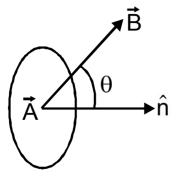
Electromagnetic Induction

Section A - Flux, Faraday's law, Lenz's law

1. MAGNETIC FLUX

Consider a closed curve enclosing an area A (as shown in the figure). Let there be a uniform magnetic field $\vec{B}$ in that region. The magnetic flux through the area $\vec{A}$ is given by



$\phi = \vec{B}.\vec{A}$ ...(i)

$= BA\cos\theta$

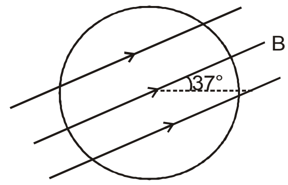
where θ is the angle which the vector B makes with the normal to the surface. If $\vec{B}$ is perpendicular to $\vec{A}$, then the flux through the closed area $\vec{A}$ is zero. SI unit of magnetic flux is weber (Wb).

Note

- Area vector is $\perp$ to the surface
- For open surface choose one direction as the area vector direction and stick to it for the whole problem.
- For closed surfaces outward normal is taken as area vector direction
- Flux is basically count of number of lines crossing a surface
- $\oint B.ds = 0$ because magnetic field lines exists in closed loop.

EXAMPLE 1

Find flux passing through Area ?



Sol. Since $\vec{A}$ is $\perp$ to $\vec{B}$

$\phi = \vec{B}.\vec{A} = 0$

2. FARADAY'S LAW OF ELECTROMAGNETIC INDUCTION

Whenever the flux of magnetic field through the area bounded by a closed conducting loop changes, an emf is produced in the loop. The emf is given by

$$\varepsilon = -\frac{d\phi}{dt} \quad ...(ii)$$

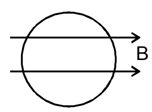
where $\phi = \int \vec{B}.d\vec{A}$ the flux of magnetic field through the area.

The emf so produced drives an electric current through the loop. If the resistance of the loop is R, then the current

$$i = \frac{\varepsilon}{R} = -\frac{1}{R}\frac{d\phi}{dt} \quad ...(iii)$$

EXAMPLE 2

A coil is placed in a constant magnetic field. The magnetic field is parallel to the plane of the coil as shown in figure. Find the emf induced in the coil.

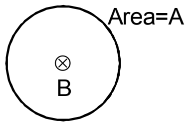


Sol. $\phi = 0$ (always) since area is perpendicular to magnetic field.

$\therefore$ emf = 0

EXAMPLE 3

Find the emf induced in the coil shown in figure. The magnetic field is perpendicular to the plane of the coil and is constant.



Sol. ϕ = BA (always) = const.

$\therefore$ emf = 0

EXAMPLE 4

Show that if the flux of magnetic induction through a coil changes from ϕ_1 to ϕ_2, then the charge q that flows through the circuit of total resistance R is given by $q = \frac{\phi_2 - \phi_1}{R}$, where R is the resistance of the coil.

Sol. Let ϕ be the instantaneous flux. Then $\frac{d\phi}{dt}$ is the instantaneous rate of change of flux which is equal to the magnitude of the instantaneous emf. so the current in the circuit $|i| = \frac{1}{R}\left(\frac{d\phi}{dt}\right)$, since the current is the rate of flow of charge, that is, $i = \frac{dq}{dt}$

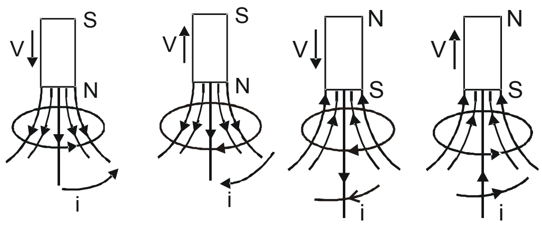
$$q = \int i dt \quad \text{or} \quad q = \int_{t=0}^{t=t}\left(\frac{1}{R}\cdot\frac{d\phi}{dt}\right)dt$$

where τ is the time during which change takes place. but at t = 0, $\phi = \phi_1$, and at t = t, $\phi = \phi_2$

$$\therefore \quad \mathbf{q} = \frac{1}{R}\int_{\phi=\phi_1}^{\phi=\phi_2} d\phi = \frac{\phi_2 - \phi_1}{R}$$

3. LENZ'S LAW

The effect of the induced emf is such as to oppose the change in flux that produces it.



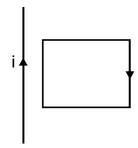
(a) (b) (c) (d)

In figure (a & b) as the magnet approaches the loop, the flux through the loop increases. The induced current sets up an induced magnetic field B_{ind} whose flux opposes this change. The direction of B_{ind} is opposite to that of external field B_{ext} due to the magnet.

In figure (c & d) the flux through the loop decreases as the magnet moves away from the loop, the flux due to the induced magnetic field tries to maintain the flux through the loop. The direction of B_{ind} is same as that of B_{ext} due to magnet.

Lenz's law is closely related to the law of conservation of energy and is actually a consequence of this general law of nature. As the north pole of the magnet moves towards the loop an induced current is produced. This opposes the motion of N-pole of the bar magnet. Thus, in order to move the magnet toward the loop with a constant velocity an external force is to be applied. The work done by this external force gets transformed into electric energy, which induces current in the loop.

There is another alternative way to find the direction of current inside the loop which is described below. Figure shows a conducting loop placed near a long, straight wire carrying a current i as shown. If the current increases continuously, then there will be an emf induced inside the loop. Due to this induced emf, an electric current is induced. To determine the direction of current inside the loop we put an arrow as shown. The right hand thumb rule shows that the normal to the loop is going into the plane. Again the same rule shows that the magnetic field at the site of the loop is also going into the plane of the diagram.



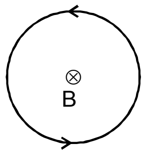
Thus $\vec{B}$ and $d\vec{A}$ are in the same direction. Therefore $\int \vec{B}.d\vec{A}$ is positive if i increases, the magnitude of flux ϕ increases. Since magnetic flux ϕ is positive and its magnitude increases, $\frac{d\phi}{dt}$ is positive. Thus ε is negative and hence the current is negative. Thus the current induced is opposite, to that of arrow.

Brain Teaser

Two identical coaxial circular loops carry equal currents circulating in the same direction. What will happen to the current in each loop if the loops approach each other ?

EXAMPLE 5

Find the direction of induced current in the coil shown in figure. Magnetic field is perpendicular to the plane of coil and it is increasing with time.

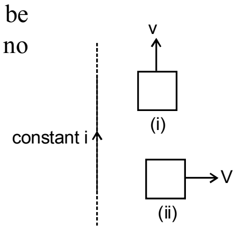


Sol. Inward flux is increasing with time. To oppose it outward magnetic field should be induced. Hence current will flow in anticlockwise.

EXAMPLE 6

Figure shows a long current carrying wire and two rectangular loops moving with velocity v.
Find the direction of current in each loop.

Sol. In loop (i) no emf will be induced because there is no flux change.



In loop (ii) emf will be induced because the coil is moving in a region of decreasing magnetic field inward in direction.
Therefore to oppose the flux decrease in inward direction, current will be induced such that its magnetic field will be inwards. For this direction of current should be clockwise.

4. CALCULATION OF INDUCED EMF

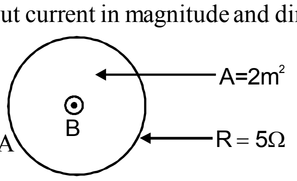
As we know that magnetic flux (ϕ) linked with a closed conducting loop = BA cos θ where B is the strength of the magnetic field, A is the magnitude of the area vector and θ is the angle between magnetic field vector and area vector.

Hence flux will be affected by change in any of them, which is discussed in the next page.

4.1 By changing the magnetic field

EXAMPLE 7

Figure shows a coil placed in decreasing magnetic field applied perpendicular to the plane of coil. The magnetic field is decreasing at a rate of 10 T/s. Find out current in magnitude and direction



Sol. $\phi = B.A$

$$emf = A.\frac{dB}{dt} = 2 \times 10 = 20 \text{ v}$$

$\therefore$ i = 20/5 = 4amp. From lenz's law direction of current will be anticlockwise.

EXAMPLE 8

The magnetic flux (ϕ_2) in a closed circuit of resistance 20 Ω varies with time (t) according to the equation $\phi = 7t^2 - 4t$ where ϕ is in weber and t is in seconds. The magnitude of the induced current at t = 0.25 s is

(A) 25 mA (B) 0.025 mA
(C) 47 mA (D) 175 mA

Sol. $\phi = 7t^2 - 4t$

$\Rightarrow$ Induced emf : $|e| = \frac{d\phi}{dt} = 14t - 4$

$\Rightarrow$ Induced current :

$$i = \frac{|e|}{R} = \frac{|14t - 4|}{20} = \frac{|14 \times 0.25 - 4|}{20}$$

(at t = 0.25 s)

$$= \frac{0.5}{20} = 2.5 \times 10^{-2} \text{ A}$$

$\therefore$ (A)

EXAMPLE 9

Consider a long infinite wire carrying a time varying current i = kt (k > 0). A circular loop of radius a and resistance R is placed with its centre at a distance d from the wire (a < < d). Find out the induced current in the loop?

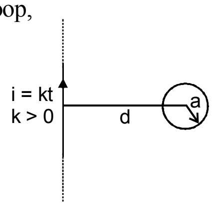
Sol. Since current in the wire is continuously increasing therefore we conclude that magnetic field due to this wire in the region is also increasing.

Magnetic field B due to wire $= \frac{\mu_0 i}{2\pi d}$ going into and perpendicular to the plane of the paper

Flux through the circular loop,

$$\phi = \frac{\mu_0 i}{2\pi d} \times \pi a^2$$

$$\phi = \frac{\mu_0 a^2 kt}{2d}$$



Induced e.m.f. in the loop

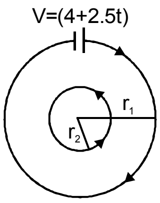
$$\varepsilon = -\frac{d\phi}{dt} = \frac{-\mu_0 a^2 k}{2d}$$

Induced current in the loop $i = \frac{|\varepsilon|}{R} = \frac{\mu_0 a^2 k}{2d\,R}$

Direction of induced current in the loop is anticlokwise.

EXAMPLE 10

Two concentric coplanar circular loops have diameters 20 cm and 2 m and resistance of unit length of the wire = 10^{-4} Ω/m. A time -dependent voltage V =(4 + 2.5 t) volts is applied to the larger as shown. The current in the smaller loop is

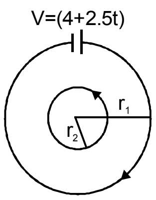


Sol. $r_1 = 1.0$ m, $r_2 = 10^{-1}$ m

Resistance of outer loop = $2\pi \times 10^{-4}\ \Omega$

Resistance of inner loop = $0.2\pi \times 10^{-4}\ \Omega$

Current in outer loop $= \dfrac{V}{R} = \dfrac{(4 + 2.5t)}{2\pi \times 10^{-4}}$ A



or $$i_0 = \left[\left(\frac{2}{\pi}\right) \times 10^4 + \left(\frac{1.25}{\pi}\right) \times 10^4 \times t\right] A$$

Magnetic field produced at the common centre (see figure)

$$B = \frac{\mu_0 i}{2r_1}$$

or

$$B = \frac{4\pi}{2} \times 10^{-7} \times \frac{[(2 + 1.25t) \times 10^4]}{\pi}$$

$$= 2 \times 10^{-3}(2 + 1.25t)\ T$$

Hence, flux linked with the inner loop,

$\phi = BA = 2 \times 10^{-3} (2 + 1.25 t) \times \pi(0.1)^2$

$= 2\pi \times 10^{-5} (2 + 1.25t)$ Wb

Hence, the e.m.f. induced in smaller loop

$$= \varepsilon = -\frac{d\phi}{dt} = -2\pi \times 10^{-5} \times 1.25$$

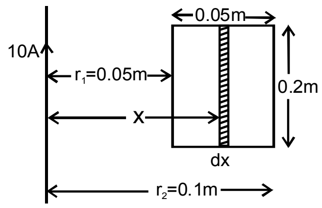
$$= -2.5\pi \times 10^{-5}\ V$$

The negative sign indicates that the induced e.m.f. (or current) is opposite to applied e.m.f. (or current) Hence, the current induced in the inner (smaller) loop is

$$i = \frac{|\varepsilon|}{R} = \frac{2.5\pi \times 10^{-5}\ V}{(0.2\pi \times 10^{-4})\Omega} = 1.25\ A$$

EXAMPLE 11

A rectangular wire frame of length 0.2 m, is located at a distance of 5×10^{-2} m from a long straight wire carrying a current of 10 A as shown in the figure. The width of the frame = 0.05 m. The wire is in the plane of the rectangle. Find the magnetic flux through the rectangular circuit. If the current decays uniformly to 0 in 0.2 s, find the emf induced in the circuit.



Sol. A current, *i* = 10 A is flowing in the long straight wire. Consider a small rectangular strip (in the rectangular wire frame) of width dx at a distance x from the straight wire.

The magnetic flux at the location of the strip,

$$B_x = \frac{\mu_0 i}{2\pi x}$$

The flux linked with the infinitesimally small rectangular strip

$$= B_x \times \text{Area of the strip} = d\phi_x = \frac{\mu_0 i}{2\pi x}\, l\, dx$$

where l is the length of the rectangular wire circuit

$= 2 \times 10^{-1}$ m

or $d\phi_x = (\mu_0\, i l/2\pi)\,(dx/x)$

Hence, the total magnetic flux linked with the rectangular frame

$$= \int d\phi_x = \varphi = \frac{\mu_0 i l}{2\pi}[\log_e x]_{r_1}^{r_2}$$

or $$\phi = \frac{\mu_0 i l}{2\pi}[\log_e r_2 - \log_e r_1] = \frac{\mu_0 i l}{2\pi}\log_e\left(\frac{r_2}{r_1}\right)$$

Substituting values, we get

$\phi = 2 \times 10^{-7} \times 10 \times 2 \times 10^{-1} \times \log_e 2$

$= 2.772 \times 10^{-7}$ Wb

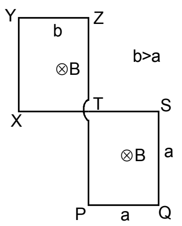
Induced e.m.f. $$|\varepsilon| = \frac{d\varphi}{dt} = \frac{\mu_0 l \log_e\left(\frac{r_2}{r_1}\right)}{2\pi}\frac{di}{dt}$$

$$= (2 \times 10^{-7} \times 2 \times 10^{-1} \log_e 2)\frac{10}{0.2}$$

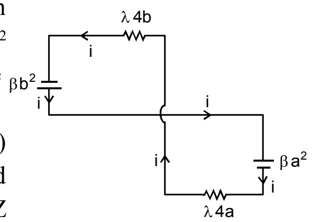
$= 1.386 \times 10^{-6}$ V = 1.386 μV

EXAMPLE 12

Figure shows a wire frame PQSTXYZ placed in a time varying magnetic field given as B = βt, where β is a positive constant. Resistance per unit length of the wire is λ. Find the current induced in the wire and draw its electrical equivalent diagram.



Sol. Induced emf in part PQST = βa^2 (in anticlockwise direction, from Lenz's Law) Similarly induced emf in part TXYZ = βb^2 (in anticlockwise direction, from Lenz's Law)



Total resistance of the part PQST = λ4a

Total resistance of the part PQST = l4b.

The equivalent circuit it is shown in the diagram.

writing KVL along the current flow

$$\beta b^2 - \beta a^2 - \lambda\, 4ai - \lambda\, 4bi = 0$$

$$i = \frac{\beta}{4\lambda}(b - a)$$

Brain Teaser :

A copper ring is held horizontally and a bar magnet is dropped through the ring with its length along the axis of the ring. Will the acceleration of the falling magnet be equal to, greater than or lesser than the acceleration due to gravity ?

4.2 BY CHANGING THE AREA

SOLVED EXAMPLES

EXAMPLE 13

A space is divided by the line AD into two regions. Region I is field free and the region II has a uniform magnetic field B directed into the paper. ACD is a semicircular conducting loop of radius r with centre at O, the plane of the loop being in the plane of the paper. The loop is now made to rotate with a constant angular velocity ω about an axis passing through O, and perpendicular to the plane of the paper in the clockwise direction. The effective resistance of the loop is R.

(a) Obtain an expression for the magnitude of the induced current in the loop.

(b) Show the direction of the current when the loop is entering into the region II.

(c) Plot a graph between the induced emf and the time of rotation for two periods of rotation.

Sol. (a) As in time t, the arc swept by the loop in the field, i.e., region II.

$$A = \frac{1}{2}r(r\theta) = \frac{1}{2}r^2\omega t$$

So the flux linked with the rotating loop at time t,

$$\phi = BA = \frac{1}{2}B\omega r^2 t \quad [\theta = \omega t]$$

and hence the induced emf in the loop,

$$\varepsilon = -\frac{d\phi}{dt} = -\frac{1}{2}B\omega r^2 = \text{constant.}$$

And as the resistance of the loop is R, the induced current in it,

$$i = \frac{\varepsilon}{R} = -\frac{B\omega r^2}{2R}$$

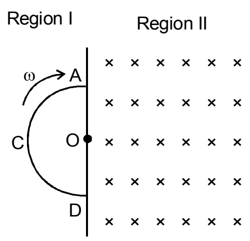


Fig (a)

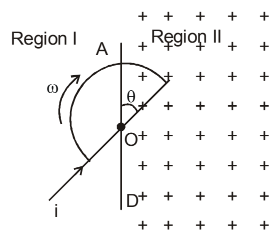


Fig (b)

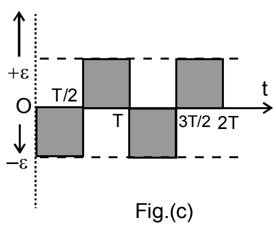


Fig.(c)

(b) When the loop is entering the region II, i.e., the field figure (b), the inward flux linked with it will increase, so in accordance with Lenz's law an anticlockwise current will be induced in it.

(c) Taking induced emf to the negative when flux linked with the loop is increasing and positive when decreasing, the emf versus time graph will be, as shown in figure (c)

EXAMPLE 14

Two parallel, long, straight conductors lie on a smooth plane surface. Two other parallel conductors rest on them at right angles so as to form a square of side a initially. A uniform magnetic field B exists at right angles to the plane containing the conductors. Now they start moving out with a constant velocity (v).

(a) Will the induced emf be time dependent?

(b) Will the current be time dependent?

Sol. (a) Yes, φ (instantaneous flux) = B (a + 2vt)^2

$\therefore \quad \varepsilon = \frac{d\varphi}{dt} = 4Bv(a + 2vt)$

(b) No, (instantaneous current) $i = \frac{\varepsilon}{R}$

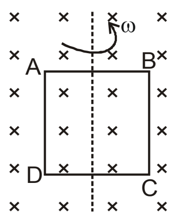
Now R = 4(a + 2vt)r where r = resistance per unit length

$\therefore \quad i = \frac{4Bv(a + 2vt)}{4r(a + 2vt)} = \frac{Bv}{r}$ (a constant)

The current will be time independent

EXAMPLE 15

Find the direction of induced of current in the wire AB. When rotated anticlockwise through angle θ, if it is placed initially as shown in the figure



Sol.

Range of Angle Rotated	Direction of induced current
0 – 90	A to B
90 – 180	A to B
180 – 270	B to A
270 – 360	B to A

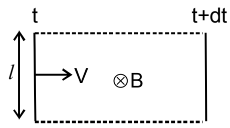
Note

Now The student can now attempt Section - A from exercise.

Section B - EMF induced in Moving Rod, Rotating Ring, Disc.

4.3 Motional Emf

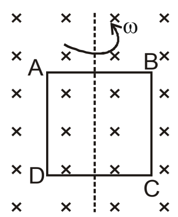
We can find emf induced in a moving rod by considering the number of lines cut by it per sec assuming there are 'B' lines per unit area. Thus when a rod of length l moves with velocity v in a magnetic field B, as shown, it will sweep area per unit time equal to lv and hence it will cut B l v lines per unit time.

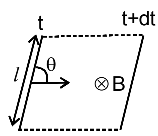


Hence emf induced between the ends of the rod = Bvl

Also emf= $\frac{d\phi}{dt}$. Here ϕ denotes flux passing through the area, swept by the rod. The rod sweeps an area equal to l vdt in time interval dt. Flux through this area = Bl vdt. Thus $\frac{d\phi}{dt} = \frac{Bl\,vdt}{dt} = Bvl$

If the rod is moving as shown in the following figure, it will sweep area per unit time = v l sin θ



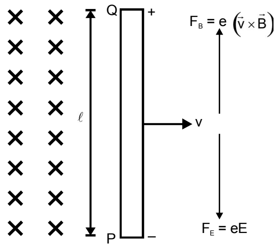


and hence it will cut B v l sin θ lines per unit time.

Thus emf = Bv$l$sinθ.

4.3.1 Mechanism of The induced EMF a cross the ends of a moving rod :

Figure shows a conducting rod of length l moving with a constant velocity v in a uniform magnetic field. The length of the rod is perpendicular to magnetic field, and velocity is perpendicular to both the magnetic field and the length of the rod. An electron inside the conductor experiences a magnetic force $\vec{F}_B = -e(\vec{v} \times \vec{B})$ directed downward along the rod. As a result electrons migrate towards the lower end and leave unbalanced positive charges at the top. This redistribution of charges sets up an electric field E directed downward. This electric field exerts a force on free electrons in the upward direction. As redistribution continues electric field grows in magnitude until a situation, when



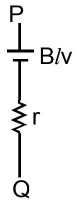
$$|q\vec{v}\times\vec{B}| = |q\vec{E}|$$

After this, there is no resultant force on the free electrons and the potential difference across the conductor is

$$\int d\varepsilon = -\vec{E}.d\vec{l} = \int(\vec{v}\times\vec{B}).d\vec{l} \qquad ...(4)$$

Thus it is the magnetic force on the moving free electrons that maintains the potential difference. So e.m.f. developed across the ends of the rod moving perpendicular to magnetic field with velocity perpendicular to the rod,

$$e = vBl \qquad ...(5)$$

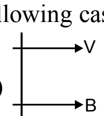


As this emf is produced due to the motion of the conductor, it is called motional emf.

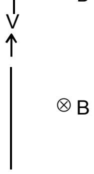
In the problems related to motional e.m.f. we can replace the rod by a battery of e.m.f. vBl.
The moving rod can be represented (or equivalent) as electrical circuit as shown in figure.

