 2.85 \times 10^{-3}$ $K = 2.8 \times 10^{-3}$

Valid b/c $K \simeq 3 \times 10^{-3}$ to 1 s.f.g
Invalid b/c K is not same to 2 s.f.g

1. Without drawing a graph, use data from Fig. 5.2 to suggest whether the expression is valid.

Done

[2]

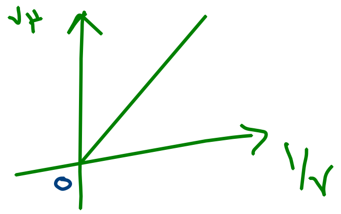
2. A graph showing the variation with $\frac{1}{r}$ of V_H is plotted.

State the features of the graph that suggest that the expression is valid.

It will be a straight line passing through the origin [1]

$V_H = K \times \frac{1}{r} + 0$

$y = m \, x + c$



(b) The Hall probe in (a) is now replaced with a small coil of wire connected to a sensitive voltmeter. The coil is arranged so that its plane is normal to the magnetic field of the wire.

(i) State Faraday's law of electromagnetic induction and hence explain why the voltmeter indicates a zero reading.

(state Faraday's law). Voltage is not induced as there is no change in magnetic flux linkage [3]

(ii) State three different ways in which an e.m.f. may be induced in the coil.

1. move to and fro / up and down

2. rotate the coil

3. Vary the current / switch current on and off / Use an alternating current [3]

5 (a) State the relation between magnetic flux density B and magnetic flux Φ, explaining any other symbols you use.

$\phi = N \times B \times A \times \sin\theta$

N: number of turns of coil placed in magnetic field.

A: Area of cross section of conductor.

sinθ: Angle between cross sectional area and magnetic field lines [2]

(b) A large horseshoe magnet has a uniform magnetic field between its poles. The magnetic field is zero outside the space between the poles.
A small Hall probe is moved at constant speed along a line XY that is midway between, and parallel to, the faces of the poles of the magnet, as shown in Fig. 5.1.

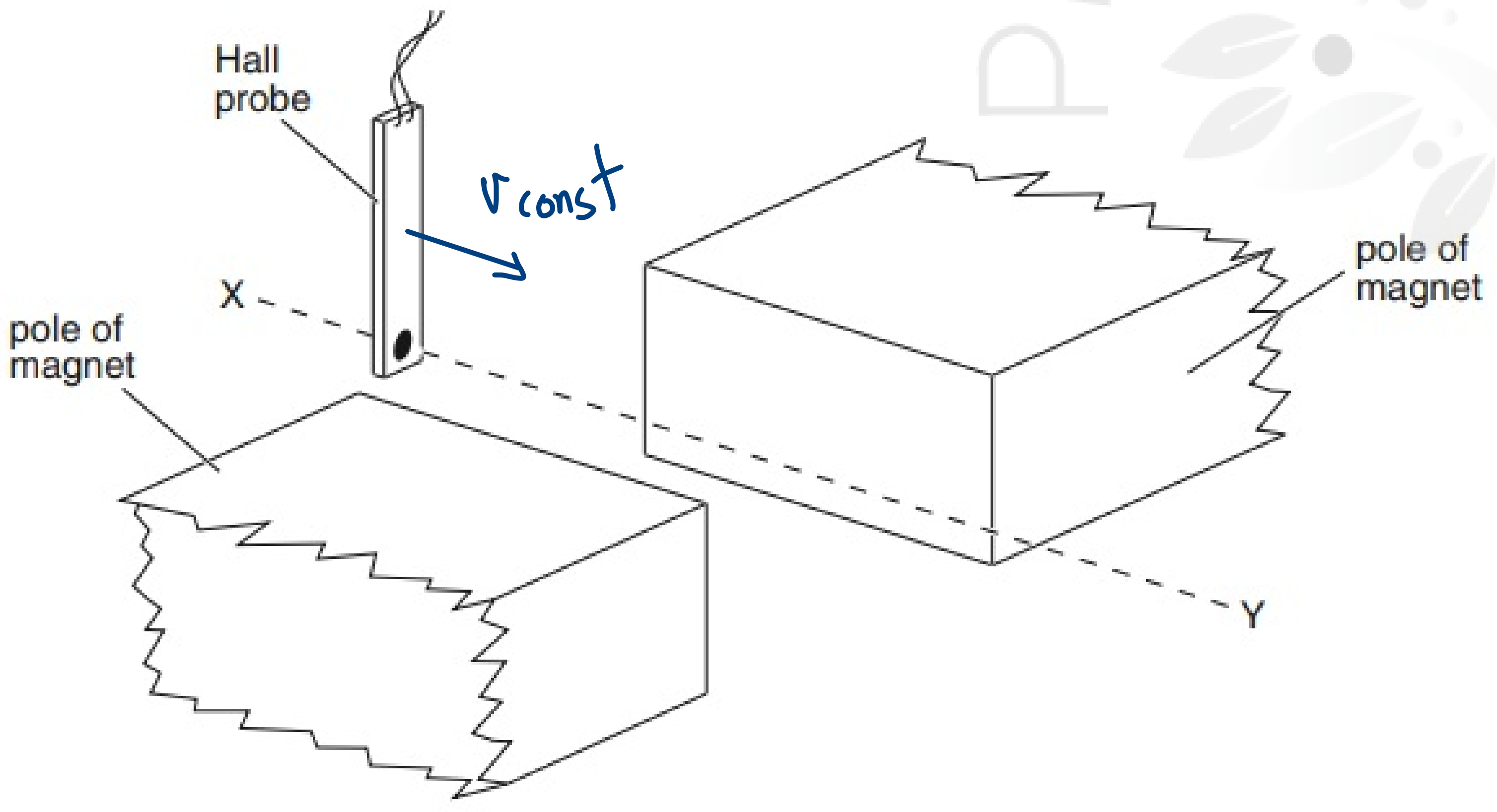


Fig. 5.1

An e.m.f. is produced by the Hall probe when it is in the magnetic field.
The angle between the plane of the probe and the direction of the magnetic field is not varied.

On the axes of Fig. 5.2, sketch a graph to show the variation with time t of the e.m.f. V_H produced by the Hall probe.