EXAMPLE 16

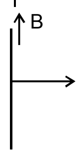
Find the value of emf induced in the rod for the following cases. The figures are self explanatory.

(a) 

Ans. emf = 0

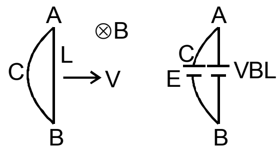
(b) 

Ans. emf = 0

(c) 

Ans. emf = 0

Figure shows a closed coil ABCA moving in a uniform magnetic field B with a velocity v. The flux passing through the coil is a constant and therefore the induced emf is zero.



Now consider rod AB, which is a part of the coil. Emf induced in the rod = B L v. Now suppose the emf induced in part ACB is E, as shown in figure. Since the emf in the coil is zero,

Emf (in ACB) + Emf (in BA) = 0

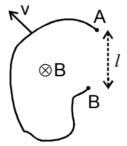
or – E + vBL = 0

or E = vBL

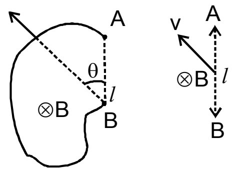
Thus emf induced in any path joining A and B is same, provided the magnetic field is uniform. Also the equivalent emf between A and B is BLv (here the two emf's are in parallel)

EXAMPLE 17

Figure shows an irregular shaped with AB moving with velocity v, as shown. Find the emf induced in the wire.



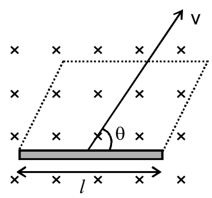
Sol. The same emf will be induced in the straight imaginary wire joining A and B, which is $Bvl \sin\theta$



EXAMPLE 18

A 0.4 meter long straight conductor moves in a magnetic field of magnetic induction 0.9 Wb/m^2 with a velocity of 7 m/sec. Calculate the emf induced in the conductor under the condition when it is maximum.

Sol. If a rod of length l is moved with velocity $\vec{v}$ and at angle θ to the length of the rod in a field $\vec{B}$ which is perpendicular to the plane of the motion, the flux linked with the area generated by the motion of rod in time t,



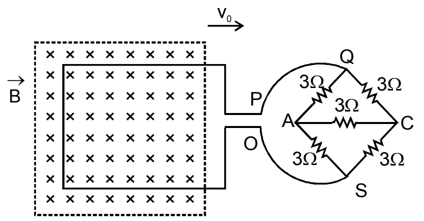
$\phi = Bl(v\sin\theta)t$ so, $|\varepsilon| = \frac{d\phi}{dt} = Bvl\sin\theta$

This will be maximum when $\sin\theta = \max = 1$, i.e., the rod is moving perpendicular to its length and then $(\varepsilon)_{max} = Bvl$

$E_{max} = 0.9 \times 7 \times 0.4 = 2.52$ V

EXAMPLE 19

A square metal wire loop of side 10 cm and resistance 1 ohm is moved with a constant velocity v_0 in a uniform magnetic field of induction B = 2 Wb/m^2 as shown in figure. The magnetic field lines are perpendicular to the plane of the loop. The loop is connected to a network of resistance each of value 3 ohm. The resistances of the lead wires OS and PQ are negligible. What should be the speed of the loop so as to have a steady current of 1 milliampere in the loop ? Find the direction of current in the loop ?



Sol. As the network AQCS is a balanced Wheatstone bridge, no current will flow through AC and hence the effective resistance of the network between QS,

$$R_{QS} = \frac{6 \times 6}{6 + 6} = 3 \text{ ohm}$$

and as the resistance of the square metal wire loop is 1 ohm, the total resistance of the circuit,

R = 3 + 1 = 4 ohm

Now if the loop moves with speed v_0, the emf induced in the loop,

$\varepsilon = Bv_0l$

So the current in the circuit, $i = \frac{\varepsilon}{R} = \frac{Bv_0l}{R}$

Substituting the given data,

In accordance with Lenz's law, the induced current in the loop will be in clockwise direction.

EXAMPLE 20

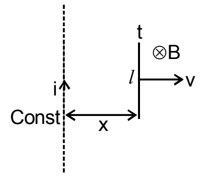
A rod of length l is kept parallel to a long wire carrying constant current i. It is moving away from the wire with a velocity v. Find the emf induced in the wire when its distance from the long wire is x.

Sol. $E = B\,l\,V = \frac{\mu_0 i l v}{2\pi x}$

OR

Emf is equal to the rate with which magnetic field lines are cut. In dt time the area swept by the rod is l v dt. The magnetic field lines cut in dt time

$= B\,l\,vdt = \frac{\mu_0 i l\, vdt}{2\pi x}$

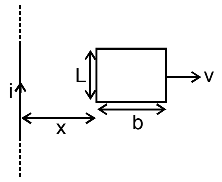


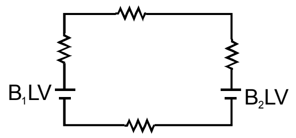
∴ The rate with which magnetic field lines are cut $= \frac{\mu_0 i l\, v}{2\pi x}$

EXAMPLE 21

A rectangular loop, as shown in the figure, moves away from an infinitely long wire carrying a current i. Find the emf induced in the rectangular loop.

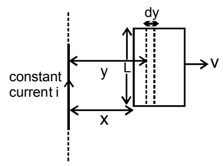
$E = B_1 L V - B_2 L v$





$$= \frac{\mu_0 i}{2\pi x} Lv - \frac{\mu_0 i}{2\pi(x+b)} Lv = \frac{\mu_0 iLbv}{2\pi x(x+b)}$$

Aliter : Consider a small segment of width dy at a distance y from the wire. Let flux through the segment be $d\phi$.



∴ $d\phi = \frac{\mu_0 i}{2\pi y} L\ dy$

∴ $\phi = \frac{\mu_0 iL}{2\pi}\int_x^{x+b}\frac{dy}{y} = \frac{\mu_0 iL}{2\pi}(\ln(x+b) - \ln x)$

Now $\frac{d\phi}{dt} = \frac{\mu_0 iL}{2\pi}\left[\frac{1}{x+b}\frac{dx}{dt} - \frac{1}{x}\frac{dx}{dt}\right]$

$= \frac{\mu_0 iL}{2\pi}\left[\frac{(-b)}{x(x+b)}\right]v = \frac{-\mu_0 ibLv}{2\pi x(x+b)}$

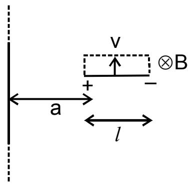
∴ induced emf $= \frac{\mu_0 ibLv}{2\pi x(x+b)}$

EXAMPLE 22

A rod of length l is placed perpendicular to a long wire carrying current i. The rod is moved parallel to the wire with a velocity v. Find the emf induced in the rod, if its nearest end is at a distance 'a' from the wire.

Sol. Consider a segment of rod of length dx, at a distance x from the wire. Emf induced in the segment

$$d_{\in} = \frac{\mu_0 i}{2\pi x} dx.v$$

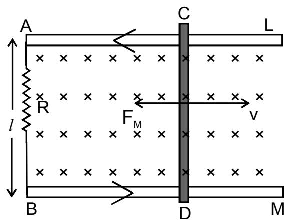


$$\therefore \qquad \in = \int_a^{a+l} \frac{\mu_0 i v dx}{2\pi x} = \frac{\mu_0 i v}{2\pi} ln\left(\frac{l+a}{a}\right)$$

EXAMPLE 23

Two parallel wires AL and BM placed at a distance l are connected by a resistor R and placed in a magnetic field B which is perpendicular to the plane containing the wires. Another wire CD now connects the two wires perpendicularly and made to slide with velocity v. Calculate the work done per second needed to slide the wire CD. Neglect the resistance of all the wires.

Sol. When a rod of length l moves in a magnetic field with velocity v as shown in figure, an emf $\varepsilon = Bvl$ will be induced in it. Due to this induced emf, a current



$i = \frac{\varepsilon}{R} = \frac{Bvl}{R}$ will flow in the circuit as shown in figure. Due to this induced current, the wire will experience a magnetic force

$$F_M = Bil = \frac{B^2 l^2 v}{R}$$

which will oppose its motion, So to maintain the motion of the wire CD, a force $F = F_M$ must be applied in the direction of motion.

The work done per second, i.e., power needed to slide the wire is given by

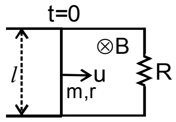
$$P = \frac{dW}{dt} = Fv = F_M v = \frac{B^2 v^2 l^2}{R}$$

Note

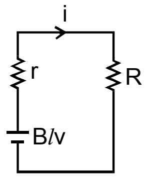
The power delivered by the external agent is converted into joule heating in a by using the circuit(as shwon above). It means magnetic field helps in converting the mechanical energy into joule heating.

EXAMPLE 24

A rod of mass m and resistance r is placed on fixed, resistanceless, smooth conducting rails (closed by a resistance R) and it is projected with an initial velocity u Find its velocity as a function of time.



Sol. Let at an instant the velocity of the rod be v. The emf induced in the rod will be vBl. The electrically equivalent circuit is shown in the following diagram.



$\therefore$ Current in the circuit $i = \frac{Blv}{R+r}$

At time t

Magnetic force acting on the rod is $F = i\, l\, B$, opposite to the motion of the rod.

$$i\,l\,B = -m\frac{dv}{dt} \qquad ...(1)$$

$$i = \frac{Blv}{R+r} \qquad ...(2)$$

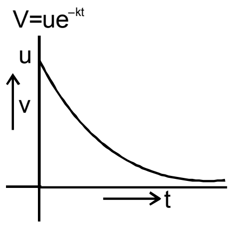
Now solving these two equation

$$\frac{B^2 l^2 v}{R+r} = -m.\frac{dv}{dt}$$

$$\Rightarrow \quad -\frac{B^2 l^2}{(R+r)m}.dt = \frac{dv}{v}$$

$$\text{let} \quad \Rightarrow -K.\,dt = \frac{dV}{V}$$

$$\int_u^v \frac{dv}{v} = \int_0^t -K.dt$$



$$ln\left(\frac{v}{u}\right) = -Kt$$

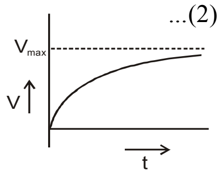
$$\Rightarrow \quad V = ue^{-Kt}$$

EXAMPLE 25

In the above question if a constant force F is applied on the rod. Find the velocity of the rod as a function of time assuming it started with zero initial velocity.

Sol. $m\dfrac{dv}{dt} = F - i\,l\,B$ ...(1)

$i = \dfrac{Blv}{R + r}$ ...(2)



$m\dfrac{dv}{dt} = F - \dfrac{B^2l^2v}{R + r}$

let $K = \dfrac{B^2l^2}{R + r}$ $\Rightarrow \displaystyle\int_0^v \frac{dV}{F - Kv} = \int_0^t \frac{dt}{m}$

$\Rightarrow$ $-\dfrac{1}{K}\ln(F - KV)\Big|_0^v = \dfrac{t}{m}$

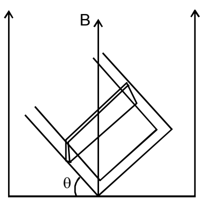
$\ln\left(\dfrac{F - kV}{F}\right) = -\dfrac{Kt}{m}$

$F - KV = F\,e^{-kt/m}$

$V = \dfrac{F}{K}\,(1 - e^{-kt/m})$

EXAMPLE 26

A square wire of length l, mass m and resistance R slides without friction down the parallel conducting wires of negligible resistance as shown in figure. The rails are connected to each other at the bottom by a resistanceless rail parallel to the wire so that the wire and rails form a closed rectangular loop. The plane of the rails makes an angle θ with horizontal and a uniform vertical field of magnetic induction B exists throughout the region. Show that the wire acquires a steady state velocity of magnitude $v = \dfrac{mgR\sin\theta}{B^2l^2\cos^2\theta}$



Sol. Force down the plane = mg sin θ

At any instant if the velocity is v the induced e.m.f

$= l\,B\cos\theta \times v$

Current in the loop $\times \dfrac{Bl\,v\cos\theta}{R}$

Force on the conductor in the horizontal direction

$= Bl \times \dfrac{Bl\,v\cos\theta}{R}$

The component of force parallel to the incline

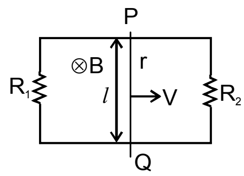
$= \dfrac{B^2l^2\,v\cos\theta}{R} \times \cos\theta$

If v is constant, $\dfrac{B^2l^2\cos^2\theta}{R} \times v = mg\sin\theta$

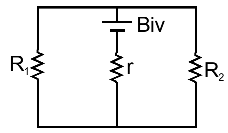
$\therefore$ $\mathbf{v} = \dfrac{mRg\sin\theta}{B^2l^2\cos^2\theta}$

EXAMPLE 27

A rod PQ of mass m and resistance r is moving on two fixed, resistanceless, smooth conducting rails (closed on both sides by resistances R_1 and R_2). Find the current in the rod at the instant its velocity is v.



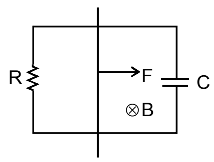
Sol. The equivalant circuit of above figure



$i = \dfrac{Blv}{r + \dfrac{R_1R_2}{R_1 + R_2}}$

EXAMPLE 28

In the above question if one resistance is replaced by a capacitor of capacitance C as shown. Find the velocity of the moving rod at time t if the initial velocity of the rod is v and a constant force F is applied on the rod.
Neglect the resistance of the rod.



Sol. At any time t, let the velocity of the rod be v.

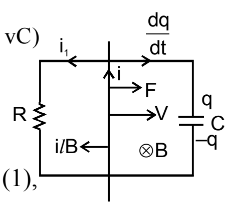
Applying Newtons law :

$F - i\,lB = ma$ ...(1)

Also $B\,l\,v = i_1\,R = \dfrac{q}{c}$

Applying KCL,

$i = i_1 + \dfrac{dq}{dt} = \dfrac{Bl\,v}{R} + \dfrac{d}{dt}(Bl\,vC)$



or $i = \dfrac{Bl\,v}{R} + Bl\,Ca$

Putting the value of i in eq. (1),

$$F - \frac{B^2 l^2 v}{R} = (m + B^2 l^2 C)a = (m + B^2 l^2 C)\frac{dv}{dt}$$

$$(m + B^2 l^2 C)\frac{dv}{F - \frac{B^2 l^2 v}{R}} = dt$$

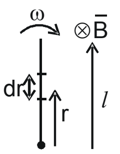
Integrating both sides, and solving we get

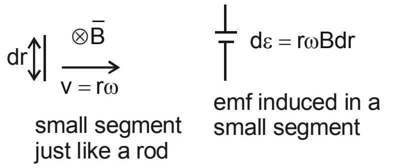
$$v = \frac{FR}{B^2 l^2}\left(1 - e^{\frac{tB^2 l^2}{R(m+CB^2 l^2)}}\right)$$

4.4 Induced e.m.f due to rotation

4.4.1 Rotation of the rod

Consider a conducting rod of length l rotating in a uniform magnetic field.

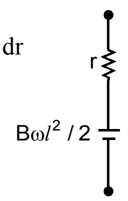




Emf induced in a small segment of length dr, of the rod = v B dr = r ω B dr

∴ emf induced in the rod

$$= \omega B \int_0^{\ell} r\,dr = \frac{1}{2}B\omega l^2$$



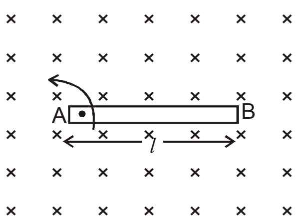
equivalent of this rod is as following

or $$\varepsilon = \frac{d\phi}{dt} = \frac{\text{flux through the area swept by the rod in time dt}}{dt}$$

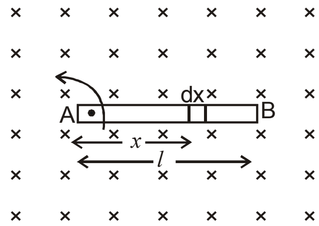
$$= \frac{B\frac{1}{2}l^2\omega dt}{dt} = \frac{1}{2}B\omega l^2$$

EXAMPLE 29

Find out the potential difference between A & B :



Sol.

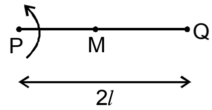


$$\int dE = \int_0^{\ell} B\omega x\,dx\,, \quad V_A - V_B = \frac{B\omega l^2}{2}$$

EXAMPLE 30

A rod PQ of length 2l is rotating about one end P in a uniform magnetic field B which is perpendicular to the plane of rotation of the rod. Point M is the mid point of the rod. Find the induced emf between M & Q if that between P & Q = 100V.

⊗ B = Uniform



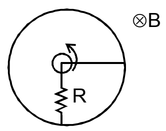
Sol. $E_{MQ} + E_{PM} = E_{PQ}$ corner $\rightarrow \frac{Bwl^2}{2} = 100$

$$E_{MQ} + \frac{B\omega\left(\frac{l}{2}\right)^2}{2} = \frac{B\omega l^2}{2}$$

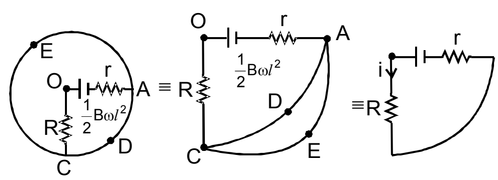
$$E_{MQ} = \frac{3}{8}B\omega l^2 = \frac{3}{4}\times 100\text{ V} = 75\text{ V}$$

EXAMPLE 31

A rod of length L and resistance r rotates about one end as shown in figure. Its other end touches a conducting ring a of negligible resistance. A resistance R is connected between centre and periphery. Draw the electrical equivalence and find the current in the resistance R. There is a uniform magnetic field B directed as shown.



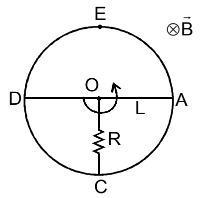
Sol.



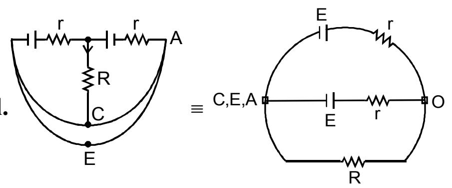
$$\text{current } i = \frac{\frac{1}{2}B\omega l^2}{R + r}$$

EXAMPLE 32

Solve the above question if the length of rod is 2L and resistance 2r and it is rotating about its centre. Both ends of the rod now touch the conducting ring.



Sol.



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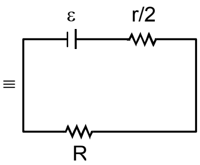
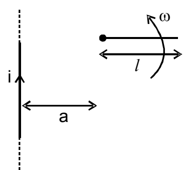


$$i = \frac{\varepsilon}{R + \frac{r}{2}} = \frac{\frac{1}{2}B\omega L^2}{R + \frac{r}{2}}$$

EXAMPLE 33

A rod of length l is rotating with an angular speed ω about its one end which is at a distance 'a' from an infinitely long wire carrying current i. Find the emf induced in the rod at the instant as shown in the figure.

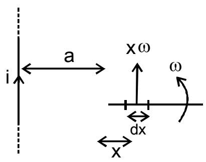


Consider a small segment of rod of length dx, at a distance x from one end of the rod.

Emf induced in the segment

$$dE = \frac{\mu_0 i}{2\pi(x + a)}(x\omega)dx$$

$$\therefore \quad E = \int_0^l \frac{\mu_0 i}{2\pi(x + a)}(x\omega)dx$$



$$= \frac{\mu_0 i\,\omega}{2\pi}\left[l - a\,ln\left(\frac{l + a}{a}\right)\right]$$

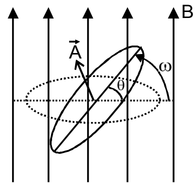
4.5 By Changing The Angle

Let us consider the case when the magnitude of the magnetic field strength and the area of the coil remains constant. When the coil is rotated relative to the direction of the field, an induced current is produced which lasts as long as the coil is rotating. We have, $\phi = BA\cos\theta$ [where B is the magnetic field strength, A is the magnitude of the area vector & θ is the angle between them] If the angular velocity with which the coil is rotating is ω, then

$\theta = \omega t$

Induced e.m.f. in the coil

$$\varepsilon = -\frac{d\phi}{dt} = BA\omega\sin\omega t$$

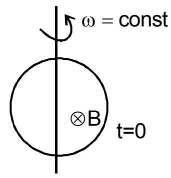


Induced current in the coil

$$= i = \frac{|\varepsilon|}{R} = \frac{B\omega A}{R}\sin\omega t$$

EXAMPLE 34

A ring rotates with angular velocity ω about an axis in the plane of the ring and which passes through the center of the ring.



A constant magnetic field B exists perpendicular to the plane of the ring. Find the emf induced in the ring as a function of time.

Sol. At any time t, $\phi = BA\cos\theta = BA\cos\omega t$

Now induced emf in the loop

$$e = \frac{-d\phi}{dt} = BA\,\omega\sin\omega t$$

If there are N turns

emf = $BA\omega N\sin\omega t$

$BA\,\omega N$ is the amplitude of the emf $e = e_m \sin\omega t$

$$i = \frac{e}{R} = \frac{e_m}{R}\sin\omega t = i_m\sin\omega t$$

$$i_m = \frac{e_m}{R}$$

The rotating coil thus produces a sinusoidally varying current or alternating current. This is the principle which is always used in generator.

5. INDUCED ELECTRIC FIELD DUE TO A TIME VARYING MAGNETIC FIELD

Consider a conducting loop placed at rest in a magnetic field $\vec{B}$. Suppose, the field is constant till t = 0 and then changes with time. An induced current starts in the loop at t = 0.

The free electrons were at rest till t = 0 (we are not interested in the random motion of the electrons.) The magnetic field cannot exert force on electrons at rest. Thus, the magnetic force cannot start the induced current. The electrons may be forced to move only by an electric field. So we conclude that an electric field appears at time t = 0.

This electric field is produced by the changing magnetic field and not by charged particles. The electric field produced by the changing magnetic field is nonelectrostatic and nonconservative in nature. We cannot define a potential corresponding to this field. We call it induced electric field. The lines of induced electric field are closed curves. There are no starting and terminating points of the field lines.

If $\vec{E}$ be the induced electric field, the force on the charge q placed in the field of $q\vec{E}$. The work done per unit charge as the charge moves through $d\vec{l}$ is $E.\,d\vec{l}$. The emf developed in the loop is, therefore,

$$\varepsilon = \oint \vec{E}.d\vec{l}$$

Using Faraday's law of induction,

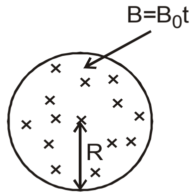
$$\varepsilon = -\frac{d\phi}{dt}$$

or, $$\oint \vec{E}.d\vec{l} = -\frac{d\phi}{dt} \qquad ...(6)$$

The presence of a conducting loop is not necessary to have an induced electric field. As long as $\vec{B}$ keeps changing, the induced electric field is present. If a loop is there, the free electrons start drifting and consequently an induced current results.

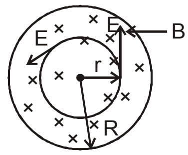
EXAMPLE 35

What will be the electric field at a distance r from axis of changing cylindrical magentic field B, which is parallel to the axis of cylinder ?



Sol. **(i)** When r < R

let at a distance r electric field is E

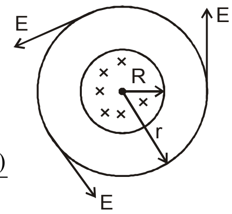


$$\varepsilon = \left|\oint \vec{E}.d\vec{l}\right| = \left|-\frac{d\phi}{dt}\right|$$

$$E.\ 2\pi r = \left|-\frac{d[B.(\pi r^2)]}{dt}\right|$$

$$E = \frac{r}{2}\frac{dB}{dt} = \frac{B_0 r}{2}$$

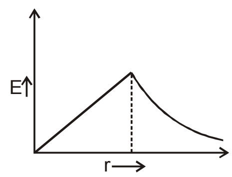
(ii) When r > R



$$\left|\oint \vec{E}.d\vec{l}\right| = \left|\frac{-d\phi}{dt}\right|$$

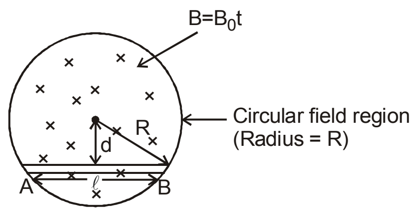
$$E.2\pi r = \frac{d(B\pi R^2)}{dt}$$

$$\Rightarrow \quad E = \frac{R^2}{2r}.\frac{dB}{dt} = \frac{B_0 R^2}{2r}$$

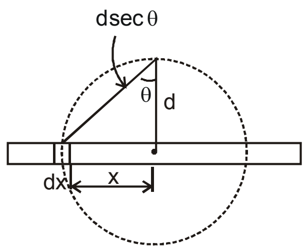


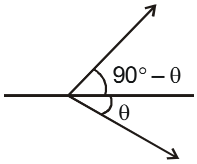
EXAMPLE 36

Find the e.m.f induced in the rod as shown in the figure.



Sol.





$$E = \frac{r}{2}\frac{dB}{dt} = \frac{d\sec\theta}{2}B_0$$

$$dE = E.dx \cos\theta = \frac{d\sec\theta B_0 dx\cos\theta}{2}$$

$$\Rightarrow \int_0^E dE = \frac{B_0 d}{2}\int_{-\ell/2}^{\ell/2} dx \Rightarrow E = \frac{B_0 \ell d}{2}$$

Alternate :

Induced emf in OA & OB is zero

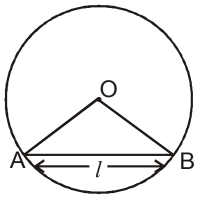
(because $\vec{B}$ & $d\vec{l}$ are perpendicular)

Total induced emf in OAB is in AB

$$\text{Area} = \frac{1}{2} l d$$

$$\phi = \frac{B_0 l dt}{2}$$

$$\frac{d\phi}{dt} = \frac{B_0 l d}{2}$$



EXAMPLE 37

A thin, nonconducting ring of mass m, carrying a charge q, can rotate freely about its axis. At the instant t = 0 the ring was at rest and no magnetic field was present. Then suddenly a magnetic field B was set perpendicular to the plane. Find the angular velocity acquired by the ring.

Sol. Due to the sudden change of flux, an electric field is set up and the ring experiences an impulsive torque and suddenly acquires an angular velocity.

$$\varepsilon(\text{induced emf}) = -\frac{d\phi}{dt} = -\frac{d}{dt}\int \vec{B}.dA$$

Also $\varepsilon = \oint \vec{E}.d\vec{l}$ where E is the induced electric field.

$$\therefore \quad \oint \vec{E}.d\vec{l} = -\frac{d}{dt}\int \vec{B}.d\vec{A} \Rightarrow E.2\pi r = -\frac{d}{dt}(B\pi r^2)$$

$$\Rightarrow \quad E = -\frac{r}{2}\frac{dB}{dt}$$

Force experienced by the ring $= q|\vec{E}|$

Torque experienced by thering

$$\tau = (qE)r = \frac{qr^2}{2}\frac{dB}{dt}$$

$\therefore$ Angular impulse experienced by the ring

$$= \int \tau\, dt = \frac{qr^2}{2}\int \frac{dB}{dt}dt = qr^2\frac{B}{2}$$

Also angular impulse acquired = $l\omega$ where l is moment of inertia of the ring about its axis = mr^2

$\therefore$ $mr^2\,\omega = qr^2\,B/2$

$\Rightarrow$ Angular velocity acquired by the ring $\omega = qB/2m$

Note

Now The student can now attempt Section - A from exercise.

Section C - Self Induction, Mutual Induction

6. SELF INDUCTION

Self induction is induction of emf in a coil due to its own current change. Total flux $N\phi$ passing through a coil due to its own current is proportional to the current and is given as $N\phi = L\,i$ where L is called coefficient of self induction or inductance. The inductance L is purely a geometrical property i.e., we can tell the inductance value even if a coil is not connected in a circuit. Inductance depends on the shape and size of the loop and the number of turns it has.

If current in the coil changes by ΔI in a time interval Δt, the average emf induced in the coil is given as

$$\varepsilon = -\frac{\Delta(N\phi)}{\Delta t} = -\frac{\Delta(LI)}{\Delta t} = -\frac{L\Delta l}{\Delta t}$$

The instantaneous emf is given as

$$\varepsilon = -\frac{d(N\phi)}{dt} = -\frac{d(LI)}{dt} = -\frac{Ldl}{dt}$$

S.I unit of inductance is wb/amp or Henry (H)

L - self inductance is +ve quantity.

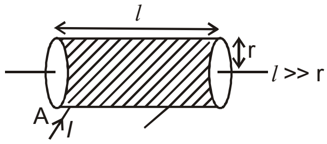
L depends on : (1) Geometry of loop

(2) Medium in which it is kept. L does not depend upon current. L is a scalar quantity.

Brain Teaser

If a circuit has large self-inductance, what inference can you draw about the circuit.

6.1 Self Inductance of solenoid



Let the volume of the solenoid be V, the number of turns per unit length be n. Let a current I be flowing in the solenoid. Magnetic field in the solenoid is given as $B = \mu_0 nI$. The magnetic flux through one turn of solenoid $\phi = \mu_0 n\, I\, A$.

The total magnetic flux through the solenoid = $N\phi$

$$= N\,\mu_0\, n\, I\, A$$

$$= \mu_0\, n^2\, I\, A\, l$$

$\therefore$ $L = \mu_0\, n^2\, l\, A = \mu_0\, n^2\, V$

$\phi = \mu_0\, n\, i\, \pi r^2\, (nl)$

$$L = \frac{\phi}{i} = \mu_0\, n^2\, \pi r^2\, l$$

Inductance per unit volume = $\mu_0\, n^2$

EXAMPLE 38

The current in a coil of self-inductance L = 2H is increasing according to the law $i = 2\sin t^2$. Find the amount of energy spent during the period when the current changes from 0 to 2 ampere.

Sol. Let the current be 2 amp at $t = \tau$

Then $2 = 2\sin\tau^2 \Rightarrow \tau = \sqrt{\frac{\pi}{2}}$

When the instantaneous current is i, the self induced emf is $L\frac{di}{dt}$. If the amount of charge that is displaced in time dt is dq, then the elementary work done

$$= L.\left(\frac{di}{dt}\right)dq = L.\frac{di}{dt}idt = Lidi$$

$$W = \int_0^{\tau} Lidi = \int_0^{\tau} L(2\sin t^2)d(2\sin t^2)$$

$$W = \int_0^{\tau} 8\,L\,\sin t^2 \cos t^2 (tdt) = 4L\int_0^{\tau} \sin 2t^2 (tdt)$$

Let $\theta = 2t^2$

Differentiating $d\theta = 4t\,dt$

$\therefore$ $W = 4L\int \frac{\sin\theta d\theta}{4}$

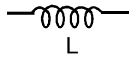
$= L(-\cos\theta) = -L\cos 2t^2$

$$W = -L\left[\cos 2t^2\right]_0^{\sqrt{\pi/2}}$$

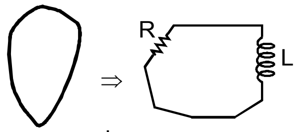
$= 2L = 2 \times 2 = 4$ joule

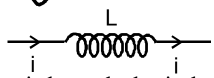
7. INDUCTOR

It is represent by

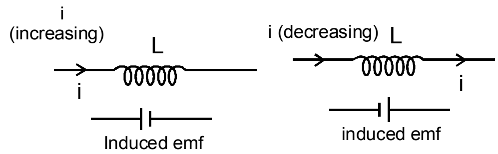


electrical equivalence of loop

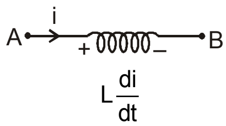




If current i through the inductor is increasing the induced emf will oppose the **increase** in current and hence will be opposite to the current. If current i through the inductor is decreasing the induced emf will oppose the **decrease** in current and hence will be in the direction of the current.



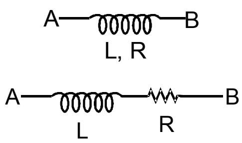
Over all result



$$V_A - L\frac{di}{dt} = V_B$$

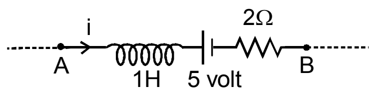
Note

If there is a resistance in the inductor (resistance of the coil of inductor) then :



EXAMPLE 39

AB is a part of circuit. Find the potential difference $v_A - v_B$ if

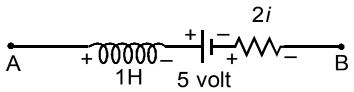


(i) current i = 2A and is constant

(ii) current i = 2A and is increasing at the rate of 1 amp/sec.

(iii) current i = 2A and is decreasing at the rate 1 amp/sec.

Sol.



$$L\frac{di}{dt} = 1\frac{di}{dt}$$

writing KVL from A to B

$$V_A - 1\frac{di}{dt} - 5 - 2\,i = V_B$$

(i) Put $i = 2$, $\frac{di}{dt} = 0$

$V_A - 5 - 4 = V_B$

$\therefore$ $V_A - V_B = 9$ volt

(ii) Put $i = 2$, $\frac{di}{dt} = 1$;

$V_A - 1 - 5 - 4 = V_B$

or $V_A - V_B = 10\ V_0$

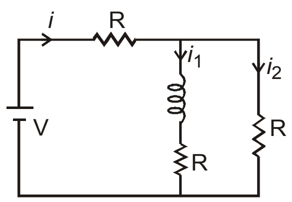
(iii) Put $i = 2$, $\frac{di}{dt} = -1$

$V_A + 1 - 5 - 2 \times 2 = V_B$

$V_A = 8$ volt

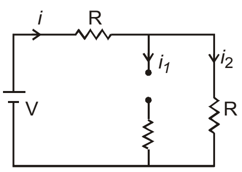
EXAMPLE 40

Find current i, i_1 and i_2 in the following circuit.

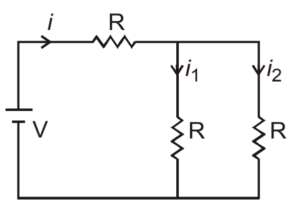


Sol. at $t = 0$

$$i = i_2 = \frac{V}{2R} \text{ and } i_1 = 0$$



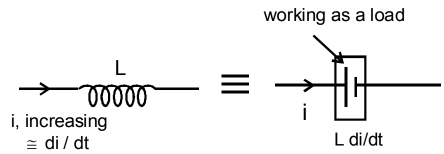
at $t = \infty$



$\Rightarrow$ $i_1 = i_2 = \frac{i}{2} = \frac{V}{2R}$

7.1 Energy stored in an inductor :

If current in an inductor at an instant is i and is increasing at the rate di/dt, the induced emf will oppose the current. Its behaviour is shown in the figure.



Power consumed by the inductor $= i\,L\frac{di}{dt}$

Energy consumed in dt time $= i\,L\frac{di}{dt}\,dt$

$\therefore$ total energy consumed as the current increases from

$$0 \text{ to } I = \int_0^i ILdi = \frac{1}{2}Li^2$$

$$= \frac{1}{2}Li^2 \Rightarrow U = \frac{1}{2}Li^2$$

Note

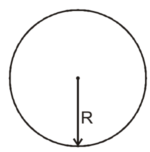
This energy is stored in the magnetic field with energy density

$$\frac{dU}{dV} = \frac{B^2}{2\mu} = \frac{B^2}{2\mu_0\mu_r}$$

Total Energy $U = \int \frac{B^2}{2\mu_0\mu_r}dV$

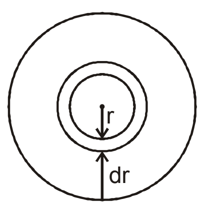
EXAMPLE 41

Find out the energy per unit length ratio inside the solid long wire having current density J.



Sol. Take a ring of radius r and thickness dr as an element inside the wire

$$\frac{dE}{dv} = \frac{B^2}{2\mu_0}$$



using $B = \frac{\mu_0 jr}{2}$

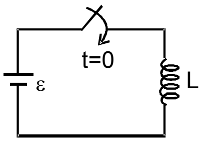
$$\frac{dE}{dv} = \frac{\mu_0^2 J^2 r^2}{4(2\mu_0)}$$

$\Rightarrow$ $\int dE = \int \frac{\mu_0 j^2 r^2}{8} 2\pi r dr \ell$

$\Rightarrow$ $\frac{E}{\ell} = \frac{\pi\mu_0 j^2 R^4}{16}$

EXAMPLE 42

A circuit contains an ideal cell and an inductor with a switch. Initially the switch is open. It is closed at t = 0. Find the current as a function of time.



Sol. $\varepsilon = L\dfrac{di}{dt}$

$\Rightarrow \quad \int_0^i \varepsilon dt = \int_0^i L di$

$\varepsilon t = Li \;\Rightarrow\; i = \dfrac{\varepsilon t}{L}$

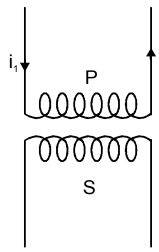
8. MUTUAL INDUCTANCE

Consider two coils P and S placed close to each other as shown in the figure. When the current passing through a coil increases or decreases, the magnetic flux linked with the other coil also changes and an induced e.m.f. is developed in it. This phenomenon is known as mutual induction. This coil in which current is passed is known as primary and the other in which e.m.f. is developed is called as secondary.

Let the current through the primary coil at any instant be i_1. Then the magnetic flux ϕ_2 in the secondary at any time will be proportional to i_1 i.e., $\phi_2 \propto i_1$

Therefore the induced e.m.f. in secondary when i_1 changes is given by

$\varepsilon = -\dfrac{d\phi_2}{dt}$ i.e., $\varepsilon \propto -\dfrac{di_1}{dt}$



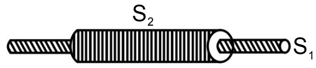
$\therefore \quad \varepsilon = -M\dfrac{di_1}{dt} = -\dfrac{dM i_1}{dt}$

$\Rightarrow \quad \phi_2 = M i_1$

where M is the constant of proportionality and is known as mutual inductance of two coils. It is defined as the e.m.f. induced in the secondary coil by unit rate of change of current in the primary coil. The unit of mutual inductance is henry (H).

Mutual Inductance of a Pair of Solenoids one Suurounding the other coil

Figure shows a coil of N_2 turns and radius R_2 surrounding a long solenoid of length l_1, radius R_1 and number of turns N_1.



To calculate mutual inductance M between them, let us assume a current i_1 through the inner solenoid S_1 There is no magnetic field outside the solenoid and the field inside has magnitude,

$$B = \mu_0\left(\frac{N_1}{l_1}\right)i_1$$

and is directed parallel to the solenoid's axis. The magnetic flux ϕ_{B_2} through the surrounding coil is, therefore,

$$\phi_{B_2} = B(\pi R_1^2) = \frac{\mu_0 N_1 i_1}{l_1}\pi R_1^2$$

Now, $\quad M = \dfrac{N_2\phi_{B_2}}{i_1} = \left(\dfrac{N_2}{i_1}\right)\left(\dfrac{\mu_0 N_1 i_1}{l_1}\right)\pi R_1^2$

$\Rightarrow \quad \dfrac{\mu_0 N_1 N_2 \pi R_1^2}{l_1}$

Notice that M is independent of the radius R_2 of the surrounding coil. This is because solenoid's magnetic field is confined to its interior.

Brain Teaser

What is the meaning of the statement "The coefficient of mutual inductance for a pair of coils is large" ?

Note

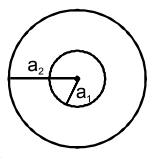
$M \le \sqrt{L_1 L_2}$

For two coils in series if mutual inductance is considered then

$$L_{eq} = L_1 + L_2 \pm 2M$$

EXAMPLE 43

Find the mutual inductance of two concentric coils of radii a_1 and a_2 ($a_1 << a_2$) if the planes of coils are same.



Sol. Let a current i flow in coil of radius a_2.

Magnetic field at the centre of coil = $\dfrac{\mu_0 i}{2a_2}\pi a_1^2$

or $\quad M i = \dfrac{\mu_0 i}{2a_2}\pi a_1^2 \quad$ or $\quad M = \dfrac{\mu_0 \pi a_1^2}{2a_2}$

EXAMPLE 44

Solve the above question, if the planes of coil are perpendicular.

Sol. Let a current i flow in the coil of radius a_1. The magnetic field at the centre of this coil will now be parallel to the plane of smaller coil and hence no flux will pass through it, hence M =0

EXAMPLE 45

Solve the above problem if the planes of coils make θ angle with each other.

Sol. If i current flows in the larger coil, magnetic field produced at the centre will be perpendicular to the plane of larger coil.

Now the area vector of smaller coil which is perpendicular to the plane of smaller coil will make an angle θ with the magnetic field.

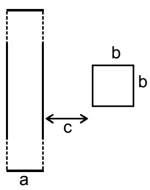
Thus flux = $\vec{B}.\vec{A} = \frac{\mu_0 i}{2a_2} . \pi a_1^2 \cos\theta$

or $$M = \frac{\mu_0 \pi a_1^2 \cos\theta_1}{2a_2}$$

EXAMPLE 46

Find the mutual inductance between two rectangular loops, shown in figure.

Sol. Let current i flow in the loop having ∞-by long sides. Consider a segment of width dx at a distance x as shown flux through the regent



$$d\phi = \left[\frac{\mu_0 i}{2\pi x} - \frac{\mu_0 i}{2\pi(x+a)}\right] b\, dx$$

$$\Rightarrow \quad \phi = \int_c^{c+b} \left[\frac{\mu_0 i}{2\pi x} - \frac{\mu_0 i}{2\pi(x+a)}\right] b\, dx$$

$$= \frac{\mu_0 ib}{2\pi}\left[\ln\frac{c+b}{c} - \ln\frac{a+b+c}{a+c}\right]$$

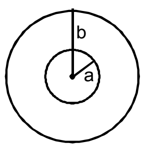
EXAMPLE 47

Figure shows two concentric coplanar coils with radii a and b (a << b). A current i = 2t flows in the smaller loop. Neglecting self inductance of larger loop

(a) Find the mutual inductance of the two coils

(b) Find the emf induced in the larger coil

(c) If the resistance of the larger loop is R find the current in it as a function of time



Sol. (a) To find mutual inductance, it does not matter in which coil we consider current and in which flux is calculated (Reciprocity theorem) Let current i be flowing in the larger coil. Magnetic

field at the centre = $\frac{\mu_0 i}{2b}$.

flux through the smaller coil = $\frac{\mu_0 i}{2b}\pi a^2$

∴ $M = \frac{\mu_0}{2b}\pi a^2$

(ii) | emf induced in larger coil |

$= M\left[\left(\frac{di}{dt}\right) \text{in smaller coil}\right]$

$= \frac{\mu_0}{2b}\pi a^2 \ (2) = \frac{\mu_0 \pi a^2}{b}$

(iii) current in the larger coil = $\frac{\mu_0 \pi a^2}{bR}$

Note

Now The student can now attempt Section - C from exercise.