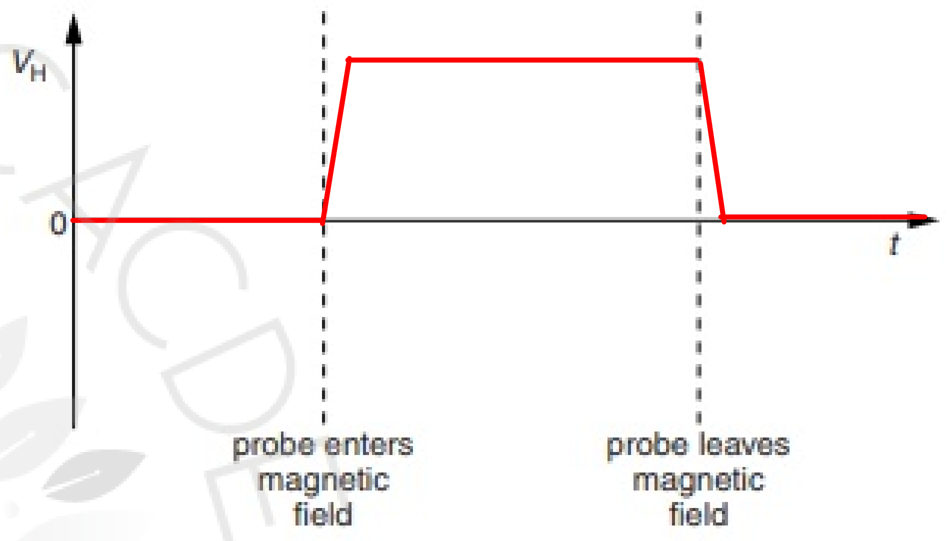


Fig. 5.2

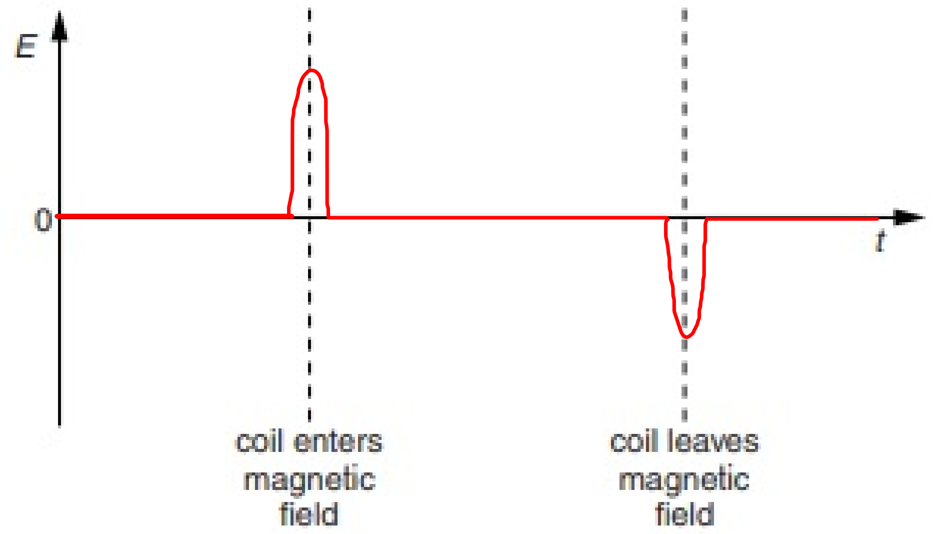
[2]

(c) (i) State Faraday's law of electromagnetic induction.

The e.m.f produced across the ends of a conductor placed in a magnetic field is directly proportional to the rate of change of magnetic flux linkage through it. [2]

(ii) The Hall probe in **(b)** is replaced by a small flat coil of wire. The coil is moved at constant speed along the line XY. The plane of the coil is parallel to the faces of the poles of the magnet.

On the axes of Fig. 5.3, sketch a graph to show the variation with time t of the e.m.f. E induced in the coil.



Magnetic Materials:-

1) Soft magnets :- They get magnetised and demagnetised easily and temporarily. Iron (electromagnets)

Iron improves magnetic flux linkage

2) Hard magnets:- They get magnetised and demagnetised with difficulty and permanently. Steel (Permanent magnets)

10 (a) A coil of insulated wire is wound on a copper core, as illustrated in Fig. 10.1.

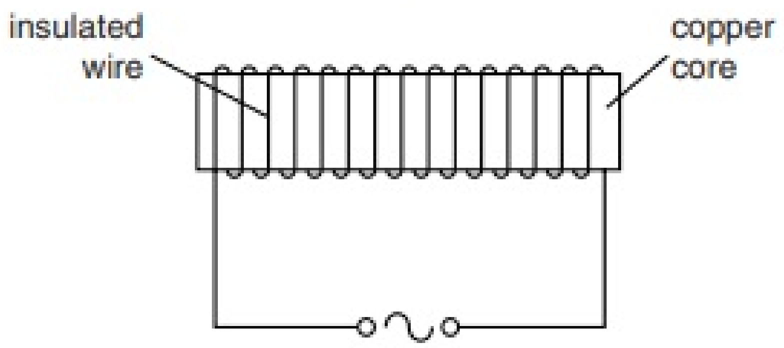


Fig. 10.1

An alternating current is passed through the coil.

The heating effect of the current in the coil is negligible.

Explain why the temperature of the core rises.

The magnetic flux linkage is constantly changing due to the alternating current in the wire. Due to this change in magnetic flux, many small e.m.f.s are induced in the iron core in different paths/localizations. These give rise to eddy currents that heat up the iron core as they flow through it's resistance. [4]

(b) Two hollow tubes of equal length hang vertically as shown in Fig. 10.2.