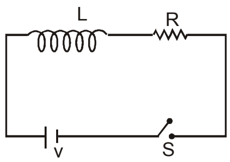
Section D - L-R circuit, L-C Oscillations

9. L.R. CIRCUIT

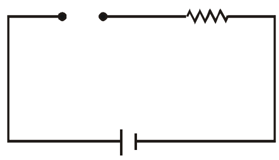
As the switch S is closed in given figure, current in circuit wants to rise upto $\frac{v}{R}$ in no time but inductor

opposes it $\left(\frac{di}{dt} \to \frac{V}{L}\right)$

hence at time t = 0 inductor will behave as an open circuit



at t = 0

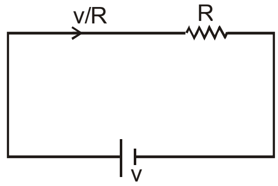


As the time passes, i in the circuit rises and $\frac{di}{dt}$ decreases. At any instant t.

$$\frac{Ldi}{dt} + iR = V$$

current reaches the value $\frac{v}{R}$ at time t = ∞ or we can say, inductor will behave as a simple wire.

at t = ∞

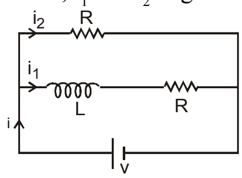


EXAMPLE 48

Find value of current i, i_1 and i_2 in given figure at

(a) time t = 0

(b) time t = ∞

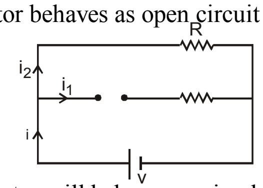


Sol. (a) At time t = 0 inductor behaves as open circuit

$i = v/R$

$i_1 = 0$

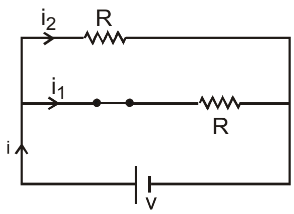
$i_2 = i = v/R$



(b) At time t = ∞. Inductor will behaves as simple wire

$$i = \frac{v}{(R/2)} = \frac{2v}{R}$$

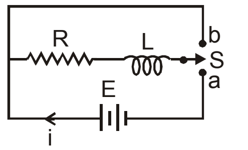
$$i_1 = i_2 = \frac{v}{R}$$



10. GROWTH AND DECAY OF CURRENT IN L-R CIRCUIT

10.1 Growth of Current

Consider a circuit containing a resistance R, an inductance L, a two way key and a battery of e.m.f E connected in series as shown in figure. When the switch S is connected to a, the current in the circuit grows from zero value. The inductor opposes the growth of the current. This is due to the fact that when the current grows through inductor, a back e.m.f. is developed which opposes the growth of current in the circuit. So the rate of growth of current is reduced. During the growth of current in the circuit, let i be the current in the circuit at any instant t. Using Kirchhoff's voltage law in the circuit, we obtain



$$E - L\frac{di}{dt} = R\,i \quad \text{or} \quad E - Ri = L\frac{di}{dt}$$

or $$\frac{di}{E - Ri} = \frac{dt}{L}$$

Multiplying by – R on both the sides, we get

$$\frac{-R\,di}{E - Ri} = \frac{-Rdt}{L}$$

Integrating the above equation, we have

$$\log_e(E - Ri) = -\frac{R}{L}t + A \qquad ...(1)$$

where A is integration constant. The value of this constant can be obtained by applying the condition that current i is zero just at start i.e., at t = 0. Hence

$\log_e E = 0 + A$

or $A = \log_e E \qquad ...(2)$

Substituting the value of A from equation (2) in equation (1), we get

$$\log_e(E - Ri) = -\frac{R}{L}t + \log_e E$$

or $$\log_e\left(\frac{E - Ri}{E}\right) = -\frac{R}{L}t$$

or $$\left(\frac{E - Ri}{E}\right) = \exp\left(-\frac{R}{L}t\right)$$

or $$1 - \frac{Ri}{E} = \exp\left(-\frac{R}{L}t\right)$$

or $$\frac{Ri}{E} = \left\{1 - \exp\left(-\frac{R}{L}t\right)\right\}$$

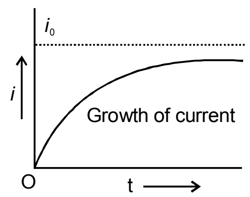
∴ $$i = \frac{E}{R}\left\{1 - \exp\left(-\frac{R}{L}t\right)\right\}$$

The maximum current in the circuit $i_0 = E/R$. So

$$i = i_0\left\{1 - \exp\left(-\frac{R}{L}t\right)\right\} \qquad ...(3)$$

Equation (3) gives the current in the circuit at any instant t. It is obvious from equation (3) that $i = i_0$, when

$$\exp\left(-\frac{R}{L}t\right) = 0 \text{ i.e., at } t = \infty$$



Hence the current never attains the value i_0 but it approaches it asymptotically. A graph between current and time is shown in figure.

- We observe the following points

(i) When t = (L/R) then

$$i = i_0\left\{1 - \exp\left(-\frac{R}{L}\times\frac{L}{R}\right)\right\} = i_0\ \{1 - \exp(-1)\}$$

$$= i_0\left(1 - \frac{1}{e}\right) = 0.63\ i_0$$

Thus after an interval of (L/R) second, the current reaches to a value which is 63% of the maximum current. The value of (L/R) is known as time constant of the circuit and is represented by τ. Thus the time constant of a circuit may be defined as the time in which the current rises from zero to 63% of its final value. In terms of τ,

$$i = i_0\left(1 - e^{\frac{-t}{\tau}}\right)$$

(ii) The rate of growth of current (di/dt) is given by

$$\frac{di}{dt} = \frac{d}{dt}\left[i_0\left\{1 - \exp\left(-\frac{R}{L}t\right)\right\}\right]$$

$$\Rightarrow \quad \frac{di}{dt} = i_0\left(\frac{R}{L}\right)\exp\left(-\frac{R}{L}t\right) \qquad ...(4)$$

From equation (3), $\exp\left(-\frac{R}{L}t\right) = \frac{i_0 - i}{i_0}$

$$\therefore \quad \frac{di}{dt} = i_0\left(\frac{R}{L}\right)\left(\frac{i_0 - i}{i_0}\right) = \frac{R}{L}(i_0 - i) \qquad ...(5)$$

This shows that the rate of growth of the current decreases as i tends to i_0. For any other value of current, it depends upon the value of R/L. Thus greater is the value of time constant, smaller will be the rate of growth of current.

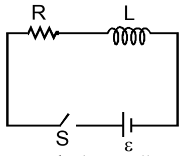
Note

- Final current in the circuit = $\frac{\varepsilon}{R}$, which is independent of L.
- After one time constant, current in the circuit=63% of the final current (verify yourself)
- More time constant in the circuit implies slower rate of change of current.
- If there is any change in the circuit containing inductor then there is no instantaneous effect on the flux of inductor.

$$L_1 i_1 = L_2 i_2$$

EXAMPLE 49

At t = 0 switch is closed (shown in figure) after a long time suddenly the inductance of the inductor is made η times lesser $(\frac{L}{\eta})$ then its initial value, find out instant current just after the operation.

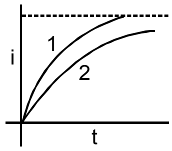


Sol. Using above result (note 4)

$$L_1 i_1 = L_2 i_2 \quad \Rightarrow \quad i_2 = \frac{\eta\varepsilon}{R}$$

EXAMPLE 50

Which of the two curves shown has less time constant.



Sol. curve 1

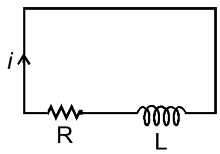
10.2 Decay of Current

Let the circuit be disconnected from battery and switch S is thrown to point b in the figure. The current now begins to fall. In the absence of inductance, the current would have fallen from maximum i_0 to zero almost instantaneously. But due to the presence of inductance, which opposes the decay of current, the rate of decay of current is reduced.

suppose during the decay of current, i be the value of current at any instant t. Using Kirchhoff's voltage law in the circuit, we get

$$-L\frac{di}{dt} = Ri \qquad \text{or} \qquad \frac{di}{dt} = -\frac{R}{L}i$$

Integrating this expression, we get



$$\log_e i = -\frac{R}{L}t + B$$

where B is constant of integration. The value of B can be obtained by applying the condition that when t = 0, $i = i_0$

$$\therefore \quad \log_e i_0 = B$$

Substituting the value of B, we get

$$\log_e i = -\frac{R}{L}t + \log_e i_0$$

or $$\log_e \frac{i}{i_0} = -\frac{R}{L}t$$

or $$(i/i_0) = \exp\left(-\frac{R}{L}t\right) \qquad ...(6)$$

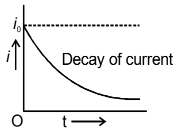
or $$i = i_0 \exp\left(-\frac{R}{L}t\right) = i_0 \exp\left(-\frac{t}{\tau}\right)$$

where τ = L/R = inductive time constant of the circuit.
It is obvious from equation that the current in the circuit decays exponentially as shown in figure.

- We observe the following points

(i) After t = L/R, the current in the circuit is given by

$$i = i_0 \exp\left(-\frac{R}{L} \times \frac{L}{R}\right) = i_0 \exp(-1)$$



$= (i_0 / e) = i_0/2.718 = 0.37\ i_0$

So after a time (L/R) second, the current reduces to 37% of the maximum current i_0. (L/R) is known as time constant τ. This is defined as the time during which the current decays to 37% of the maximum current during decay.

(ii) The rate of decay of current in given by

$$\frac{di}{dt} = \frac{d}{dt}\left\{i_0 \exp\left(-\frac{R}{L}t\right)\right\}$$

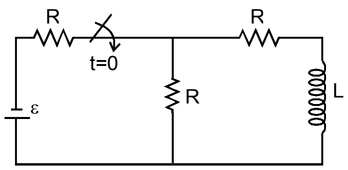
$$\Rightarrow \quad \frac{di}{dt} = \frac{R}{L} i_0 \exp\left(-\frac{R}{L}t\right) = -\frac{R}{L} i \qquad ...(7)$$

or $$-\frac{di}{dt} = \frac{R}{L} i$$

This equation shows that when L is small, the rate of decay of current will be large i.e., the current will decay out more rapidly.

EXAMPLE 51

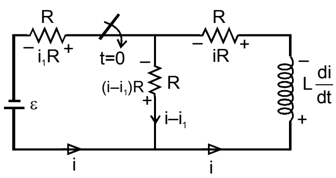
In the following circuit the switch is closed at t = 0. Initially there is no current in inductor. Find out current the inductor coil as a function of time.



Sol. At any time t

$$-\varepsilon + i_1 R - (i - i_1) R = 0$$
$$-\varepsilon + 2i_1 R - i R = 0$$
$$i_1 = \frac{iR + \varepsilon}{2R}$$

Now, $-\varepsilon + i_1 R + iR + L.\frac{di}{dt} = 0$



$$-\varepsilon + \left(\frac{iR+\varepsilon}{2}\right) + iR + i.\frac{di}{dt} = 0$$

$$\Rightarrow \quad -\frac{\varepsilon}{2} + \frac{3IR}{2} = -L\frac{di}{dt}$$

$$\left(\frac{-\varepsilon + 3iR}{2}\right)dt = -L.\ di$$

$$\Rightarrow \quad -\frac{-di}{dt} = \frac{di}{-\varepsilon + 3iR}$$

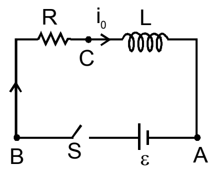
$$-\int_0^t \frac{dt}{2L} = \int_0^i \frac{di}{-\varepsilon + 3iR} \Rightarrow -\frac{t}{2L} = \frac{1}{3R}\ln\left(\frac{-\varepsilon + 3iR}{-\varepsilon}\right)$$

$$-\ln\left(\frac{-\varepsilon + 3iR}{-\varepsilon}\right) = \frac{3Rt}{2L}$$

$$i = +\frac{\varepsilon}{3R}\left(1 - e^{-\frac{3Rt}{2L}}\right)$$

EXAMPLE 52

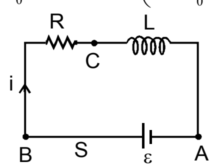
Figure shows a circuit consisting of a ideal cell, an inductor L and a resistor R, connected in series. Let the switch S be closed at t = 0. Suppose at t = 0 current in the inductor is i_0 then find out equation of current as a function of time



Sol. Let an instant t current in the circuit is i which is increasing at the rate di/dt.
Writing KVL along the circuit, we have

$$\varepsilon - L\frac{di}{dt} - iR = 0 \Rightarrow L\frac{di}{dt} = \varepsilon - iR$$

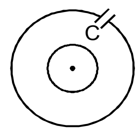
$$\Rightarrow \quad \int_{i_0}^{i} \frac{di}{\varepsilon - iR} = \int_0^t \frac{dt}{L} \Rightarrow \ln\left(\frac{\varepsilon - iR}{\varepsilon - i_0R}\right) = -\frac{Rt}{L}$$



$$\Rightarrow \quad \varepsilon - iR = (\varepsilon - i_0R)e^{-Rt/L} \Rightarrow i = \frac{\varepsilon - (\varepsilon - i_0R)e^{-Rt/L}}{R}$$

EXAMPLE 53

If the current in the inner loop changes according to $i = 2t^2$ then, find



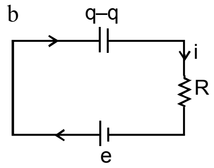
Sol. $M = \frac{\mu_0}{2b}\pi a^2$

|emf induced in larger coil|

$= M\left[\left(\frac{di}{dt}\right)\text{in smaller coil}\right]$

$e = \frac{\mu_0}{2b}\pi a^2\ (4t) = \frac{2\mu_0 \pi a^2 t}{b}$

Applying KVL : -



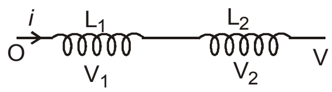
$+e - \frac{q}{c} - iR = 0$

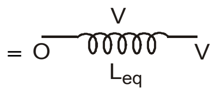
$\Rightarrow \frac{2\mu_0\pi a^2 t}{b} - \frac{q}{c} - iR = 0$

differentiate wrt time : $\frac{2\mu_0\pi a^2}{b} - \frac{i}{c} - \frac{di}{dt}R = 0$ on

solving it $i = \frac{2\mu_0\pi a^2 C}{b}\left[1 - e^{-t/RC}\right]$

11. SERIES COMBINATION OF INDUCTORS





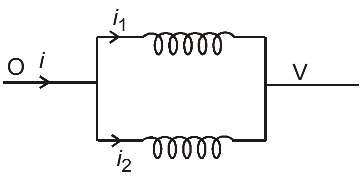
$\therefore \quad V = V_1 + V_2$

$L_{eq}\frac{di}{dt} = L_1\frac{di}{dt} + L_2\frac{di}{dt}$

$L_{eq} = L_1 + L_2 + ...$

Parallel Combination of inductor

$i = i_1 + i_2 \quad \Rightarrow \quad \frac{di}{dt} = \frac{di_1}{dt} + \frac{di_2}{dt}$



$\frac{v}{L_{eq}} = \frac{v}{L_1} + \frac{v}{L_2}$

Note

Now The student can now attempt Section - C from exercise.

Section E - Induced, Properties of EM Waves

12. BASIC EQUATIONS OF ELECTRICITY AND MAGNETISM

The whole concept of electricity and magnetism can be explained by the four basic equations we have deal so far.

(1) $\oint E \cdot ds = \frac{Q}{\epsilon_0}$ (Gauss law for electrostatic)

(2) $\oint B \cdot ds = 0$ (Gauss law for magnetism)

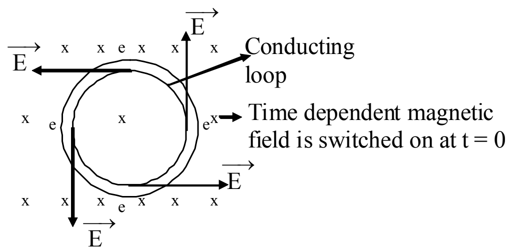
(3) $\oint B \cdot d\ell = \mu_0 i$ (Ampere's law for Magnetism)

(4) $\oint E \cdot d\ell = 0$ (Ampere's law for electrostatic)

The above stated equation are true for non-time varying fields

13. FARADAYS LAW FOR TIME VARYING MAGNETIC FIELD

To understand the concept of faradays law we consider a circular conducting loop placed in a region where time dependent magnetic field is present



From the earlier concept we know that an induced emf will be produced in the conducting loop due to which current will flow in the loop.

For current to flow a force must act on the electron which will move then from static state. This force cannot be due to magnetic field (since magnetic force does not act on stationary charge). Hence this force must be due to an electric field which has been generated due to changing Magnetic field.

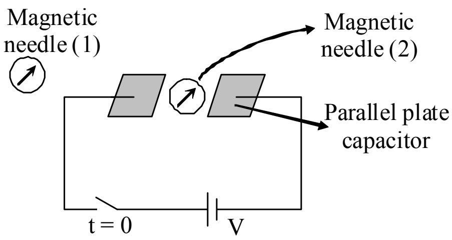
Note

This electric field is non conservative in nature.
Faraday stated this fact in his equation

$$\oint E.dl = -\left(\frac{d\phi_B}{dt}\right)$$

14. CONCEPT OF DISPLACEMENT CURRENT (MODIFIED AMPERE'S LAW)

Maxwell tried to generalis the concept of faradays law that if changing magnetic field can produce changing electric field then the reverse should also be true i.e. changing electric field must produce magnetic fied. To understand the concept of displacement current let us try to understand this experiment when the switch was closed at t = 0 both the needles deflected.



Deflection of needle (1) is under stood as M.F. is produced due to current flowing in the wire.
But why did needle 2 deflect? It is lying in between the two plates of capacitor where there is no current. This magnetic field between the plates is due to the changing electric field between the plates (During charging of capacitor). Hence maxwell conducted that changing electric field produces a magnetic field
For Needle (1) Amper's law

$$\oint B \cdot d\ell = \mu_0 i_c \qquad .... (1)$$

For needle (2) Amper's law

$$\oint B \cdot d\ell = \mu_0 \epsilon_0 \frac{d\phi_E}{dt} \qquad .... (2)$$

Hence there are two methods of producing M.F.
(a) Due to flow of electron which is known as conduction current
(b) Due to changing electric field
combining eq. (1) and eq. (2)

$$\oint B \cdot d\ell = \mu_0 \left[i_C + \left(\varepsilon_0 \frac{d\phi_E}{dt} \right) \right]$$

Modifield ampere's law

Note

$\varepsilon_0 \frac{d\phi_E}{dt}$ is known as displacement current

15. FINAL FORM OF MAXWELL'S EQUATION

(a) $\oint E \cdot ds = \frac{q}{\epsilon_0}$

(b) $\oint B \cdot ds = 0$

(c) $\oint E \cdot dl = -\frac{d\phi_B}{dt}$

(d) $\oint B \cdot dl = \mu_0 \left[I + \epsilon_0 \frac{d\phi_E}{dt} \right]$

The above equation is known as Maxwell's equation for time varying form.
Howover for free space there are no charges and no conduction current the equations that are significant.

$$\oint E \cdot d\ell = -\frac{d\phi_B}{dt}$$
$$\oint B \cdot d\ell = \mu_0 \epsilon_0 \frac{d\phi_E}{dt}$$

Solving these two differential equation the equation of electric field and magnetic field that satisfies these differential equations are obtained

$E_y = E_0 \sin\omega(t - x/c)$
$B_z = B_0 \sin \omega(t - x/c)$

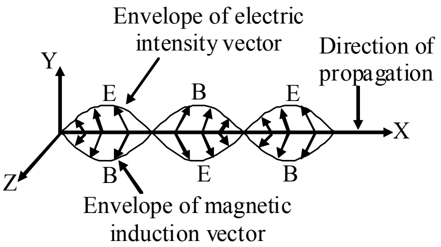
Here $\frac{E_0}{B_0} = C$ and $\frac{1}{\sqrt{\mu_0 \epsilon_0}} = C$

16. TRANSVERSE NATURE OF ELECTRO MAGNETIC WAVE AND ITS PROPERTIES

16.1 Electromagnetic waves :

The idea of electromagnetic waves was given by Maxwell and experimental verification was provided by Hertz and other scientists. A brief history of electromagnetic waves is as follows:
On the basis of experimental study of electromagnetic induction, Faraday concluded that a magnetic field changing with time at a point produces a time varying electric field at that point. Maxwell in 1864 pointed out an electric field changing with time at a point also produces a time varying magnetic field. The two fields are mutually perpendicular to each other. This idea led Maxwell to conclude that the mutually perpendicular time varying electric and magnetic fields produce electromagnetic disturbances in space. These disturbances have the properties of wave which are called as electromagnetic waves.
According to Maxwell, **the electromagnetic**

waves are those waves in which there are sinusoidal variation of electric and magnetic field vectors at right angle to each other as well as right angles to the direction of wave propagation. An electromagnetic wave is shown in fig.



The velocity of electromagnetic wave in free space is given by

$$c = \frac{1}{\sqrt{(\mu_0 \in_0)}}$$

where μ_0 ($1 = 1.257 \times 10^{-6}$ T mA^{-1}) and $\in_0$ ($= 8.854 \times 10^{-12}$ $C^2N^{-1}m^{-2}$) are permeability and permittivity of free space respectively. The velocity of electromagentic waves in free space is equal to the velocity of light. Therefore, light is electromagnetic waves. The electromagnetic waves are transverse in nature.

16.2 Transverse nature of electromagnetic waves:

We have seen that electromagnetic waves consists of a sinusoidally verying electric and magnetic field. These fields act right angles to each other as well as right angles to the direction of propagation of waves. These fields are represented by

$E = E_0 \sin \omega(t - x/c)$

and $B = B_0 \sin \omega(t - x/c)$

respectively. The two fields combine to constitute electromagnetic wave. The electromagnetic wave propagates in space in a direction perpendicular to the directions of both fields as shown in fig. The electric field vectors (E) is along Y-axis and magnetic field vector (B) along Z-axis while the wave propagation direction is along X-axis. As both the fields are perpendicular to the direction of propagation of electromagnetic wave and hence the electromagnetic waves are transverse in nature.

17. POYNTING VECTOR (DERIVATION AND REQUIRED)

Poynting vector is a vector that describes the magnitude and direction of energy flow rate.

$$\boxed{\vec{S} = \frac{\vec{E} \times \vec{B}}{\mu_0}}$$

$\vec{S} \rightarrow$ Poynting vector

The magnitude of poynting vector represents the rate at which energy flows through a unit surface area perpendicular to the direction of wave propogation SI unit J/sm^2 or w/m^2

18. ENERGY DENSITY AND INTENSITY

We know that electric and magnetic field have energy and since EM wave have both these components hence it carries energy with it.

We know that energy density associated with E.F.

$$= \frac{1}{2} \in_0 E^2$$

We know that energy density associated with M.F. $= \dfrac{B^2}{2\mu_0}$

Thus total energy of EM wave is given by

$$U = U_E + U_B \text{ or } \frac{1}{2} \in_0 E^2 + \frac{B^2}{2\mu_0}$$

putting the values of E.F. and M.F.

$$U = \frac{1}{2} \in_0 E_0^2 \sin^2\omega(t - x/c) + \frac{B_0^2 \sin^2 \omega(t - x/c)}{2\mu_0}$$

If we take the average value over a long period of time

$$\left[\sin^2 \omega\left(t - \frac{x}{c}\right)\right]_{Av} = \frac{1}{2}$$

$$\therefore \quad \boxed{U_{av} = \frac{1}{4} \in E_0^2 + \frac{1}{4\mu_0} B_0^2}$$

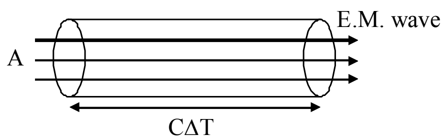
The above equation can also be written as

$$U_{av} = \frac{\in_0 E_0^2}{2} \text{ or } U_{av} = \frac{B_0^2}{2\mu_0}$$

Intensity :

Energy crossing per unit area per unit time perpendicular to the direction of propogation is called intensity of wave.

Energy contained in the volume :



$$U = U_{av} \times \text{vol} = \frac{1}{2} \in_0 E^2 (AC\Delta T)$$

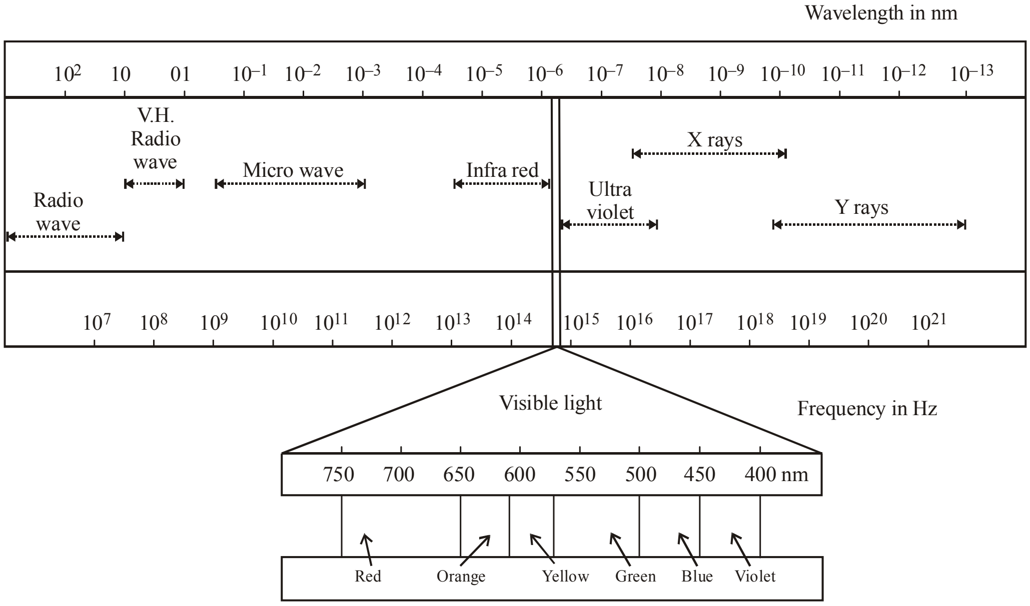
$$\text{intensity} = \frac{U}{A\Delta T} = \frac{\in_0 E^2 C}{2}$$

$$\therefore \quad \boxed{I = \frac{1}{2} \in_0 CE_0^2 \quad \text{or} \quad \frac{1}{2\mu_0} B_0^2}$$

19. ELECTROMAGNETIC SPECTRUM

Orderly arrangement of electromagnetic radiations according to their wavelength or frequency is called as electromagnetic spectrum.

The electromagnetic spectrum encompasses radiowaves, microwaves, infrared rays, visible light, ultraviolet rays, X-rays and gamma rays fig. shown the most commonly enecountered.



Name	Frequency range (Hz)	Wavelength range (m)
γ-ray	$5 \times 10 \quad - 3 \times 10$	$6 \times 10^{20\,-13} - 1 \times 10^{19\,-10}$
X-ray	$3 \times 10^{19} - 1 \times 10^{16}$	$1 \times 10^{-10} - 3 \times 10^{-8}$
Ultraviolet	$1 \times 10^{16} - 8 \times 10^{14}$	$3 \times 10^{-8} - 4 \times 10^{-7}$
Visible light	$8 \times 10^{14} - 4 \times 10^{14}$	$4 \times 10^{-7} - 8 \times 10^{-7}$
Infra-red	$4 \times 10^{14} - 1 \times 10^{13}$	$8 \times 10^{-7} - 3 \times 10^{-5}$
Micro-waves	$3 \times 10^{11} - 1 \times 10^{9}$	$1 \times 10^{-3} - 3 \times 10^{-1}$
Ultra high radio frequencies	$3 \times 10^{9} - 3 \times 10^{8}$	$1 \times 10^{-1} - 1$
Very high Radio frequencies	$3 \times 10^{9} - 3 \times 10^{7}$	$1 - 10$
Radio frequencies	$3 \times 10^{7} - 3 \times 10^{4}$	$10 - 10^{4}$

Colour	Wavelength (m)
Violet	$4 \times 10^{-7} - 4.5 \times 10^{-7}$
Blue	$4.5 \times 10^{-7} - 5 \times 10^{-7}$
Green	$5.5 \times 10^{-7} - 5.7 \times 10^{-7}$
Yellow	$5.7 \times 10^{7} - 5.9 \times 10^{-7}$
Orange	$5.9 \times 10^{-7} - 6.2 \times 10^{-7}$
Red	$6.2 \times 10^{-7} - 7.5 \times 10^{-7}$

Note

Now The student can now attempt Section - E from exercise.

Section A - Flux, Faraday's law, Lenz's law

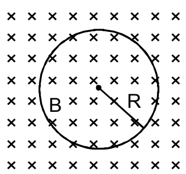
1. A flux of 1m Wb passes through a strip having an area A = 0.02 m^2. The plane of the strip is at an angle of 60º to the direction of a uniform field B. The value of B is-

(A) 0.1 T (B) 0.058 T
(C) 4.0 mT (D) none of the above.

2. The number of turns in a long solenoid is 500. The area of cross-section of solenoid is 2×10^{-3} m^2. If the value of magnetic induction, on passing a current of 2 amp, through it is 5×10^{-3} tesla, the magnitude of magnetic flux connected with it in webers will be

(A) 5×10^{-3} (B) 10^{-2}
(C) 10^{-5} (D) 2.5

3. A conducting loop of radius R is present in a uniform magnetic field B perpendicular the plane of the ring. If radius R varies as a function of time 't', as $R = R_0 + t$. The e.m.f induced in the loop is



(A) $2\pi (R_0 + t)$ B clockwise
(B) $\pi(R_0 + t)B$ clockwise
(C) $2\pi(R_0 + t)B$ anticlockwise
(D) zero

4. The instantaneous flux associated with a closed circuit of 10Ω resistance is indicated by the following reaction $\phi = 6t^2 - 5t + 1$, then the value in amperes of the induced current at t = 0.25 sec will be:

(A) 1.2 (B) 0.8
(C) 6 (D) 0.2

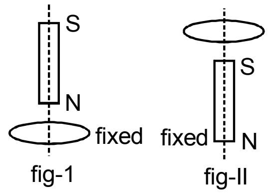
5. An electron is moving in a circular orbit of radius R with an angular acceleration α. At the centre of the orbit is kept a conducting loop of radius r, (r << R). The e.m.f induced in the smaller loop due to the motion of the electron is

(A) zero, since charge on electron in constant

(B) $\frac{\mu_0 e r^2}{4R}\alpha$ (C) $\frac{\mu_0 e r^2}{4\pi R}\alpha$

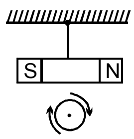
(D) none of these

6. A vertical bar magnet is dropped from position on the axis of a fixed metallic coil as shown in fig-I. In fig-II the magnet is fixed and horizontal coil is dropped. The acceleration of the magnet and coil are a_1 and a_2 respectively then



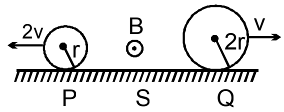
(A) $a_1 > g,\ a_2 > g$ (B) $a_1 > g,\ a_2 < g$
(C) $a_1 < g,\ a_2 < g$ (D) $a_1 < g,\ a_2 > g$

7. A negative charge is given to a nonconducting loop and the loop is rotated in the plane of paper about its centre as shown in figure. The magnetic field produced by the ring affects a small magnet placed above the ring in the same plane :



(A) the magnet does not rotate
(B) the magnet rotates clockwise as seen from below.
(C) the magnet rotates anticlockwise as seen from below
(D) no effect on magnet is there.

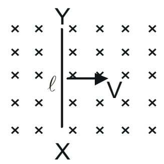
8. Two conducting rings P and Q of radii r and 2r rotate uniformly in opposite directions with centre of mass velocities 2v and v respectively on a conducting surface S. There is a uniform magnetic field of magnitude B perpendicular to the plane of the rings. The potential difference between the highest points of the two rings is



(A) zero (B) 4 Bvr
(C) 8 Bvr (D) 16 Bvr

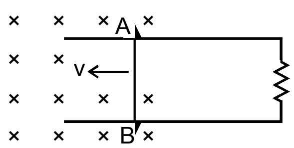
Section B - EMF induced in Moving Rod, Rotating Ring, Disc.

9. A small conducting rod of length l, moves with a uniform velocity v in a uniform magnetic field B as shown in fig-



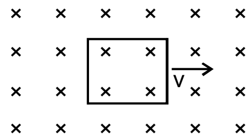
(A)Then the end X of the rod becomes positively charged
(B) the end Y of the rod becomes positively charged
(C) the entire rod is unevely charged
(D) the rod becomes hot due to joule heating.

10. Consider the situation shown in fig. The resistanceless wire AB is slid on the fixed rails with a constant velocity. If the wire AB is replaced by a resistanceless semicircular wire, the magnitude of the induced current will



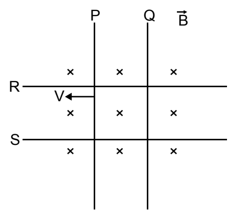
(A) increase (B) remain the same
(C) decrease
(D) increase or decrease depending on whether the semicircle bulges towards the resistance or away from it.

11. A conducting square loop of side I and resistance R moves in its plane with a uniform velocity v perpendicular to one of its sides. A uniform and constant magnetic field B exists along the perpendicular to the plane of the loop in fig. The current induced in the loop is



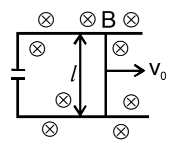
(A) BIυ/R clockwise
(B) BIυ/R anticlockwise
(C) 2BIυ/R anticlockwise
(D) zero

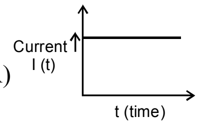
12. Two identical conductors P and Q are placed on two frictionless fixed conducting rails R and S in a uniform magnetic field directed into the plane. If P is moved in the direction shown in figure with a constant speed, then rod Q

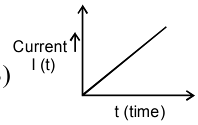


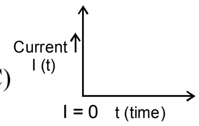
(A) will be attracted towards P
(B) will be repelled away from P
(C) will remain stationary
(D) may be repelled or attracted towards P

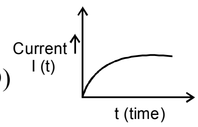
13. Two infinitely long conducting parallel rails are connected through a capacitor C as shown in the figure. A conductor of length l is moved with constant speed v_0. Which of the following graph truly depicts the variation of current through the conductor with time ?



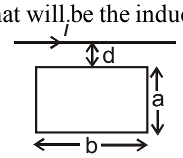
(A) 

(B) 

(C) 

(D) 

14. A long straight wire is parallel to one edge as in fig. If the current in the long wire is varies in time as $I = I_0 e^{-t/\tau}$, what will be the induced emf in the loop ?



(A) $\frac{\mu_0 bI}{\pi\tau}\ln\left(\frac{d+a}{d}\right)$ (B) $\frac{\mu_0 bI}{2\pi\tau}\ln\left(\frac{d+a}{d}\right)$

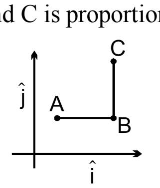
(C) $\frac{2\mu_0 bI}{\pi\tau}\ln\left(\frac{d+a}{d}\right)$ (D) $\frac{\mu_0 bI}{\pi\tau}\ln\left(\frac{d}{d+a}\right)$

15. The magnetic field in a region is given by $\vec{B} = B_0\left(1+\frac{x}{a}\right)\hat{k}$. A square loop of edge-length d is placed with its edge along x & y axis. The loop is moved with constant velocity $\vec{V} = V_0\hat{i}$. The emf induced in the loop is

(A) $\frac{V_0 B_0 d^2}{a}$ (B) $\frac{V_0 B_0 d^2}{2a}$

(C) $\frac{V_0 B_0 a^2}{d}$ (D) None

16. There is a uniform magnetic field B normal to the xy plane. A conductor ABC has length AB = l_1, parallel to the x-axis, and length BC = l_2, parallel to the y-axis. ABC moves in the xy plane with velocity $v_x\hat{i} + v_y\hat{j}$. The potential difference between A and C is proportional to



(A) $v_x l_1 + v_y l_2$ (B) $v_x l_2 + v_y l_1$

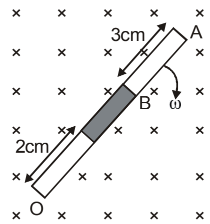
(C) $v_x l_2 - v_y l_1$ (D) $V_x l_1 - v_y l_2$

17. A rod of length l rotates with a uniform angular velocity ω about its perpendicular bisector. A uniform magnetic field B exists parallel to the axis of rotation. The potential difference between the two ends of the rod is

(A) zero (B) $\frac{1}{2}\omega B\ell^2$

(C) $B\omega\ell^2$ (D) $2B\omega\ell^2$

18. A rod of length 10 cm made up of conducting and non-conducting material (shaded part is non-conducting). The rod is rotated with constant angular velocity 10 rad/sec about point O, in constant magnetic field of 2 tesla as shown in the figure. The induced emf between the point A and B of rod will be



(A) 0.029 V (B) 0.1 V

(C) 0.051 V (D) 0.064 V

19. The north pole of a magnet is brought near a coil. The induced current in the coil as seen by an observer on the side of magnet will be

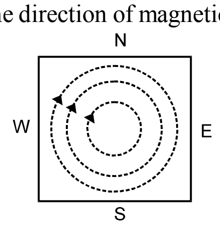
(A) in the clockwise direction

(B) in the anticlockwise direction

(C) initially in the clockwise and then anticlockwise direction

(D) initially in the anticlockwise and then clockwise direction.

20. A metal sheet is placed in a variable magnetic field which is increasing from zero to maximum. Induced current flows in the directions as shown in figure. The direction of magnetic field will be -



(A) normal to the paper, inwards

(B) normal to the paper, outwards.

(C) from east to west

(D) from north to south

Section C - Self Induction, Mutual Induction

21. The coefficient of mutual induction between two coils is 4H. If the current in the primary reduces from 5A to zero in 10^{-3} second then the induced e.m.f. in the secondary coil will be-
(A) 10^4 V (B) 25×10^3 V
(C) 2×10^4 V (D) 15×10^3 V

22. The number of turns in a coil of wire of fixed radius is 600 and its self inductance is 108 mH. The self inductance of a coil of 500 turns will be-
(A) 74 mH (B) 75 mH
(C) 76 mH (D) 77 mH

23. A long solenoid contains 1000 turns/cm and an alternating current of peak value 1 A is flowing in it. A search coil of area of cross-section 1×10^{-4} m^2 and having 50 turns is placed inside the solenoid with its plane perpendicular to the axis of the solenoid. A peak voltage of $2\pi^2 \times 10^{-2}$V is produced in the search coil. The frequency of current in the solenoid will be –
(A) 50 Hz (B) 100 Hz
(C) 500 Hz (D) 1000 Hz

24. The magnetic flux through a stationary loop with resistance R varies during interval of time T as ϕ = at (T – t). The heat generated during this time neglecting the inductance of loop will be

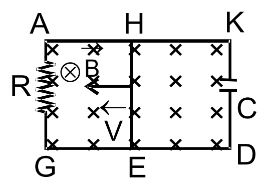
(A) $\frac{a^2T^3}{3R}$ (B) $\frac{a^2T^2}{3R}$

(C) $\frac{a^2T}{3R}$ (D) $\frac{a^2T^3}{R}$

25. A closed planar wire loop of area A and arbitrary shape is placed in a uniform magnetic field of magnitude B, with its plane perpendicular to magnetic field. The resistance of the wire loop is R. The loop is now turned upside down by 180° so that its plane again becomes perpendicular to the magnetic field. The total charge that must have flowen through the wire ring in the process is
(A) < AB/R (B) = AB/R
(C) = 2AB/R (D) None

26. Two coil A and B have coefficient of mutual inductance M = 2H. The magnetic flux passing through coil A changes by 4 Weber is 10 seconds due to the change in current in B. Then
(A) change in current in B in this time interval is 0.5 A
(B) the change in current in B in this time interval is 2A
(C) the change in current in B in this time interval is 8A
(D) a change in current of 1A in coil A will produce a change in flux passing through B by 4 Weber.

27. In the circuit shown in figure, a conducting wire HE is moved with a constant speed V towards left. The complete circuit is placed in a uniform magnetic field $\vec{B}$ perpendicular to the plane of the circuit directed in inward direction. The current in HKDE is

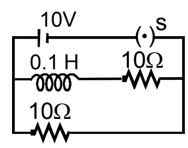


(A) clockwise (B) anticlockwise
(C) alternating (D) Zero

28. Induction furnaces work on the principle of :
(A) self-induction (B) mutual induction
(C) eddy currents (D) none of the above

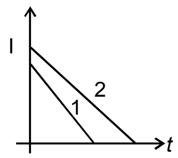
Section D - L-R circuit, L-C Oscillations

29. In the adjoining circuit, initially the switch S is open. The switch 'S' is closed at t = 0. The difference between the maximum and minimum current that can flow in the circuit is



(A) 2 Amp
(B) 3 Amp
(C) 1 Amp
(D) nothing can be concluded

30. Two identical inductance carry currents that vary with time according to linear laws (as shown in figure). In which of two inductance is the self induction emf greater ?



(A) 1 (B) 2

(C) same

(D) data are insufficient to decide

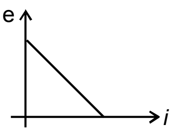
31. L, C and R represent physical quantities inductance, capacitance and resistance. The combination which has the dimensions of frequency is

(A) $\frac{1}{RC}$ and $\frac{R}{L}$ (B) $\frac{1}{\sqrt{RC}}$ and $\sqrt{\frac{R}{L}}$

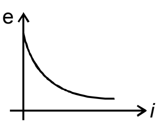
(C) $\sqrt{LC}$ (D) $\frac{C}{L}$

32. In an L-R circuit connected to a battery of constant e.m.f E switch S is closed at time t = 0. If e denotes the magnitude of induced e.m.f across inductor and i the current in the circuit at any time t. Then which of the following graphs shows the variation of e with *i* ?

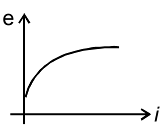
(A)



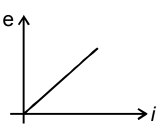
(B)



(C)



(D)



33. A current of 2A is increasing at a rate of 4A/s through a coil of inductance 2H. The energy stored in the inductor per unit time is

(A) 2J/s (B) 1 J/s

(C) 16 J/s (D) 4 J/s

34. A long solenoid of N turns has a self inductance L and area of cross section A. When a current i flows through the solenoid, the magnetic field inside it has magnitude B. The current i is equal to :

(A) BAN/L (B) BANL

(C) BN/AL (D) B/ANL

35. The current in an L - R circuit in a time $t = 2L/R$ reduces to-

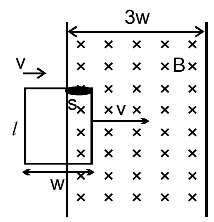
(A) 36.5% of maximum

(B) 13.5% of maximum

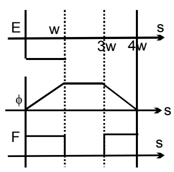
(C) 0.50% of maximum

(D) 63.2% of maximum

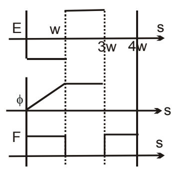
36. A rectangular loop of dimensions *l* & w and resistance R moves with constant velocity V to the right as shown in the figure. It continues to move with same speed through a region containing a uniform magnetic field B directed into the plane of the paper & extending a distance 3 W. Sketch the flux, induced emf & external force acting on the loop as a function of the distance.



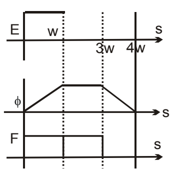
(A)



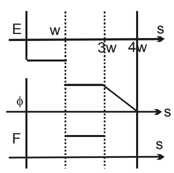
(B)



(C)



(D)



37. An LR circuit with a battery is connected at t = 0. Which of the following quantities is not zero just after the circuit

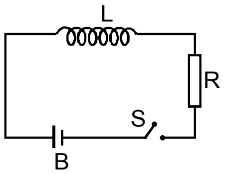
(A) current in the circuit

(B) magnetic field energy in the inductor

(C) power delivered by the battery

(D) emf induced in the inductor

38. In figure, the switch S is closed so that a current flows in the iron-core inductor which has inductance L and the resistance R. When the switch is opened, a spark is obtained in it at the contacts. The spark is due to



(A) a slow flux change in L

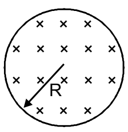
(B) a sudden increase in the emf of the battery B

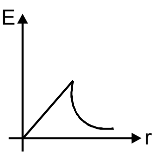
(C) a rapid flux change in L

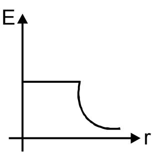
(D) a rapid flux change in R

Section E - Induced, Properties of EM Waves

39. A cylindrical space of radius R is filled with a uniform magnetic induction B parallel to the axis of the cylinder. If B changes at a constant rate, the graph showing the variation of induced electric field with distance r from the axis of cylinder is



(A)


(B)


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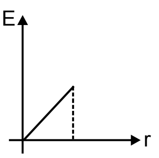
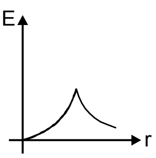
(C)


(D)


40. Elecromagnetic waves travel in a medium with a speed of 2×10^8 m/s. The relative permeability of the medium is 1. What is the relative permittivity of the medium-

(A) 2.25 (B) 3.25

(C) 4.25 (D) 5.25

41. A light beam travelling in the X-direction is described by the electric field E_y=(300V/m) sinω (t – x/c). An electron is constrained to move along the Y-direction with a speed of 2.0×10^7 m/s. Find the maximum electric force and the maximum magnetic force on the electron respectively.

(A) 4.8×10^{-17} N, 3.2×10^{-18} N

(B) 9.6×10^{-17} N, 6.4×10^{-18} N

(C) 2.4×10^{-17} N, 1.6×10^{-18} N

(D) 3.6×10^{-17} N, 2.5×10^{-18} N

42. An L – C circuit contain a 400 pF capacitor and a 100 μF inductor. It is set into oscillation coupled to an antenna. The wavelength of the radiated electromagnetic waves is :

(A) 377 mm (B) 377 cm

(C) 3.77 cm (D) 377 m.