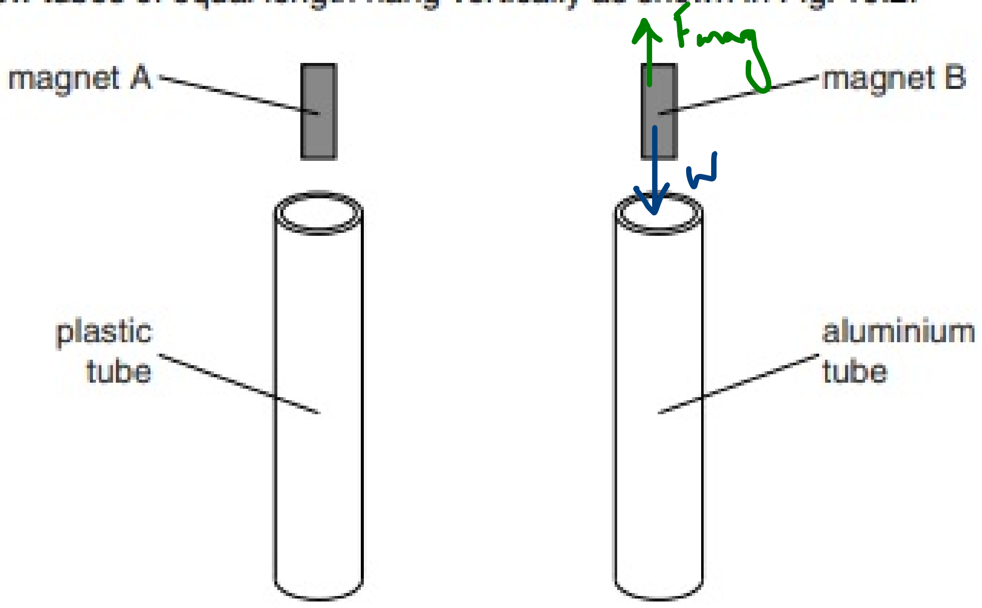


Fig. 10.2

The magnets do not touch the sides of the tubes.

Explain why magnet B takes much longer than magnet A to fall through the tube.

As the magnet falls, it induces an e.m.f in the aluminium tube due to it's translatory motion. These induced e.m.f.s will create currents in the aluminium tube such that they will form magnetic fields to oppose the motion of the magnet. The magnet therefore experiences a resistive force upwards and the resultant acceleration on it is less than g and so it takes longer to fall. [5]

[Total: 9]

10 Two coils P and Q are placed close to one another, as shown in Fig. 10.1.

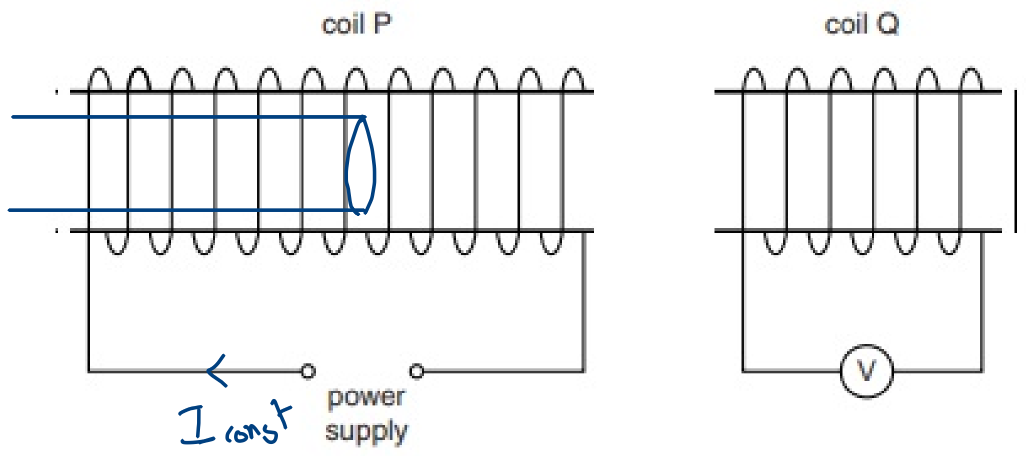


Fig. 10.1

(a) The current in coil P is constant.

An iron rod is inserted into coil P.

Explain why, during the time that the rod is moving, there is a reading on the voltmeter connected to coil Q.

The iron causes a change in the magnetic flux density of coil P. Therefore a change in magnetic flux linkage is experienced and e.m.f is induced. .... [2]

$$E = \frac{-d\phi}{dt}$$

$$E = \frac{-d(N \times B \times A)}{dt}$$

const, const

$$E = \underbrace{N \times A}_{} \times \frac{-dB}{dt}$$

const

$$E \propto \frac{-dB}{dt} \Rightarrow B \propto I \Rightarrow E \propto \frac{-dI}{dt}$$

$$B = \frac{\mu_0 I}{2\pi r}$$

$$B = \mu_0 n I$$

$$B = \frac{\mu_0 I}{2\pi r}$$

(b) The current in coil P is now varied as shown in Fig. 10.2.

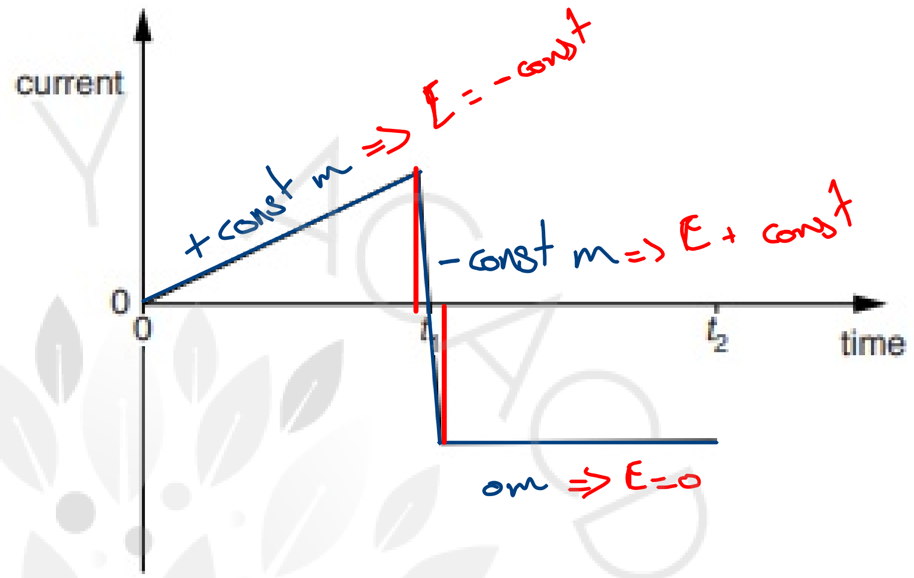


Fig. 10.2

$$E \propto -\frac{dI}{dt} \Rightarrow -\frac{\Delta I}{\Delta t} \Rightarrow \frac{\Delta y}{\Delta x} = m$$

E is -ve gradient of current time graph

On Fig. 10.3, show the variation with time of the reading of the voltmeter connected to coil Q for time $t = 0$ to time $t = t_2$.

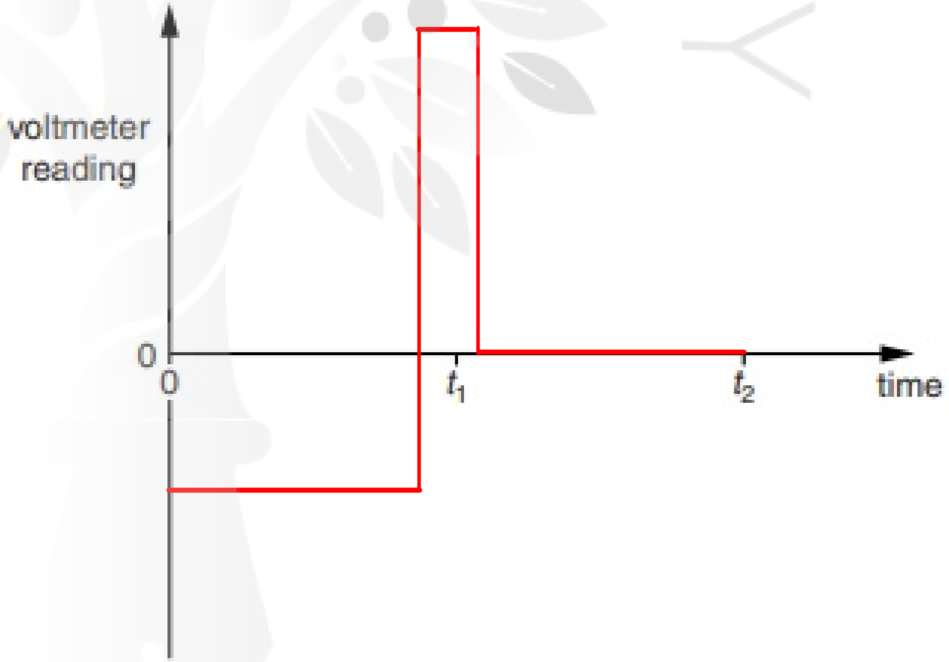


Fig. 10.3

[4]

[Total: 6]

10 (a) (i) Define *magnetic flux*.

It is defined as the product of the magnetic field density to the perpendicular cross sectional of a single loop of current carrying conductor placed in a magnetic field. [2]

(ii) State Faraday's law of electromagnetic induction.

The e.m.f produced across the ends of a conductor placed in a magnetic field is directly proportional to the rate of change of magnetic flux linkage through it. [2]

(b) A solenoid has a coil C of wire wound tightly about its centre, as shown in Fig. 10.1.

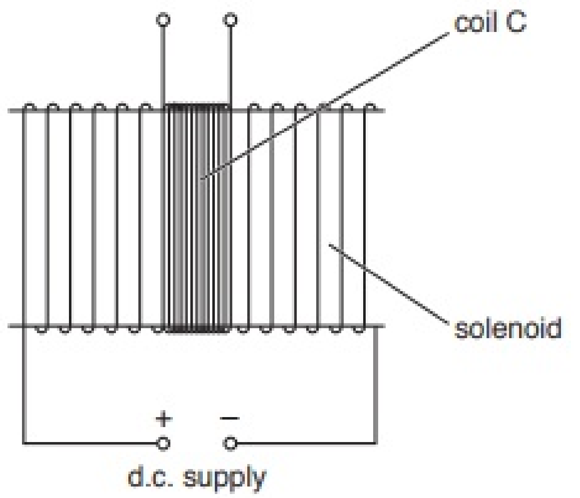


Fig. 10.1

The coil C has 96 turns.

The uniform magnetic flux Φ (in weber) in the solenoid is given by the expression

$$\Phi = 6.8 \times 10^{-6} \times I$$

where I is the current (in amperes) in the solenoid.

Calculate the average electromotive force (e.m.f.) induced in coil C when a current of 3.5 A is reversed in the solenoid in a time of 2.4 ms.

$$E = -\frac{d\phi}{dt} = -\frac{d(\overset{\text{const}}{6.8\times10^{-6}} \times I)}{dt} = -6.8\times10^{-6} \times \frac{\Delta I}{\Delta t}$$

$$= \left(-6.8\times10^{-6} \times \frac{-7}{2.4\times10^{-3}}\right) \times 96$$

$$= 1.904$$

$$\Delta I = I_f - I_i = -3.5 - (3.5) = -7$$

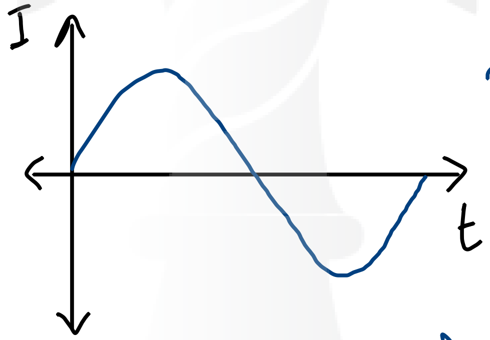
e.m.f. = 1.9 V [2]

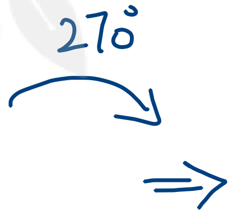
(c) The d.c. supply in Fig. 10.1 is now replaced with a sinusoidal alternating supply.

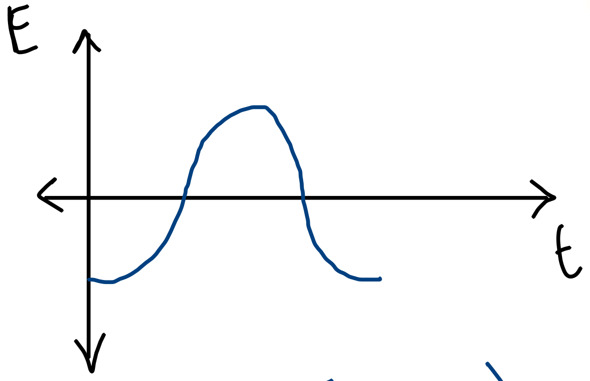
Describe qualitatively the e.m.f. that is now induced in coil C.