43. The frequency of radiowaves corresponding to a wavelength 10 m is :

(A) 3×10^7 s^{-1} (B) 3×10^9 s^{-1}

(C) 3×10^{-9} s^{-1} (D) $1/3\times10^{-7}$ s^{-1}

44. In a plane e.m. wave, the electric field oscillates sinusoidally at a frequency of 2.0×10^{10} Hz and amplitude 48 V m^{-1}. The wavelength of the wave is :

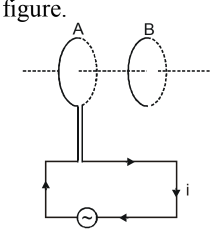
(A) 24×10^{-10} m (B) 1.5×10^{-2} m

(C) 4.16×10^{-8} m (D) 3×10^8 m

Exercise - 2 (Level-I) Objective Problems | JEE Main

Section A - Flux, Faraday's law, Lenz's law

1. Two circular coils A and B are facing each other as shown in figure.



The current i through A can be altered

(A) there will be repulsion between A and B if i is increased

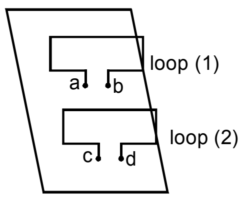
(B) there will be attraction between A and B if i is increased

(C) there will be neither attraction nor repulsion when i is changed

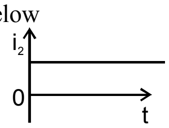
(D) attraction or repulsion between A and B depends on the direction of current.

It does not depend whether the current increased or decreased

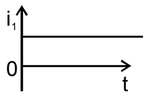
2. An electric current i_1 can flow either direction through loop (1) and induced current i_2 in loop (2). Positive i_1 is when current is from 'a' to 'b' in loop (1) and positive i_2 is when the current is from 'c' to 'd' in loop (2)

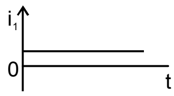


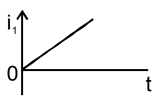
In an experiment, the graph of i_2 against time 't' is as shown below

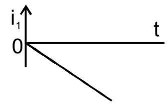


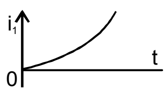
Which one(s) of the following graphs could have caused i_2 to behave as give above.

(A) 

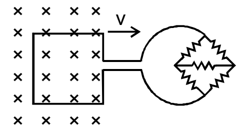
(B) 

(C) 

(D) 

(E) 

3. A square metal loop of side 10 cm and resistance 1 Ω is moved with a constant velocity partly inside a magnetic field of 2 Wbm^{-2}, directed into the paper, as shown in the figure. This loop is connected to a network of five resistors each of value 3 Ω. If a steady current of 1 mA flows in the loop, then the speed of the loop is



(A) 0.5 cms^{-1} (B) 1 cms^{-1}

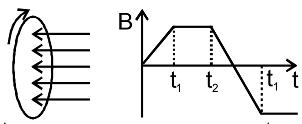
(C) 2 cms^{-1} (D) 4 cms^{-1}

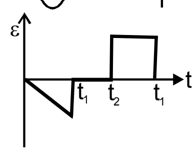
4. The dimension of the ratio of magnetic flux and the resistance is equal to that of :

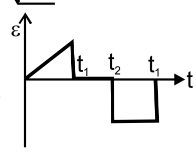
(A) induced emf (B) charge

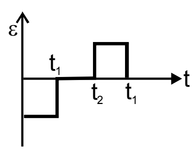
(C) inductance (D) current

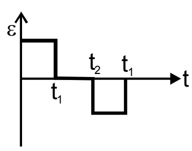
5. A wire loop is placed in a region of time varying magnetic field which is oriented orthogonally to the plane of the loop as shown in the figure. The graph shows the magnetic field variation as the function of time. Assume the positive emf is the one which drives a current in the clockwise direction and seen by the observer in the direction of B. Which of the following graphs best represents the induced emf as a function of time.



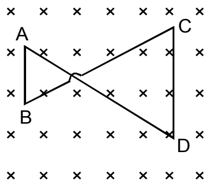
(A) 

(B) 

(C) 

(D) 

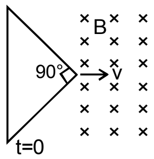
6. A conducting wire frame is placed in a magnetic field which is directed into the paper. The magnetic field is increasing at a constant rate. The directions of induced currents in wires AB and CD are

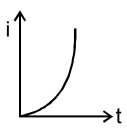


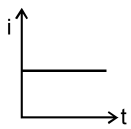
(A) B to A and D to C (B) A to B and C to D
(C) A to B and D to C (D) B to A and C to D

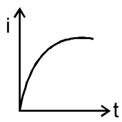
Section B - EMF induced in Moving Rod, Rotating Ring, Disc.

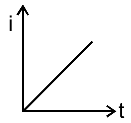
7. The figure shows an isosceles triangle wire frame with apex angle equal to $\pi/2$. The frame starts entering into the region of uniform magnetic field B with constant velocity v at t = 0. The longest side of the frame is perpendicular to the direction of velocity. If i is the instantaneous current through the frame then choose the alternative showing the correct variation of i with time.



(A) 

(B) 

(C) 

(D) 

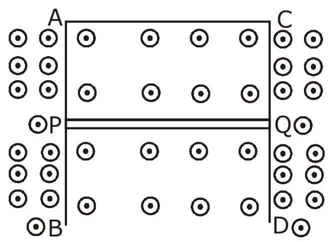
8. A metallic rod of length L and mass M is moving under the action of two unequal forces F_1 and F_2 (directed opposite to each other) acting at its ends along its length. Ignore gravity and any external magnetic field. If specific charge of electrons is (e/m), then the potential difference between the ends of the rod is steady state must be

(A) $|F_1 - F_2|$ mL/eM (B) $(F_1 - F_2)$ mL/eM
. (C) [mL/eM] $ln\,[F_1/F_2]$ (D) None

9. Two parallel long straight conductors lie on a smooth surface. Two other parallel conductors rest on them at right angles so as to form a square of side a initially. A uniform magnetic field B exists at right angles to the plane containing the conductors. They all start moving out with a constant velocity v. If r is the resistance per unit length of the wire the current in the circuit will be

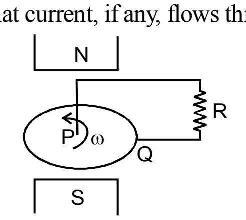
(A) $\frac{Bv}{r}$ (B) $\frac{Br}{v}$
(C) Bvr (D) Bv

10. BACD is a fixed conducting smooth rail placed in a vertical plane. PQ is a conducting rod which is free to slide on the rails. A horizontal uniform magnetic field exists in space as shown. If the rod PQ is released from rest then,



(A) The rod PQ will move downward with constant acceleration
(B) The rod PQ will move upward with constant acceleration
(C) The rod will move downward with decreasing acceleration and finally acqcure a constant velocity
(D) either A or B

11. A metal disc rotates freely, between the poles of a magnet in the direction indicated. Brushes P and Q make contact with the edge of the disc and the metal axle. What current, if any, flows through R?



(A) a current from P to Q
(B) a current from Q to P
(C) no current, because the emf in the disc is opposed by the back emf
(D) no current, because the emf induced in one side of the disc is opposed by the emf induced in the other side.

12. In the **previous question,** if B is normal to the plane of the rails

(A) Bil = mg tan θ (B) Bil = mg sin θ

(C) Bil = mg cos θ

(D) equilibrium cannot be reached

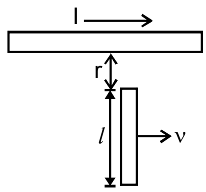
13. A conducting rod of length l moves with velocity v a direction parallel to a long wire carrying a steady current I. The axis of the rod is maintained perpendicular to the wire with near end a distance raway as shown in the fig. Find the emf induced in the rod.

(A) $\frac{\mu_0 Iv}{\pi}\ln\left(\frac{r+l}{r}\right)$

(B) $\frac{2\mu_0 Iv}{\pi}\ln\left(\frac{r+l}{r}\right)$

(C) $\frac{\mu_0 Iv}{\pi}\ln\left(\frac{l}{r+l}\right)$

(D) $\frac{\mu_0 Iv}{2\pi}\ln\left(\frac{r+l}{r}\right)$



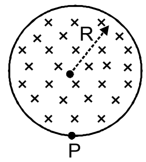
14. A uniform magnetic field of induction B is confined to a cylindrical region of radius R. The magnetic field is increasing at a constant rate of $\frac{dB}{dt}$ (tesla/second). An electron of charge q, placed at the point P on the periphery of the field experiences an acceleration

(A) $\frac{1}{2}\frac{eR}{m}\frac{dB}{dt}$ toward left

(B) $\frac{1}{2}\frac{eR}{m}\frac{dB}{dt}$ toward right

(C) $\frac{eR}{m}\frac{dB}{dt}$ toward left

(D) zero



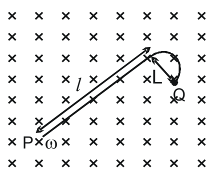
15. When a 'J' shaped conducting rod is rotating in its own plane with constant angular velocity ω, about one of its end P, in a uniform magnetic field $\vec{B}$ directed normally into the plane of paper) then magnitude of emf induced across it will be

(A) $B\omega\sqrt{L^2+l^2}$

(B) $\frac{1}{2}B\omega L^2$

(C) $\frac{1}{2}B\omega(L^2+l^2)$

(D) $\frac{1}{2}B\omega l^2$



16. A rectangular coil of single turn, having area A, rotates in a uniform magnetic field B an angular velocity ω about an axis perpendicular to the field. If initially the plane of coil is perpendicular to the field, then the average induced e.m.f. when it has rotated through 90° is

(A) $\frac{\omega BA}{\pi}$ (B) $\frac{\omega BA}{2\pi}$

(C) $\frac{\omega BA}{4\pi}$ (D) $\frac{2\omega BA}{\pi}$

17. For L - R circuit, the time constant is equal to

(A) twice the ratio of the energy stored in the magnetic field to the rate of dissipation of energy in the resistance.

(B) ratio of the energy stored in the magnetic field to the rate of dissipation of energy in the resistance.

(C) half the ratio of the energy stored in the magnetic field to the rate of dissipation of energy in the resistance

(D) square of the ratio of the energy stored in the magnetic field to the rate of dissipation of energy in the resistance.

Section C - Self Induction, Mutual Induction

18. On making a coil of copper wire of length ℓ and coil radius r, the value of self inductance is obtained as L. If the coil of same wire, but of coil radius r/2, is made, the value of self inductance will be-

(A) 2L (B) L

(C) 4L (D) L/2

19. A thin copper wire of length 100 metres is wound as a solenoid of length l and radius r. Its self inductance is found to be L. Now if the same length of wire is wound as a solenoid of length l but of radius r/2, then its self inductance will be-

(A) 4L (B) 2L

(C) L (D) L/2

20. A small coil of radius r is placed at the centre of a large coil of radius R, where R >> r. The coils are coplanar. The coefficient of mutual inductance between the coils is

(A) $\frac{\mu_0\pi r}{2R}$ (B) $\frac{\mu_0\pi r^2}{2R}$

(C) $\frac{\mu_0\pi r^2}{2R^2}$ (D) $\frac{\mu_0\pi r}{2R^2}$

21. The role of self-inductance in a circuit is equivalent to :

(A) momentum (B) force

(C) energy (D) inertia

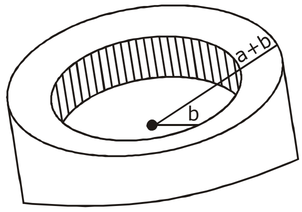
22. The approximate formula expressing the mutual inductance of two thin co-axial loops of the same radius 'a' when their centres are separated by a distance ℓ, with $\ell >> a$ is :

(A) $\frac{1}{2}\frac{\mu_0 \pi a^4}{l^3}$ (B) $\frac{1}{2}\frac{\mu_0 a^4}{l^2}$

(C) $\frac{\mu_0}{4\pi}.\frac{\pi a^2}{l^2}$ (D) $\frac{\mu_0}{\pi}.\frac{a^4}{l^3}$

23. Consider a toroid with N turns as shown in Figure. The space inside the solenoid is filled up with uniform paramagnetic substance of permeability μ_r, the inductance is :

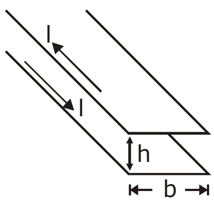
$$\left[\text{Where } L_0 = \frac{\mu_r \mu_0 N^2 a}{2\pi}\ell n\left(1+\frac{a}{b}\right)\right]$$



(A) $2\ L_0$ (B) $\frac{L_0}{2}$

(C) L_0 (D) $4\ L_0$

24. The inductance per unit length of the double tape shown with h<<b is : (Here I is the linear density of currents) is :



(A) $\mu_0 \frac{b}{h}$ (B) $\mu_0 \frac{h}{b}$

(C) $2\mu_0 \frac{h}{b}$ (D) $2\mu_0 \frac{b}{h}$

25. Two coil of self-inductances 2 mH and 8 mH are placed so close together that the effective flux in one coil is completely linked with the other. the mutual inductance between those coils is:

(A) 16 mH (B) 10 mH

(C) 6 mH (D) 4 mH

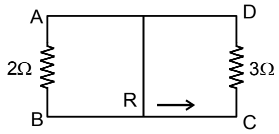
26. The coefficient of self-induction of two coils are 0.01 H and 0.03 H respectively. If they oppose each other then the resultant self induction will be, if M = 0.01 H

(A) 2H (B) 0.2 H

(C) 0.02 H (D) zero.

Section D - L-R circuit, L-C Oscillations

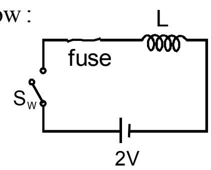
27. A rectangular loop with a sliding connector of length 10 cm is situated in uniform magnetic field perpendicular to plane of loop. The magnetic induction is 0.1 tesla and resistance of connector (R) is 1 ohm. The sides AB and CD have resistances 2 ohm and 3 ohm respectively. Find the current in the connector during its motion with constant velocity one meter/sec.



(A) $\frac{1}{110}$A (B) $\frac{1}{220}$A

(C) $\frac{1}{55}$A (D) $\frac{1}{440}$A

28. In the circuit shown, the cell is ideal. The coil has an inductance of 4H and zero resistance. F is a fuse of zero resistance and will blow when the current through it reaches 5A. The switch is closed at t = 0. The fuse will blow :



(A) just after t = 0

(B) after 2s

(C) after 5 s

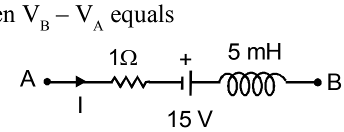
(D) after 10s

29. In **Previous Problem** if I is reversed in direction, then $V_B - V_A$ equals

(A) 5V (B) 10 V

(C) 15 V (D) 20 V

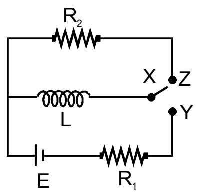
30. The network shown in the figure is part of a complete circuit. If at a certain instant, the current I is 5A and it is decreasing at a rate of 10^3 As^{-1} then $V_B - V_A$ equals



(A) 20 V (B) 15 V

(C) 10 V (D) 5 V

31. In the circuit shown, X is joined to Y for a long time, and then x is joined to Z. The total heat produced in R_2 is :



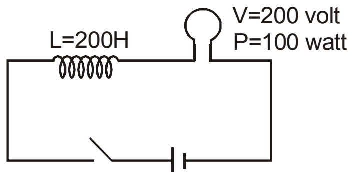
(A) $\frac{LE^2}{2R_1^2}$

(B) $\frac{LE^2}{2R_2^2}$

(C) $\frac{LE^2}{2R_1R_2}$

(D) $\frac{LE^2R_2}{2R_1^2}$

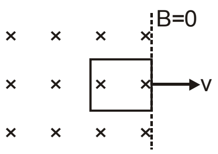
32. Calculate the ratio of power desipatted by the bulb at t = 1 sec and t = 2 sec after closing the switch-



(A) $\frac{e^2}{e^4-1}$ (B) $\left(\frac{e^2}{(e^2+1)}\right)^2$

(C) $\frac{e^2-1}{e^4+1}$ (D) None of these

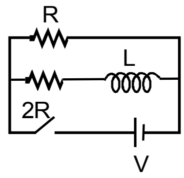
33. Figure shows a square loop of side 0.5 m and resistance 10Ω. The magnetic field has a magnitude B = 1.0T. The work done in pulling the loop out of the field uniformly in 2.0 s is



(A) 3.125×10^{-3} J (B) 6.25×10^{-4} J
(C) 1.25×10^{-2} J (D) 5.0×10^{-4} J

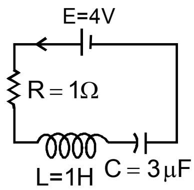
34. Two coils of self inductance 100 mH and 400 mH are placed very close to each other. Find the maximum mutual inductance between the two when 4 A current passes through them
(A) 200 mH (B) 300 mH
(C) $100\sqrt{2}$ mH (D) none of these

35. The ratio of time constant in charging and discharging in the circuit shown in figure is



(A) 1 : 1 (B) 3 : 2
(C) 2 : 3 (D) 1 : 3

36. The current in the given circuit is increasing with a rate a = 4 amp/s. The charge on the capacitor at an instant when the current in the circuit is 2 amp will be :



(A) 4 μC (B) 5 μC
(C) 6μC (D) none of these

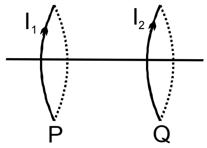
Section E - Induced, Properties of EM Waves

37. There are three wavelengths, 10^7 m, 10^{-10} m and 10^{-7} m, Find their respective names :
(A) Radio waves, X-rays, visible rays
(B) X-rays, visible rays, Radio waves
(C) X-rays, γ-rays, visible rays
(D) Visible rays, γ-rays and X-rays

38. The electric field associated with an e.m. wave in vacuum is given by $\vec{E} = \hat{i}$ 40 cos (kz–6×10^8 t), where E, z and t are in volt/m, meter and second respectively. The value of wave vector k is :
(A) 3 m^{-1} (B) 2 m^{-1}
(C) 0.5 m^{-1} (D) 6 m^{-1}

Section A - Flux, Faraday's law, Lenz's law

1. Two circular coils P & Q are fixed coaxially & carry currents I_1 and I_2 respectively



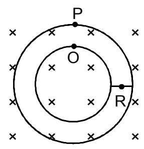
(A) if $I_2 = 0$ & P moves towards Q, a current in the same direction as I_1 is induced in Q

(B) if $I_1 = 0$ & Q moves towards P, a current in the opposite direction to that of I_2 is induced in P.

(C) When $I_1 \neq 0$ and $I_2 \neq 0$ are in the same direction then the two coils tend to move apart.

(D) when $I_1 \neq 0$ and $I_2 \neq 0$ are in opposite directions then the coils tends to move apart.

2. Figure shown plane figure made of a conductor located in a magnetic field along the inward normal to the plane of the figure. The magnetic field starts diminishing. Then the induced current



(A) at point P is clockwise

(B) at point Q is anticlockwise

(C) at point Q is clockwise

(D) at point R is zero

3. A bar magnet is moved along the axis of copper ring placed far away from the magnet. Looking from the side of the magnet, an anticlockwise current is found to be induced in the ring. Which of the following may be true ?

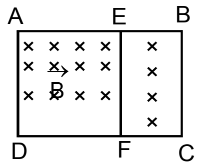
(A) The south pole faces the ring and the magnet moves towards it.

(B) The north pole faces the ring and the magnet moves towards it.

(C) The south pole faces the ring and the magnet moves away from it.

(D) The north pole faces the ring and the magnet moves away from it.

4. A rectangular frame ABCD made of a uniform metal wire has a straight connection between E & F made of the same wire as shown in the figure. AEFD is a square of side 1 m & EB = FC = 0.5 m. The entire circuit is placed in a steadily increasing uniform magnetic field directed into the place of the paper & normal to it. The rate of change of the magnetic field is 1 T/s, the resistance per unit length of the wire is 1 Ω/m. Find the current in segments AE, BE & EF.



(A) $I_{EA} = \frac{7}{22}A$

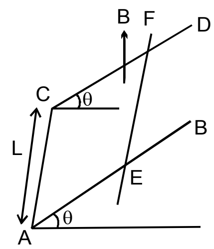
(B) $I_{BE} = \frac{3}{11}A$

(C) $I_{FE} = \frac{1}{22}A$

(D) None of these

Section B - EMF induced in Moving Rod, Rotating Ring, Disc.

5. AB and CD are smooth parallel rails, separated by a distance l, and inclined to the horizontal at an angle θ. A uniform magnetic field of magnitude B, directed vertically upwards, exists in the region. EF is a conductor of mass m, carrying a current i. For EF to be in equilibrium,



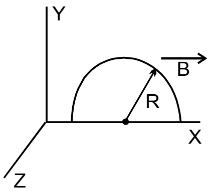
(A) i must flow from E to F

(B) Bil = mg tan θ

(C) Bil = mg sin θ

(D) Bil = mg

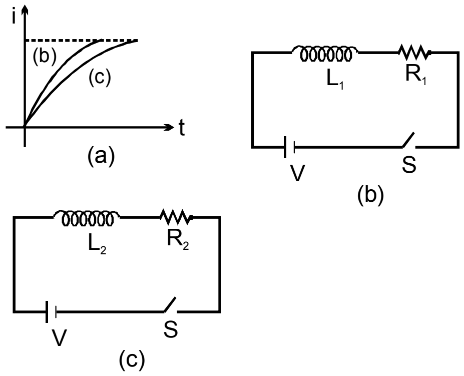
6. A semicircle conducting ring of radius R is placed in the xy plane, as shown in the figure. A uniform magnetic field is set up along the x-axis. No net emf, will be induced in the ring. if



(A) it moves along the x-axis
(B) it moves along the y-axis
(C) it moves along the z-axis
(D) it remains stationary

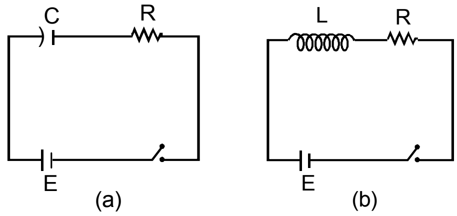
Section D - L-R circuit, L-C Oscillations

7. Current growth in two L-R circuits (b) and (c) as shown in figure (a). Let L_1, L_2, R_1 and R_2 be the corresponding values in two circuits. Then



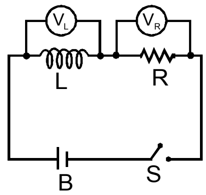
(A) $R_1 > R_2$ (B) $R_1 = R_2$
(C) $L_1 > L_2$ (D) $L_1 < L_2$

8. The switches in figures (a) and (b) are closed at t = 0



(A) The charge on C just after t = 0 is EC.
(B) The charge on C long after t = 0 is EC.
(C) The current in L just after t = 0 is E/R.
(D) The current in L long after t = 0 is E/R.

9. An inductance L, resistance R, battery B and switch S are connected in series. Voltmeters V_L and V_R are connected across L and R respectively. When switch is closed :



(A) The initial reading in V_L will be greater than in V_R
(B) The initial reading in V_L will be lesser than V_R
(C) The initial readings in V_L and V_R will be the same.
(D) The reading in V_L will be decreasing as time increases.

10. Two different coils have self inductance 8mH and 2mH. The current in one coil is increased at a constant rate. The current in the second coil is also increased at the same constant. At a certain instant of time, the power given to the two coils is the same. At that time the current, the induced voltage and the energy stored in the first coil are I_1, V_1 and W_1 respectively. Corresponding values for the second coil at the same instant are I_2, v_2 and W_2 respectively. Then :

(A) $\frac{I_1}{I_2} = \frac{1}{4}$ (B) $\frac{I_1}{I_2} = 4$

(C) $\frac{W_2}{W_1} = 4$ (D) $\frac{V_2}{V_1} = \frac{1}{4}$

Section A - Flux, Faraday's law, Lenz's law

1. A charged ring of mass m = 50 gm, charge 2 coulomb and radius R = 2m is placed on a smooth horizontal surface. A magnetic field varying with time at a rate of (0.2 t) Tesla/sec is applied on to the ring in a direction normal to the surface of ring. Find the angular speed attained in a time t_1 = 10 sec.

2. Find the dimension of the quantity $\frac{L}{RCV}$, where symbols have usual meaning.

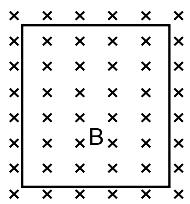
3. There exists a uniform cylindrically symmetric magnetic field directed along the axis of a cylinder but varying with time as B = kt. If an electron is released from rest in this field at a distance of 'r' from the axis of cylinder, its acceleration, just after it is released would be (e and m are the electronic charge and mass respectively)

4. A conducting circular loop is placed in a uniform magnetic field of 0.02 T, with its plane perpendicular to the field. If the radius of the loop starts shrinking at a constant rate of 1.0 mm/s, then find the emf induced in the loop, at the instant when the radius is 4 cm.

Section B - EMF induced in Moving Rod, Rotating Ring, Disc.

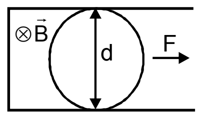
5. A metal rod of resistance 20Ω is fixed along a diameter of a conducting ring of radius 0.1 m and lies on x-y plane. There is a magnetic field $\vec{B} = (50T)\hat{k}$. The ring rotates with an angular velocity ω = 20 rad/sec about its axis. An external resistance of 10Ω is connected across the centre of the ring and rim. Find the current through external resistance.

6. A uniform magnetic field of 0.08 T is directed into the plane of the page and perpendicular to it as shown in the figure. A wire loop in the plane of the page has constant area 0.010 m^2. The magnitude of magnetic field decrease at a constant rate of 3.0×10^{-4} Ts^{-1}. Find the magnitude and direction of the induced emf in the loop.



7. The horizontal component of the earth's magnetic field at a place is 3×10^{-4} T and the dip is $\tan^{-1}(4/3)$. A metal rod of length 0.25 m placed in the north-south position is moved at a constant speed of 10 cm/s towards the east. Find the e.m.f induced in the rod.

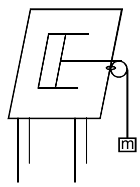
8. Two long parallel conducting horizontal rails are connected by a conducting wire at one end. A uniform magnetic field B exists in the region of space. A light uniform ring of diameter d which is practically equal to separation between the rails, is placed over the rails as shown in the figure. If resistance of ring is λ per unit length, calculate the force required to pull the ring with uniform velocity v.



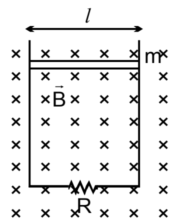
9-10. A pair of parallel horizontal conducting rails of negligible resistance shorted at one end is fixed on a table, The distance between the rails is L. A conducting massless rod of resistance R can slide on the rails frictionlessly. The rod is tied to a massless string which passes over a pulley fixed to the edge of the table. A mass m, tied to the other end of the string hangs vertically. A constant magnetic field B exists perpendicular to the table. If the system is released from rest, calculate.

9. the terminal velocity achieved by the rod.

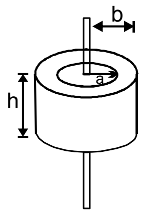
10. the acceleration of the mass at the instant when the velocity of the rod is half the terminal velocity.



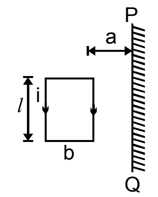
11. A horizontal wire is free to slide on the vertical rails of a conducting frame as shown in figure. The wire has a mass m and length l and the resistance of the circuit is R. If a uniform magnetic field B is directed perpendicular to the frame, then find the terminal speed of the wire as it falls under the force of gravity.



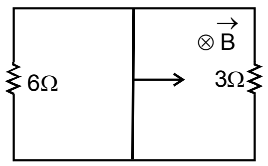
12. A long straight wire is arranged along the symmetry axis of a toroidal coil of rectangular cross-section, whose dimensions are given in the figure. The number of turns on the coil is N, and relative permeability of the surrounding medium is unity. Find the amplitude of the emf induced in this coil, if the current $i = i_m \cos \omega t$ flows along the straight wire.



13. A rectangular loop with current I has dimension as shown in figure. Find the magnetic flux ϕ through the infinite region to the right of line PQ.



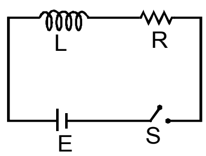
14. A rectangular loop with a sliding connector of length l = 1.0 m is situated in a uniform magnetic field B = 2T perpendicular to the plane of loop. Resistance of connector is r = 2Ω. Two resistances of 6Ω and 3Ω are connected as shown in figure. Find the external force required to keep the connector moving with a constant velocity v = 2m/s.



Section C, D - Self Induction, Mutual Induction, L-R circuit, L-C Oscillations

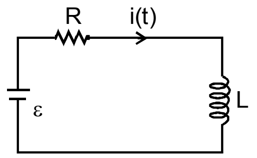
15. An emf of 15 volt is applied in a circuit containing 5 H inductance and 10 Ω resistance. Find the ratio of the currents at time t = ∞ and t = 1 second.

16. In the circuit shown in figure switch S is closed at time t = 0. Find the charge which passes through the battery in one time constant.

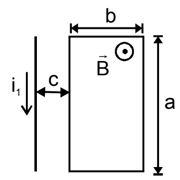


17. Two coils, 1 & 2, have a mutual inductance = M and resistance R each. A current flows in coil 1, which varies with time as : $I_1 = kt^2$, where K is a constant and 't' is time. Find the total charge that has flown through coil 2, between t = 0 and t = T.

18. Suppose the emf of the battery, the circuit shown varies with time t so the current is given by i(t) = 3 + 5t, where *i* is in amperes & t is in seconds. Take R = 4Ω, L = 6H & find an expression for the battery emf as function of time.



19. The mutual inductance between the rectangular loop and the long straight wire as shown in figure is M.



20. Two coils are at fixed locations. When coil 1 has no current and the current in coil 2 increases at the rate 15.0 A/s the e.m.f. in coil 1 in 25.0 mV, when coil 2 has no current and coil 1 has a current of 3.6 A, flux linkage in coil 2 is

21. How many meters of a thin wire are required to manufacture a solenoid of length l_0 = 100 cm and inductance L = 1 mH, if the solenoid's cross-sectional diameter is considerably less than its length.

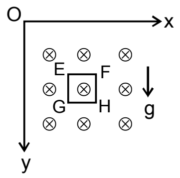
22. Find the inductance of a solenoid of length ℓ whose winding is made of copper wire of mass m. the winding resistance is equal to R. The solenoid diameter is considerably less than its length.

23. If the radius of outside cylinder is η times the inside one for a cable consisting of two thin walled co-axial metallic cylinders, the inductance per unit length is :

Exercise - 3 | Level-II Subjective | JEE Advanced

Section A - Flux, Faraday's law, Lenz's law

1-3. A magnetic field $B = (B_0\, y/a)\,\hat{k}$ is into the plane of paper in the +z direction. B_0 and a are positive constants. A square loop EFGH of side a, mass m and resistance R, in x-y plane, starts falling under the influence of gravity. Note the directions of x and y in the figure. Find



1. the induced current in the loop and indicate its direction,

2. the total Lorentz force acting on the loop and indicate its direction.

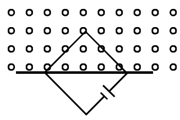
3. an expression for the speed of the loop, v(t) and its terminal value.

(Question No. 4 to 5)

A square wire loop with 2 m sides in perpendicular to a uniform magnetic field, with half the area of the loop in the field. The loop contains a 20 V battery with negligible internal resistance. If the magnitude of the field varies with time according to B = 0.042 – 0.87 t, with B in tesla & t in sec.

4. What is the total emf in the circuit ?

5. What is the direction of the current through the battery ?



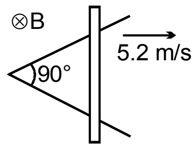
Section B - EMF induced in Moving Rod, Rotating Ring, Disc.

6. Two straight conducting rails from a right angle where their ends are joined. A conducting bar contact with the rails starts at vertex at the time t = 0 & moves symmetrically with a constant velocity of 5.2 m/s to the right as shown in figure. A 0.35 T magnetic field points out of the page. Calculate :

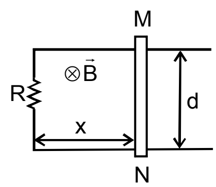
(i) The flux through the triangle by the rails & bar at t = 3.0 s.

(ii) The emf around the triangle at that time.

(iii) In what manner does the emf around the triangle vary with time.

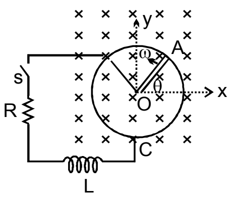


7. Two long parallel rails, a distance l apart and each having a resistance λ. per unit length are joined at one end by a resistance R. A perfectly conducting rod MN of mass m is free to slide along the rails without friction. There is a uniform magnetic field of induction B normal to the plane of the paper and directed into the paper. A variable force F is applied to the rod MN such that, as the rod moves, a constant current i flows through R. Find the velocity of the rod and the applied force F as function of the distance x of the rod from R



Section C, D - Self Induction, Mutual Induction, L-R circuit, L-C Oscillations

8-9. A metal rod OA of mass m & length r is kept rotating with a constant angular speed ω in a vertical plane about a horizontal axis at the end O. The free end A is arranged to slide without friction along a fixed conducting circular ring in the same plane as that of rotation. A uniform & constant. magnetic induction $\vec{B}$ is applied perpendicular & into the plane of rotation as shown in figure. An inductor L and an external resistance R are connected through a switch S between the point O & a point C on the ring to form an electrical circuit. Neglect the resistance of the ring and the rod. Initially, the switch is open.

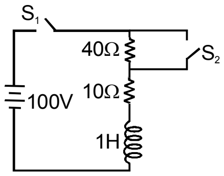


8. What is the induced emf across the terminals of the switch ?

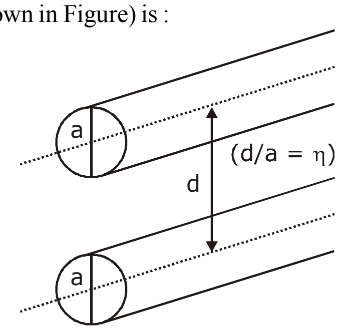
9. (i) Obtain an expression for the current as a function of time after switch S is closed.

(ii) Obtain the time dependence of the torque required to maintain the constant angular speed, given that the rod OA was along the positive X-axis at t = 0.

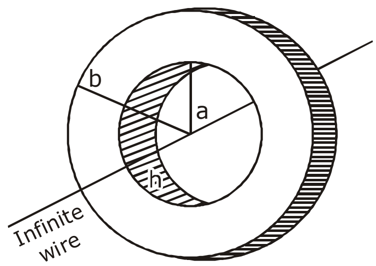
10. In the circuit shown in the figure the switched S_1 and S_2 are closed at time t = 0. After time t = (0.1) *l*n 2 sec, switch S_2 is opened. Find the current in the circuit at time t = (0.2) *l*n 2 sec.



11. The inductance per unit length of the system (as shown in Figure) is :

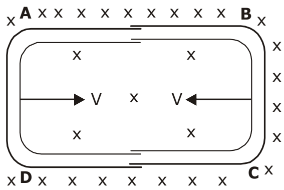


12. Consider a coil of circular ring cross section with inside radius a and the outside radius b. The thickness is h. The coil has N turns and there is an infinite wire as shown in figure., the mutual inductance of the system is :



1. One conducting U-tube can slide inside another as shown in figure, maintaining electrical contacts between the tubes. The magnetic field B is perpendicular to the plane of the figure. If each tube moves towards the other at a constant speed v, then the emf induced in the circuit in terms of B, l and v, where l is the width of each tube, will be

(AIEEE 2005)



(A) Blv (B) –Blv
(C) zero (D) 2 Blv

2. A long solenoid has 200 turns/cm and carries a current I. The magnetic field at its centre is 6.28×10^{-2} Wb/m^2. Another long solenoid has 100 turns/cm and it carries a current I/3. The value of the magnetic field at its centre is

(AIEEE 2006)

(A) $1.05 \times 10^{-2}\, Wb/m^2$
(B) $1.05 \times 10^{-5}\, Wb/m^2$
(C) $1.05 \times 10^{-3}\, Wb/m^2$
(D) $1.05 \times 10^{-4}\, Wb/m^2$

3. The flux linked with a coil at any instant t is given by $\phi = 10t^2 - 50t + 250$. The induced emf at t = 3s is **(AIEEE 2006)**

(A) –190 V (B) –10 V
(C) 10 V (D) 190 V

4. In an AC generator, a coil with N turns, all of the same area A and total resistance R, rotates with frequency ω in a magnetic field B. The maximum value of emf generated in the coil is

(AIEEE 2006)

(A) $NABR\omega$ (B) NAB
(C) $NABR$ (D) $NAB\omega$

5. Two coaxial solenoids are made by winding thin insulated wire over a pipe of cross-sectional area A = 10 cm^2 and length = 20 cm. If one of the solenoids has 300 turns and the other 400 turns, their mutual inductance is $(\mu_0 = 4\pi \times 10^{-7}\, TmA^{-1})$

(AIEEE 2008)

(A) $2.4\pi \times 10^{-5}\, H$ (B) $4.8\pi \times 10^{-4}\, H$
(C) $4.8\pi \times 10^{-5}\, H$ (D) $2.4\pi \times 10^{-4}\, H$

6. A horizontal straight wire 20 m long extending from east to west falling with a speed of 5.0 m/s, at right angles to the horizontal component of the earth's magentic field 0.30×10^{-4} Wb/m^2. The instantaneous value of the emf induced in the wire will be

(AIEEE 2011)

(A) 6.0 mV (B) 3 mV
(C) 4.5 mV (D) 1.5 mV

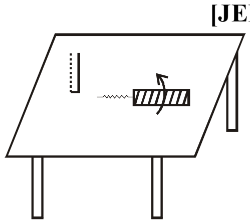
7. A coil is suspended in a uniform magnetic field with the plane of the coil parallel to the magnetic lines. When a current is passed through the coil, it starts oscillating; it is very difficult to stop. But if an aluminium plate is placed near to the coil, it stops, This is due to

(AIEEE 2012)

(A) development of air current when the plate is placed
(B) induction of electrical charge on the plate
(C) shielding of magnetic lines of force as aluminium is a paramagnetic material
(D) electromagnetic induction in the aluminium plate giving rise to electromagnetic damping.

8. A metallic rod of length 'l' is tied to a string of length 2 l and made to rotate with angular speed ω on a horizontal table with one end of the string fixed. If there is a vertical magnetic field 'B' in the region, the e.m.f. induced across the ends of the rod is:

[JEE MAIN 2013]



(A) $\frac{4B\omega l^2}{2}$ (B) $\frac{5B\omega l^2}{2}$
(C) $\frac{2B\omega l^2}{2}$ (D) $\frac{3B\omega l^2}{2}$

9. Match List-I (Electromagnetic wave type) with List-II (Its association/application) and select the correct option from the choices given below the lists: **[JEE MAIN 2014]**

List-I		List-II	
(a)	Infrared waves	(i)	To treat muscular strain
(b)	Radio waves	(ii)	For broadcasting
(c)	X-rays	(iii)	To detect fracture of bones
(d)	Ultraviolet rays	(iv)	Absorbed by the ozone layer of the atmosphere

	(a)	(b)	(c)	(d)
(A)	(iii)	(ii)	(i)	(iv)
(B)	(i)	(ii)	(iii)	(iv)
(C)	(iv)	(iii)	(ii)	(i)
(D)	(i)	(ii)	(iv)	(iii)

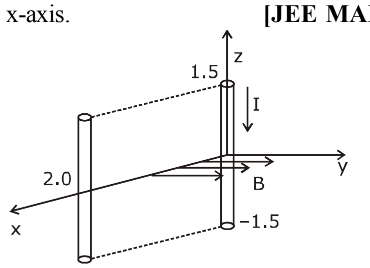
10. A circular loop of radius 0.3 cm lies parallel to a much bigger circular loop of radius 20 cm. The centre of the small loop is on the axis of the bigger loop. The distance between their centres is 15 cm. If a current of 2.0 A flows through the smaller loop, then the flux linked with bigger loop is **[JEE MAIN 2013]**

(A) 9.2×10^{-11} Wb (B) 6×10^{-11} Wb
(C) 3.3×10^{-11} Wb (D) 6×10^{-9} Wb

11. The magnetic field in a travelling electromagnetic wave has a peak value of 20 nT. The peak value of electric field strength is : **[JEE MAIN 2013]**

(A) 9 V/m (B) 12 V/m
(C) 3 V/m (D) 6 V/m

12. A conducor lies along the z-axis at $-1.5 \le z < 1.5$ m and carries a fixed current of 10.0 A in $-\hat{a}_z$ direction (see figure). For a field $\vec{B} = 3.0\times10^{-4}\,e^{-0.2x}\,\hat{a}_y$ T, find the power required to move the conductor at constant speed to x = 2.0 m, y = 0 m in 5×10^{-3} s. Assume parallel motion along the x-axis. **[JEE MAIN 2014]**



(A) 14.85 W (B) 29.7 W
(C) 1.57 W (D) 2.97 W

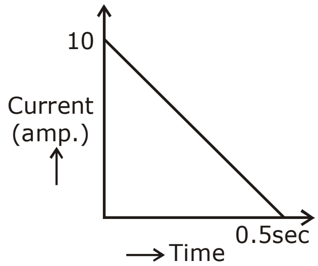
13. During the propagation of electromagnetic waves in a medium : **[JEE MAIN 2014]**

(A) Electric energy density is equal to the magnetic energy density.
(B) Both electric and magnetic energy densities are zero.
(C) Electric energy density is double of the magnetic energy density.
(D) Electric energy density is half of the magnetic energy density.

14. Arrange the following electromagnetic radiations per quantum in the order of increasing energy : **[JEE MAIN 2016]**

(1) Blue light (2) Yellow light
(3) X–ray (4) Radiowave.
(A) 1,2,4,3 (B) 3,1,2,4
(C) 2,1,4,3 (D) 4,2,1,3

15. In a coil of resistance 100 Ω, a current is induced by changing the magnetic flux through it as shown in the figure. The magnitude of change in flux through the coil is - **[JEE MAIN 2017]**



(A) 275 Wb (B) 200 Wb
(C) 225 Wb (D) 250 Wb

16. An EM wave from air enters a medium. The electric fields are $\vec{E}_1 = E_{01}.\hat{x}\cos\left[2\pi v\left(\frac{z}{c} - t\right)\right]$ in air and $\vec{E}_2 = E_{02}.\hat{x}\cos[k(2z - ct)]$ in medium, where the wave number k and frequency v refer to their values in air. The medium is non-magnetic. If ϵ_{r_1} and ϵ_{r_2} refer to relative permittivities of air and medium respectively, which of the following options is correct ? **[JEE MAIN 2018]**

(A) $\frac{\epsilon_{r_1}}{\epsilon_{r_2}} = \frac{1}{2}$ (B) $\frac{\epsilon_{r_1}}{\epsilon_{r_2}} = 4$

(C) $\frac{\epsilon_{r_1}}{\epsilon_{r_2}} = 2$ (D) $\frac{\epsilon_{r_1}}{\epsilon_{r_2}} = \frac{1}{4}$

Exercise - 4 | Level-II   Previous Year | JEE Advanced

1. An infinitely long cylindrical conducting rod is kept along +Z direction. A constant magnetic field is also present in +Z direction. Then current induced will be

(A) 0

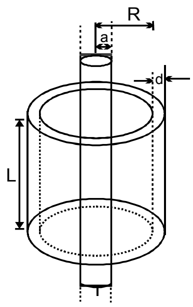
(B) along +Z direction

(C) along clockwise as seen from +Z

(D) along anticlockwise as seen from +Z

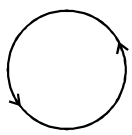
[JEE' 2005 (Scr)]

2. A long solenoid of radius a and number of turns per unit length n is enclosed by cylindrical shell of radius R, thickness d (d<<R) and length L. A variable current $i = i_0 \sin\omega t$ flows through the coil. If the resistivity of the material of cylindrical shell is ρ, find the induced current in the shell.



[JEE 2005]

3. In the given diagram, a line of force of a particular force field is shown. Out of the following options, it can never represent



(A) an electrostatic field

(B) a magnetostatic field

(C) a gravitational field of a mass at rest

(D) an induced electric field

[JEE 2006]

4. Match the following Columns

[JEE 2006]

Column I	**Column II**
(A) Dielectric ring uniformly charged	(P) Time independent electrostatic field out of system
(B) Dielectric ring uniformly charged	(Q) Magnetic field rotating with angular velocity
(C) Constant current i_0 in ring field	(R) Induced electric
(D) Current $i = i_0 \cos \omega t$ in ring	(S) Magnetic moment

Paragraph (Q. 5 to 7)

Modern trains are based on Maglev technology in which trains are magnetically leviated, which runs its EDS Maglev system. There are coils on both sides of wheels. Due to motion of train, current induces in the coil of track which levitate in. This is in accordance with Lenz's law. If trains lower down then due to Lenz's law a repulsive force increases due to which train gets uplifted and if it goes much high then there is a net downward force due to gravity. The advantage of Maglev train is that there is no friction between the train and the track, thereby reducing power consumption and enabling the train to attain very high speeds.

Disadvantage of Maglev train is that as it slows down the electromagnetic forces decreases and it becomes deffficult to keep it leviated and as it moves forward according to Lenz's law ther is an electromagnetic drag froce.