The e.m.f is also alternating with the same frequency. The induced e.m.f will be out of phase (Learn this) [2]

[Total: 8]







$I = I_0 \sin(\omega t)$ $\quad$ $E \propto -E_0 \cos(\omega t)$

9 (a) State what is meant by the *magnetic flux linkage* of a coil.

It is defined as the product of the magnetic field strength to the perpendicular cross sectional area of a coil placed in a magnetic field and to the number of turns of the coil. ($\phi = N \times B \times A \sin\theta$)

...[3]

(b) A coil of wire has 160 turns and diameter 2.4 cm. The coil is situated in a uniform magnetic field of flux density 7.5 mT, as shown in Fig. 9.1.

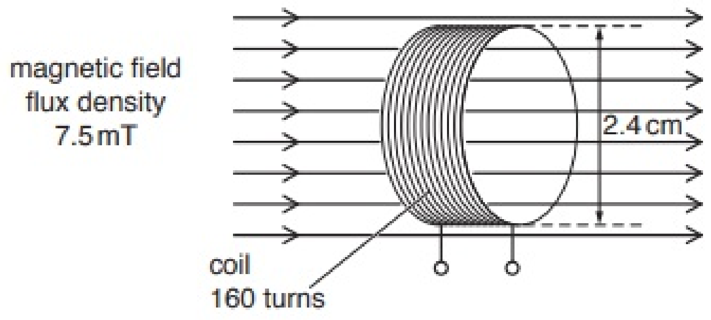


Fig. 9.1

The direction of the magnetic field is along the axis of the coil.

The magnetic flux density is reduced to zero in a time of 0.15 s. $B_f = 0$ $B_i = 7.5\,mT$

Show that the average e.m.f. induced in the coil is 3.6 mV.

$$E = \frac{-d\phi}{dt} = \frac{-d(B \times A)}{dt} = -A \times \frac{\Delta B}{\Delta t} = -A \times \frac{B_f - B_i}{\Delta t}$$

$$= 160 \times \left[\frac{\pi(2.4\times10^{-2})^2}{4} \times \frac{0-(7.5\times10^{-3})}{0.15}\right]$$

$$= 3.6\times10^{-3}\,V$$

(c) The magnetic flux density *B* in the coil in **(b)** is now varied with time *t* as shown in Fig. 9.2.

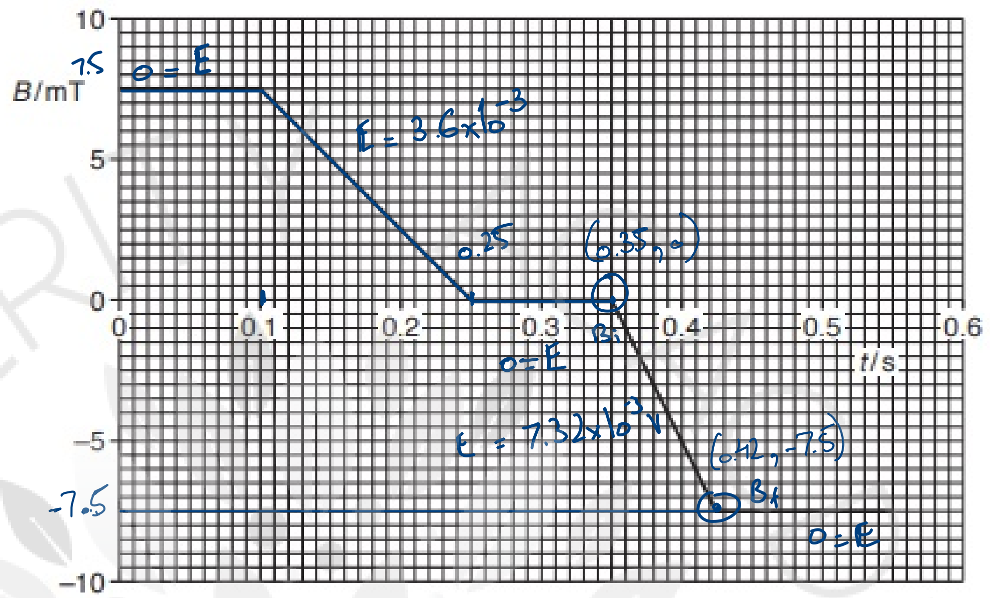


Fig. 9.2

$$E = \frac{-d\phi}{dt}$$

$$E = -A \times \frac{dB}{dt}$$

$$E \propto \frac{-dB}{dt}$$

$$E_1 = K\left(\frac{dB}{dt}\right)_1$$

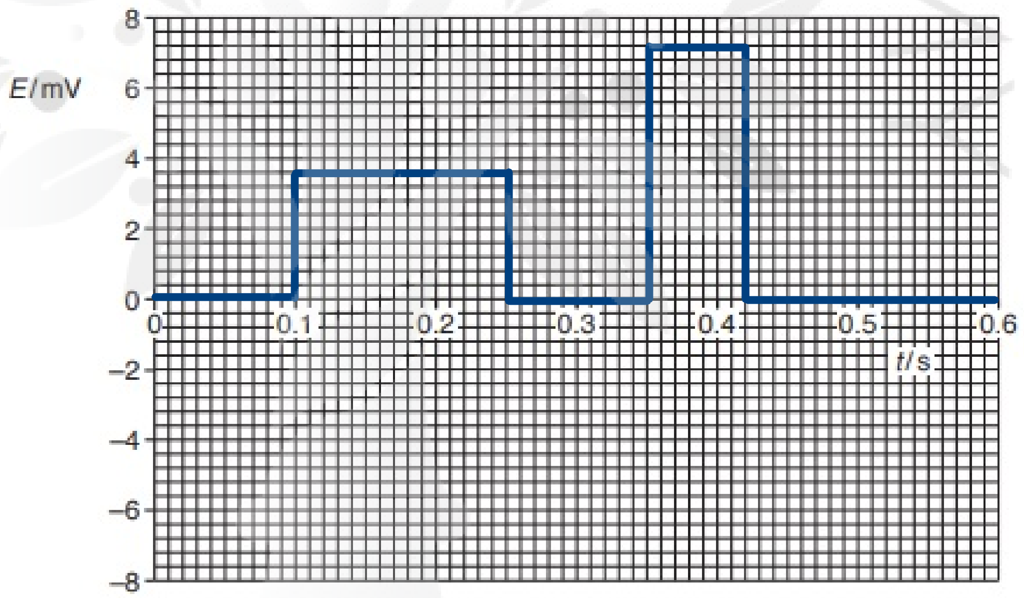
$$\frac{E_1}{\left(\frac{dB}{dt}\right)_1} = \frac{E_2}{\left(\frac{dB}{dt}\right)_2}$$

$$\frac{3.6\times10^{-3}}{\frac{-7.5\times10^{-3}}{0.15}} = \frac{E_2}{\frac{-7.5\times10^{-3}-0}{0.42-0.35}}$$

$$E_2 = \frac{(3.6\times10^{-3}) \times \left(\frac{-7.5\times10^{-3}}{0.42-0.35}\right)}{\left(\frac{-7.5\times10^{-3}}{0.15}\right)}$$

$$E_2 = 7.32\times10^{-3}$$

Use data in **(b)** to show, on Fig. 9.3, the variation with time *t* of the e.m.f. *E* induced in the coil.

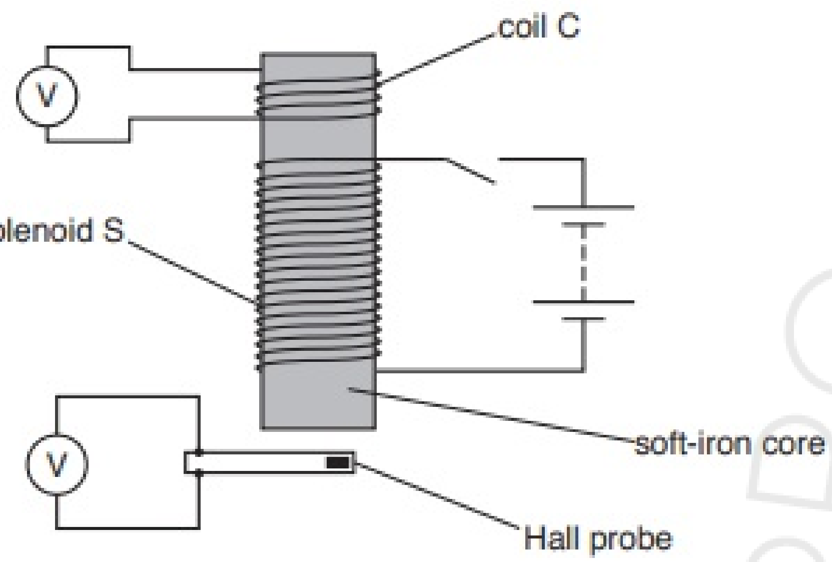


4 marks

9 **(a)** State Faraday's law of electromagnetic induction.

The e.m.f produced across the ends of a conductor placed in a magnetic field is directly proportional to the rate of change of magnetic flux linkage through it. [2]

(b) A solenoid S is wound on a soft-iron core, as shown in Fig. 9.1.



$E = -\frac{d\phi}{dt}$

Fig. 9.1

A coil C having 120 turns of wire is wound on to one end of the core. The area of cross-section of coil C is 1.5 cm^2.

A Hall probe is close to the other end of the core.

When there is a constant current in solenoid S, the flux density in the core is 0.19 T. The reading on the voltmeter connected to the Hall probe is 0.20 V.

The current in solenoid S is now reversed in a time of 0.13 s at a constant rate. $B_i = 0.19$ $B_f = -0.19$

(i) Calculate the reading on the voltmeter connected to coil C during the time that the current is changing.

$$E = -\frac{d\phi}{dt} = -\frac{d(B \times A)}{dt} = -A \times \frac{dB}{dt} \Rightarrow E = \left[-A \times \frac{B_f - B_i}{\Delta t}\right] \times 120$$

$$E = \left[\left[-1.5 \times (10^{-2})^2\right] \times \frac{-0.19 - 0.19}{0.13}\right] \times 120 = 0.053\text{V}$$

(ii) Complete Fig. 9.2 for the voltmeter readings for the times before, during and after the direction of the current is reversed.

	before current changes	during current change when current is zero	after current changes
reading on voltmeter connected to coil C / V	0	0.053	0
reading on voltmeter connected to Hall probe / V	0.20	0	-0.20

Fig. 9.2

[4]

[Total: 8]

10 **(a)** A cross-section through a current-carrying solenoid is shown in Fig. 10.1.

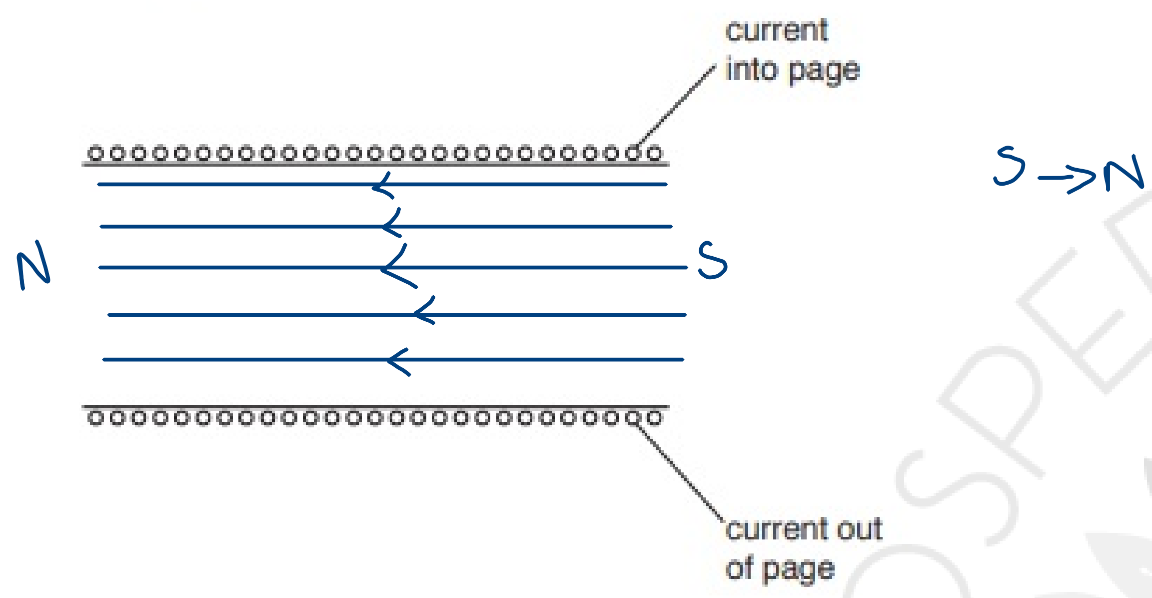


Fig. 10.1

On Fig. 10.1, draw field lines to represent the magnetic field inside the solenoid. [3]

(b) State Faraday's law of electromagnetic induction.