[JEE 2006]

5. What is the advantage of this system?

(A) No friction hence no power consumption

(B) No electric power is used

(C) Gravitation force is zero

(D) Electrostatic force draws the train

6. What is the disadvantage of this system?

(A)Train experiences upward force according to Lenz's law

(B) Friction force create a drag on the train

(C) Retardation

(D) By Lenz's law train experience a drag

7. Which force causes the train to elevate up?

(A) Electrostatic force

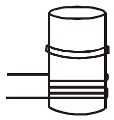
(B) Time varying electric field

(C) Magnetic force

(D) Induced electric field

8. **Statement-I**

A vertical iron rod has a coil of wire wound over it at the bottom end. An alternating current flows in the coil. The rod goes through a conducting ring as shown in the figure The ring can float at a certain height above the coil



because

Statement - II

In the above situation, a current is induced in the ring which interacts with the horizontal component of the magnetic field to produce an average force in the upward direction.

(A) Statement-1 is True, Statement-2 is True; Statement-2 **is** a correct explanation for Statement-1

(B) Statement-1 is True, Statement-2 is True; Statement-2 **is NOT** a correct explanation for Statement-1

(C) Statement-1 is True, Statement-2 is False

(D) Statement-1 is False, Statement-2 is True

[JEE 2007]

9. This section contains 2 questions. Each questions contains statements given in two columns, which have to be matched. The statements in **Column I** are labelled A, B, C and D, while the statements in **Column II** are labelled *p*, *q*, *r*, *s* and *t*. Any given statement in **Column I** can have correct matching with one or more statement(s) in **Column II**. The appropriate bubbles corresponding to the answers to these questions have to be darkened as illustrated in the following example :

If the correct matches are A – *p*, *s* and *t*; B – *q* and *r* ; C – *p* and *q*; and D – *s* and *t*; then the correct darkening of bubbles will look like the following.

Column II gives certain systems undergoing a process. **Column I** suggests changes in some of the parameters related to the system. Match the statements in **Column I** to the appropriate process(es) from **Column II**. **[JEE 2009]**

	Column I		**Column II**
(A)	The energy of the system is Increased	(P)	**System:** A capacitor initially uncharged Increased **Process:** It is connected to a battery
(B)	Mechanical energy is provided to the system, which is converted into energy of random motion of its parts	(Q)	**System :** A gas in an adiabatic container fitted with an adiabatic piston **Process :** The gas is compressed by pushing the piston
(C)	Internal energy of the system is converted into its mechanical energy.	(R)	**System :** a gas in a rigid container **Process :** The gas gets cooled due to colder atmosphere surrounding it
(D)	Mass of the system is decreased	(S)	**System :** A heavy nucleus initially at rest **Process :** The nucleus fissions into two fragments of nearly equal masses and some neutrons are emitted
		(T)	**System :** A resistive wire loop **Process :** The loop is placed in a time varying magnetic field perpendicular to its plane.

10. Two metallic rings *A* and *B*, identical in shape and size but having different resistivities ρ_A and ρ_B , are kept on top of two identical solenoids as shown in the figure. When current *I* is switched on in both the solenoids in identical manner, the rings *A* and *B* jump to heights h_A and h_B , respectively, with $h_A > h_B$. The possible relation(s) between their resistivities and their masses m_A and m_B is (are)

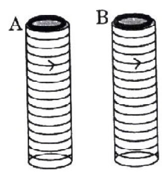
[JEE 2009]

(A) $\rho_A > \rho_B$ and $m_A = m_B$

(B) $\rho_A < \rho_B$ and $m_A = m_B$

(C) $\rho_A > \rho_B$ and $m_A > m_B$

(D) $\rho_A < \rho_B$ and $m_A < m_B$



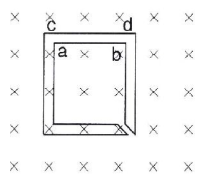
11. The figure shows certain wire segments joined together to form a coplanar loop. The loop is placed in a perpendicular magnetic field in the direction going into the plane of the figure. The magnitude of the field increases with time. I_1 and I_2 are the currents in the segments *ab* and *cd*. Then,

[JEE 2009]

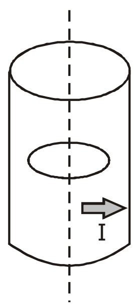
(A) $I_1 > I_2$ (B) $I_1 < I_2$

(C) I_1 is in the direction ***ba*** and I_2 is in the direction ***cd***

(D) I_1 is in the direction ***ab*** and I_2 is in the direction ***dc***



12. A long circular tube of length 10m and radius 0.3 m carries a current I along its curved surface as shown. A wire-loop of resistance 0.005 ohm and of radius 0.1 m is placed inside the tube with its axis coinciding with the axis of the tube. The current varies as $I = I_0 \cos(300\,t)$ where I_0 is constant. If the magnetic moment of the loop is $N \mu_0 I_0 \sin(300t)$, then 'N' is



[JEE 2011]

13. A current carrying infinitely long wire is kept along the diameter of a circular wire loop, without touching it. The correct statement(s) is(are)

[JEE 2012]

(A) The emf induced in the loop is zero if the current is constant.

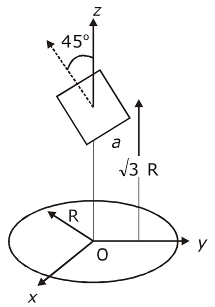
(B) The emf induced in the loop is finite if the current is constant.

(C) The emf induced in the loop is zero if the current decreases at a steady rate.

(D) The emf induced in the loop is finite if the current decreases at a steady rate.

14. A circular wire loop of radius R is placed in the x-y plane centered at the origin O. A square loop of side a(a<<R) having two turns is placed with its center at z = $\sqrt{3}$ R along the axis of the circular wire loop, as shown in figure. The plane of the square loop makes an angle of 45° with respect to the z-axis. If the mutual inductance between the loops is given by $\frac{\mu_0 a^2}{2^{p/2} R}$, then value of p is

[JEE 2012]



Paragraph for Questions 15 and 16

A point charge Q is moving in a circular orbit of radius R in the x-y plane with an angular velocity ω. This can be considered as equivalent to a loop carrying a steady current $\frac{Q\omega}{2\pi}$. A uniform magnetic field along the positive z-axis is now switched on, which increases at a constant rate from 0 to B in one second. Assume that the radius of the orbit remains constant. The application of the magnetic field induces an emf in the orbit. The induced emf is defined as the work done by an induced electric field in moving a unit positive charge around a closed loop. It is known that, for an orbiting charge, the magnetic dipole moment is proportional to the angular momentum with a proportionality constant γ.

15. The magnitude of the induced electric field in the orbit at any instant of time during the time interval of the magnetic field change is

(A) $\frac{BR}{4}$ (B) $\frac{BR}{2}$

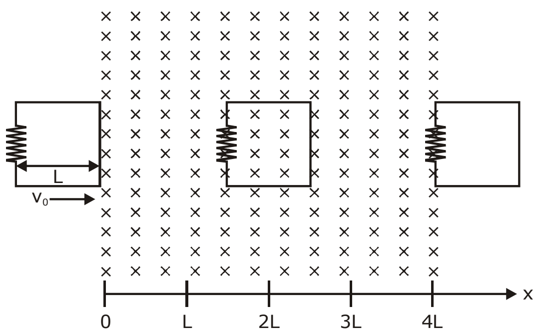
(C) BR (D) 2BR

16. The change in the magnetic dipole moment associated with the orbit, at the end of the time interval of the magnetic field change, is

(A) $-\gamma\ BQR^2$ (B) $-\gamma \frac{BQR^2}{2}$

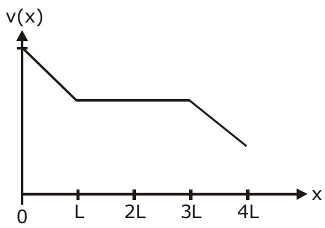
(C) $\gamma \frac{BQR^2}{2}$ (D) $\gamma\ BQR^2$

17. A rigid wire loop of square shape having side of length L and resistance R is moving along the x-axis with a constant velocity v_0 in the plane of the paper. At t = 0, the right edge of the loop enters a region of length 3L where there is a uniform magnetic field B_0 into the plane of the paper, as shown in the figure. For sufficiently large v_0, the loop eventually crosses the region. Let x be location of the right edge of the loop. Let v(x), I(x) and F(x) represent the velocity of the loop, current in the loop, and force on the loop, respectively, as a function of x. Counter-clockwise current is taken as positive. **[JEE 2016]**

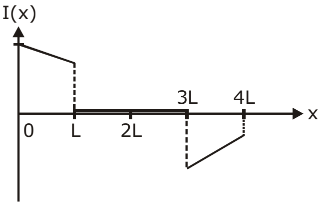


Which of the following schematic plot(s) is(are) correct ? (Ignore gravity)

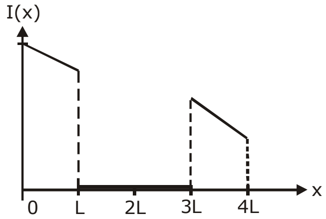
(A)



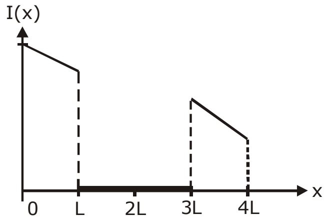
(B)



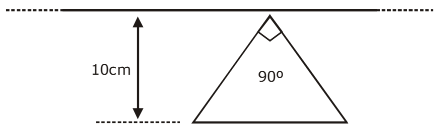
(C)



(D)



18. A conducting loop in the shape of a right angled isosceles triangle of height 10 cm is kept, such that the 90° vertex is very close to an infinitely long conducting wire (see the figure). The wire is electrically insulated from the loop. The hypotenuse of the triangle is parallel to the wire. The current in the triangular loop is in counterclockwise direction and increased at a constant rate of 10 As^{-1}. Which of the following statement(s) is (are) true? **[JEE-2016]**



(A) The induced current in the wire is in opposite direction to the current along the hypotenuse.

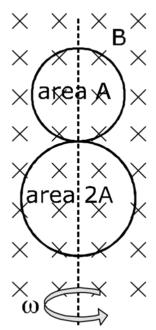
(B) There is a repulsive force between the wire and the loop.

(C) The magnitude of induced emf in the wire is $\left(\frac{\mu_0}{\pi}\right)$ volt

(D) If the loop is rotated at a constant angular speed about the wire, an additional emf of $\left(\frac{\mu_0}{\pi}\right)$ volt is induced in the wire.

19. Two inductors L_1 (inductance 1 mH, internal resistance 3 Ω) and L_2 (inductance 2 ml internal resistance 4Ω), and a resistor R (resistance 12Ω) are all connected in parallel across a 5V battery. The circuit is switched on at time t = 0. The ratio of the maximum the minimum current (I_{mass}/I_{min}) drawn from the battery is **[JEE-2016]**

20. A circular insulated copper wire loop is twisted to form two loops of area A and 2A as shown in the figure. At the point of crossing the wires remain electrically insulated from each other. The entire loop lies in the plane (of the paper). A uniform magnetic field $\vec{B}$ points into the plane of the paper. At t = 0, the loop starts rotating about the common diameter as axis with a constant angular velocity ω in the magnetic field. Which of the following options is/are correct?



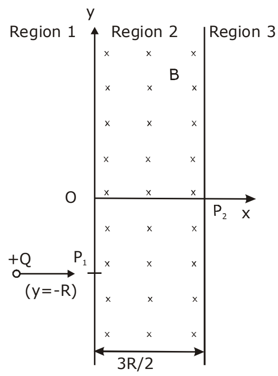
(A) The net emf induced due to both the loops is proportional to cos ωt **[JEE-2017]**

(B) The rate of change of the flux is maximum when the plane of the loops is perpendicular to plane of the paper

(C) The amplitude of the maximum net emf induced due to both the loops is equal to the amplitude of maximum emf induced in the smaller loop alone

(D) The emf induced in the loop is proportional to the sum of the areas of the two loops

21. A uniform magnetic field B exists in the region between x = 0 and $x = \frac{3R}{2}$ (region 2 in the figure) pointing normally into the plane of the paper. A particle with charge +Q and momentum p directed along x-axis enters region 2 from region 1 at point P_1 (y=–R). Which of the following option(s) is/are correct? **[JEE-2017]**



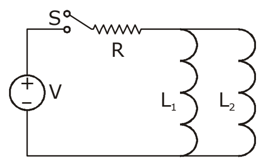
(A) For $B > \frac{2P}{3QR}$, the particle will re-enter region 1

(B) For $B = \frac{8}{13}\frac{P}{QR}$, the particle will enter region 3 through the point P_2 on x-axis

(C) For a fixed B, particles of same charge Q and same velocity v, the distance between the point P_1 and the point of re-entry into region 1 is inversely proportional to the mass of the particle.

(D) When the particle re-enters region 1 through the longest possible path in region2, the magnitude of the change in its linear momentum between point P_1 and the farthest point from y-axis is $P/\sqrt{2}$.

22. A source of constant voltage V is connected to a resistance R and two ideal inductors L_1 and L_2 through a switch S as shown. There is no mutual inductance between the two inductors. The switch S is intially open. At t = 0, the switch is closed and current begins to flow. Which of the following options is/are correct? **[JEE-2017]**



(A) At t = 0, the current through the resistance R is $\frac{V}{R}$

(B) The ratio of the currents through L_1 and L_2 is fixed at all tmes (t>0)

(C) After a long time, the current through L_2 will be $\frac{V}{R}\frac{L_1}{L_1+L_2}$

(D) After a long time, the current through L_1 will be $\frac{V}{R}\frac{L_2}{L_1+L_2}$

Paragraph - (23 to 25)   [JEE-2017]

A charged particle (electron or proton) is introduced at the origin (x = 0, y = 0, z = 0) with a given initial velocity $\vec{\upsilon}$. A uniform electric field $\vec{E}$ and a uniform magnetic field $\vec{B}$ exist everywhere. The velocity $\vec{\upsilon}$, electric field $\vec{E}$ and magnetic field $\vec{B}$ are given in columns 1,2 and 3 respectively. The quantities E_0, B_0 are positive in magnitude.

Column-1	**Column-2**	**Column - 3**
(I) Electron with $\vec{\upsilon} = 2\frac{E_0}{B_0}\hat{x}$	(i) $\vec{E} = E_0\hat{z}$	(P) $\vec{B} = -B_0\hat{x}$
(II) Electron with $\vec{\upsilon} = \frac{E_0}{B_0}\hat{y}$	(ii) $\vec{E} = -E_0\hat{y}$	(Q) $\vec{B} = B_0\hat{x}$
(III) Proton with $\vec{\upsilon} = 0$	(iii) $\vec{E} = -E_0\hat{x}$	(R) $\vec{B} = B_0\hat{y}$
(IV) Proton with $\vec{\upsilon} = 2\frac{E_0}{B_0}\hat{x}$	(iv) $\vec{E} = E_0\hat{x}$	(S) $\vec{B} = B_0\hat{z}$

23. In which case will the particle move in a straight line with constant velocity ?

(A) (IV) (i) (S) (B) (III) (ii) (R) (C) (II) (iii) (S) (D) (III) (iii) (P)

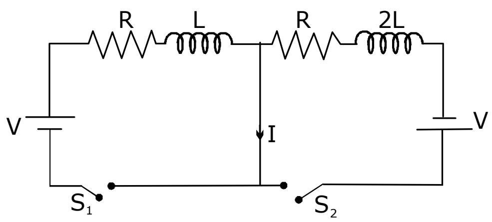
24. In which case will the particle describe a helical path with axis along the positive z-direction ?

(A) (IV) (i) (S) (B) (II) (ii) (R) (C) (III) (iii) (P) (D) (IV) (ii) (R)

25. In which case would the particle move in a straight line along the negative direction of y-axis (i.e., move along - $\hat{y}$) ?

(A) (III) (ii) (R) (B) (IV) (ii) (S) (C) (III) (ii) (P) (D) (II) (iii) (Q)

26. In the figure below, the switches S_1 and S_2 are closed simultaneously at t = 0 and a current starts to flow in the circuit. Both the batteries have the same magnitude of the electromotive force (emf) and the polarities are as indicated in the figure. Ignore mutual inductance between the inductors. The current I in the middle wire reaches its maximum magnitude I_{max} at time t = τ. Which of the following statements is (are) true? **[JEE-2018]**



(A) $I_{max} = \frac{V}{2R}$ (B) $I_{max} = \frac{V}{4R}$ (C) $\tau = \frac{L}{R}\ln 2$ (D) $\tau = \frac{2L}{R}\ln 2$

ANSWER KEYS

Exercise - 1 Objective Problems | JEE Main

1.	**B**	**2.**	**A**	**3.**	**C**	**4.**	**D**	**5.**	**B**	**6.**	**C**	**7.**	**B**
8.	**C**	**9.**	**B**	**10.**	**B**	**11.**	**B**	**12.**	**A**	**13.**	**C**	**14.**	**B**
15.	**A**	**16.**	**C**	**17.**	**A**	**18.**	**C**	**19.**	**B**	**20.**	**B**	**21.**	**C**
22.	**B**	**23.**	**A**	**24.**	**A**	**25.**	**C**	**26.**	**B**	**27.**	**D**	**28.**	**C**
29.	**C**	**30.**	**A**	**31.**	**A**	**32.**	**A**	**33.**	**C**	**34.**	**A**	**35.**	**B**
36.	**A**	**37.**	**D**	**38.**	**C**	**39.**	**A**	**40.**	**A**	**41.**	**A**	**42.**	**D**
43.	**A**	**44.**	**B**										

Exercise - 2 (Level-I) Objective Problems | JEE Main

1.	**A**	**2.**	**D**	**3.**	**C**	**4.**	**B**	**5.**	**C**	**6.**	**A**	**7.**	**D**
8.	**A**	**9.**	**A**	**10.**	**C**	**11.**	**A**	**12.**	**B**	**13.**	**D**	**14.**	**A**
15.	**C**	**16.**	**D**	**17.**	**A**	**18.**	**A**	**19.**	**C**	**20.**	**B**	**21.**	**D**
22.	**A**	**23.**	**C**	**24.**	**B**	**25.**	**D**	**26.**	**C**	**27.**	**B**	**28.**	**D**
29.	**C**	**30.**	**B**	**31.**	**A**	**32.**	**B**	**33.**	**A**	**34.**	**A**	**35.**	**B**
36.	**C**	**37.**	**A**	**38.**	**B**								

Exercise - 2 (Level-II) Multiple Correct | JEE Advanced

1.	**B,D**	**2.**	**A,C,D**	**3.**	**B,C**	**4.**	**A,B,C**	**5.**	**A,B**
6.	**A,B,C,D**	**7.**	**B,D**	**8.**	**B,D**	**9.**	**A,D**	**10.**	**A,C,D**

Exercise - 3 | Level-I Subjective | JEE Advanced

1. 200 rad/sec **2** I^{-1}

3 $E.F. = \frac{r}{2}\frac{dB}{dt} \Rightarrow$ $a = \frac{e\ E.}{m}$ $a = \frac{er}{2m}k$ directed along tangent to the circle of radius r whose center lies on the axis of cylinder. **4.** 5.0 μV

5. $\frac{1}{3}A$ **6.** 3 μV, clockwise **7.** 10 μV **8.** $\frac{4B^2vd}{\pi\lambda}$

9. $V_{terminal} = \frac{mgR}{B^2l^2}$; **10.** $\frac{g}{2}$ **11.** $\frac{mgR}{B^2l^2}$ **12.** $\frac{\mu_0 h\omega i_m N}{2\pi} l n\frac{b}{a}$

13. $\phi = \frac{\mu_0}{2\pi} IL \ln\frac{a+b}{a}$ **14.** 2 N **15.** $\frac{e^2}{e^2-1}$ **16.** $\frac{EL}{eR^2}$

17. kMT^2/R **18.** $42+20t$ volt **19.** $M = \frac{\mu_0 a}{2\pi}\ln\left(1+\frac{b}{c}\right)$ **20.** 6.00 mWb

21. 0.10 km 22. $\frac{\mu_0}{4\pi} \times \frac{mR}{\ell\rho\rho_0}$ 23. $\frac{\mu_r\mu_0}{2\pi} \text{In } \eta$

Exercise - 3 | Level-II Subjective | JEE Advanced

1. $i = \frac{B_0 av}{R}$ in anticlockwise direction, v = velocity at time t

2. $F_{nett} = B_0^2a^2V/R$ 3. $V = \frac{mgR}{B_0^2a^2}\left(1 - e^{-\frac{B_0^2a^2t}{mR}}\right)$ 4. 21.74 V

5. anticlockwise 6. (i) 85.22 Tm^2, (ii) 56.8 V; (iii) linearly

7. $\frac{I(R+2\lambda x)}{Bd}$, $\frac{2I^2 m\lambda(R+2\lambda x)}{B^2d^2}$ + BId 8. (a) $E = \frac{1}{2}B\omega r^2$

9. (i) $I = \frac{B\omega r^2 |1 - e^{-Rt/L}|}{2R}$, (ii) $\tau = \frac{mgr}{2}\cos\omega t + \frac{wB^2r^4}{4R}(1 - e^{-Rt/L})$

10. 67/32 A 11. $\frac{\mu_0}{\pi} \text{In } \eta$ 12. $\frac{\mu_0\mu_r Nh}{2\pi} \text{In} \frac{b}{a}$

Exercise - 4 | Level-I Previous Year | JEE Main

1.	**D**	**2.**	**A**	**3.**	**B**	**4.**	**D**	**5.**	**D**
6.	**B**	**7.**	**D**	**8.**	**B**	**9.**	**B**	**10.**	**A**
11.	**D**	**12.**	**D**	**13.**	**A**	**14.**	**D**	**15.**	**D**
16.	**D**								

Exercise - 4 | Level-II Previous Year | JEE Advanced

1. **A** **2.** $I = \frac{(\mu_0 n i_0 \omega \cos\omega t)\pi a^2 (Ld)}{\rho 2\pi R}$ **3.** **A,C**

4. **(A) P; (B) P, Q, S; (C) Q, S; (D) Q, R,S**

5. **A** **6.** **D** **7.** **C** **8.** **A**

9. **(A) → P,Q,S,T ; (B) → Q ; (C) → S ; (D) →S**

10.	**B,D**	**11.**	**D**	**12.**	**0006**	**13.**	**A,C**	**14.**	**7**
15.	**B**	**16.**	**BC**	**17.**	**A,B**	**18.**	**B,C**	**19.**	**8**
20.	**BC**	**21.**	**AB**	**22.**	**BCD**	**23.**	**C**	**24.**	**A**
25.	**A**	**26.**	**BD**						