The e.m.f produced across the ends of a conductor placed in a magnetic field is directly proportional to the rate of change of magnetic flux linkage through it. [2]

(c) A coil of insulated wire is wound on to a soft-iron core.

The coil is connected in series with a battery, a switch and an ammeter, as shown in Fig. 10.2.

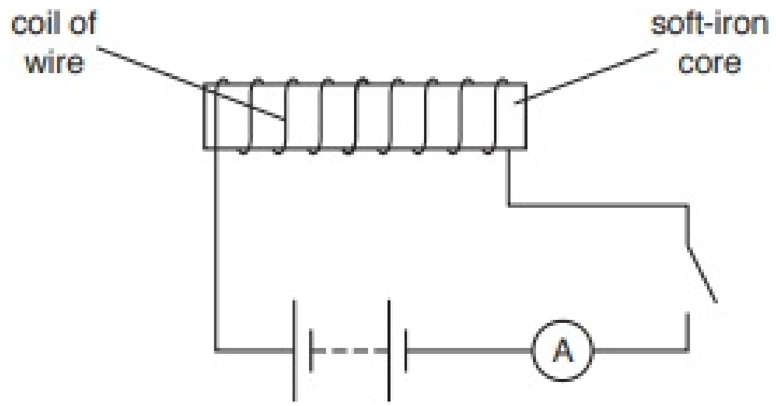


Fig. 10.2

Use laws of electromagnetic induction to explain why, when the switch is closed, the current increases **gradually** to its maximum value.

The magnetic flux linkage is changing as current is increasing in the circuit. Due to the changing magnetic flux, e.mfs are induced in the iron core that cause small eddy currents in it. According to Lenz's law, these currents are induced to produce opposing magnetic fields that hinders the growing current and so it increases gradually. [3]

[Total: 8]

8 A solenoid is connected in series with a battery and a switch, as illustrated in Fig. 8.1.

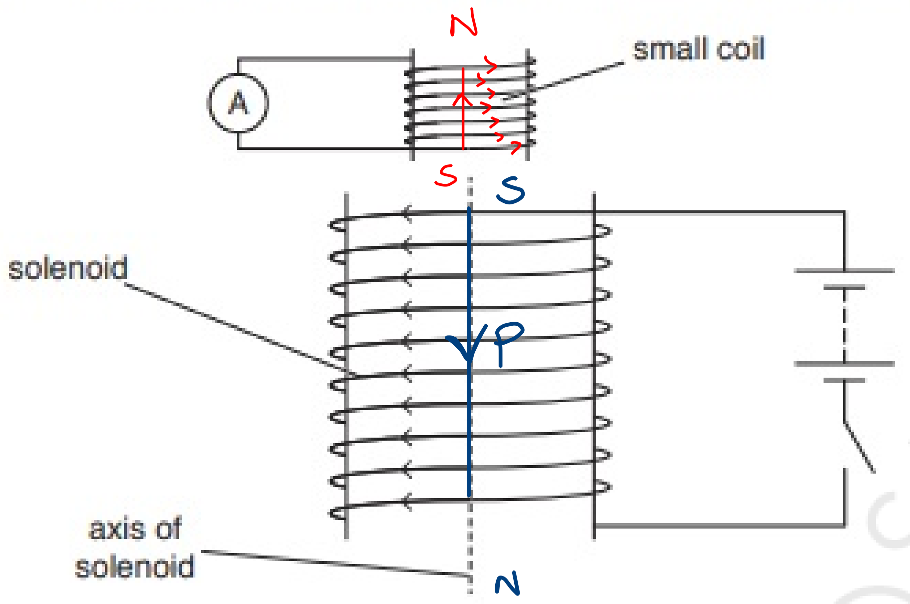


Fig. 8.1

A small coil, connected to a sensitive ammeter, is situated near one end of the solenoid.

As the current in the solenoid is switched on, there is a changing magnetic field inside the solenoid.

(a) (i) State what is meant by a *magnetic field*.

A region or space where a perpendicular current carrying conductor/moving charge experiences a force [1]

(ii) On Fig. 8.1, draw an arrow on the axis of the solenoid to show the direction of the magnetic field inside the solenoid. Label this arrow P. [1]

(b) As the current in the solenoid is switched on, there is a current induced in the small coil. This induced current gives rise to a magnetic field in the small coil.

(i) State Lenz's law.

The e.m.f induced in a conductor is directly proportional to the magnetic flux linkage. The e.m.f is induced such that it opposes the change producing it ($E = -\frac{d\phi}{dt}$) [2]

(ii) Use Lenz's law to state and explain the direction of the magnetic field due to the induced current in the small coil. On Fig. 8.1, mark this direction with an arrow inside the small coil.

As the current is increasing, the magnetic flux density of the solenoid is increasing and therefore there is a change in magnetic flux and an e.m.f is induced. The field produced will be opposite as it is trying to oppose the change producing it [3]

(c) The small coil has an area of cross-section $7.0 \times 10^{-4}\,m^2$ and contains 75 turns of wire.

A constant current in the solenoid produces a uniform magnetic flux of flux density 1.4 mT throughout the small coil.

The direction of the current in the solenoid is reversed in a time of 0.12 s.

B reverse

$B_f = -1.4mT$ $B_i = 1.4mT$

Calculate the average e.m.f. induced in the small coil.

$$E = -\frac{d\phi}{dt} = \frac{-d(B\times A)}{dt} = -A \times \frac{\Delta B}{\Delta t} = -A \times \frac{B_f - B_i}{\Delta t}$$

$$E = \left(-(7.0\times10^{-4}) \times \frac{(-1.4-1.4)\times10^{-3}}{0.12}\right)\times 75$$

$$V = 1.225\times10^{-3}$$

e.m.f. = 1.2×10^{-3} V [3]

[Total: 10]

9 **(a)** A coil of wire is situated in a uniform magnetic field of flux density B.
The coil has diameter 3.6 cm and consists of 350 turns of wire, as illustrated in Fig. 9.1.

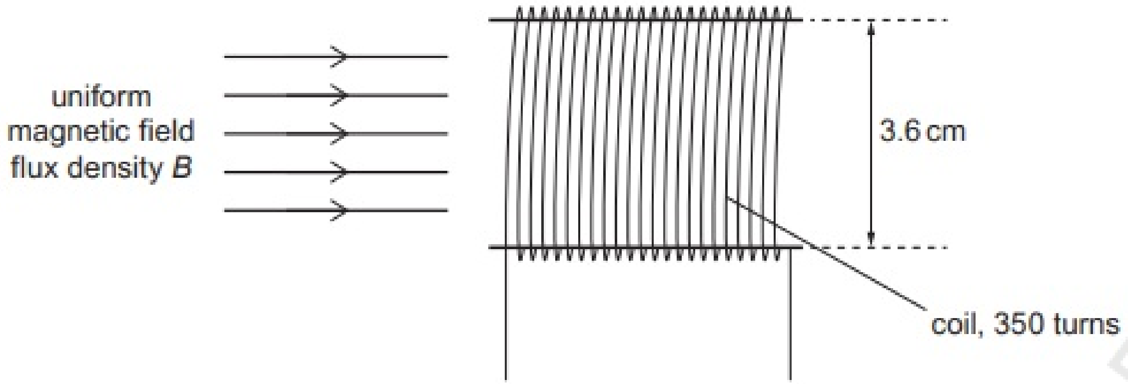


Fig. 9.1

The variation with time t of B is shown in Fig. 9.2.

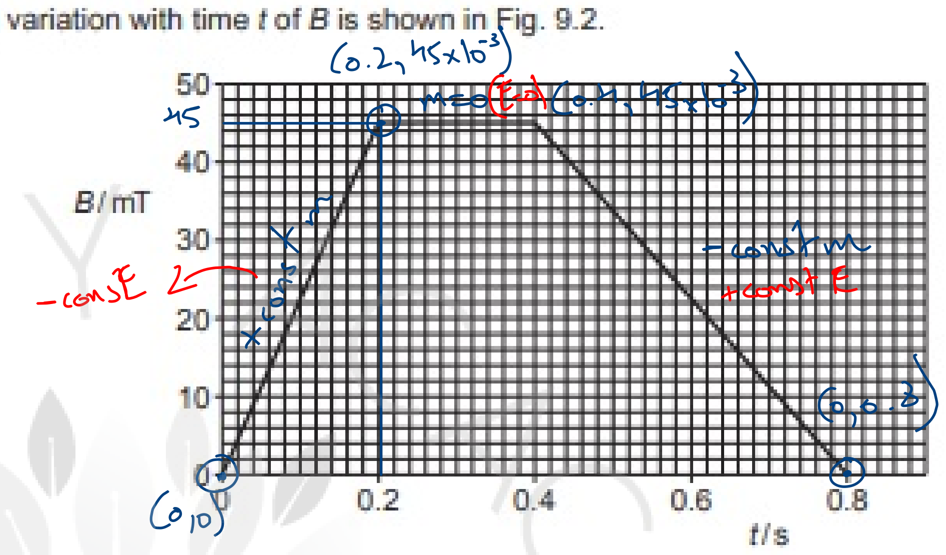


Fig. 9.2

$$E \propto -\frac{dB}{dt} \Rightarrow E = k\left(\frac{dB}{dt}\right)$$

$$\frac{E_1}{\left(\frac{dB}{dt}\right)_1} = \frac{E_2}{\left(\frac{dB}{dt}\right)_2}$$

$$\frac{0.08}{\frac{45\times10^{-3}}{0.2}} = \frac{E_2}{\frac{0-45\times10^{-3}}{0.8-0.4}} \Rightarrow \boxed{E_2 = 0.04}$$

$\boxed{+0.04}$ deduced from graph

(i) Show that, for the time t = 0 to time t = 0.20 s, the electromotive force (e.m.f.) induced in the coil is 0.080 V.

$$E = -\frac{d\phi}{dt} = \frac{-d(B\times A)}{dt} = -A\times\frac{dB}{dt} = \left[\frac{-\pi(3.6\times10^{-2})^2}{4}\times\frac{45\times10^{-3}-0}{0.2-0}\right]\times350$$

$$\boxed{E = -0.08\ V}$$

[2]

(ii) On the axes of Fig. 9.3, show the variation with time t of the induced e.m.f. E for time t = 0 to time t = 0.80 s.

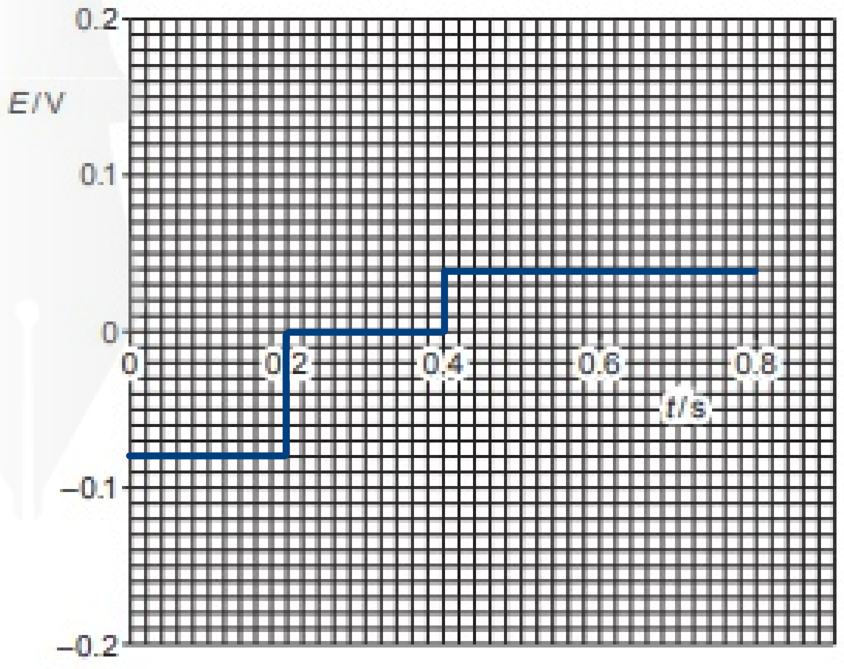


Fig. 9.3

[4]