

2nd Year Physics
Chapter # 15
Electromagnetic Induction



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Electromagnetic Induction

When a conductor is moved in the magnetic field an emf is induced in it and induced current starts flowing in the circuit, this process is called electro-magnetic induction.

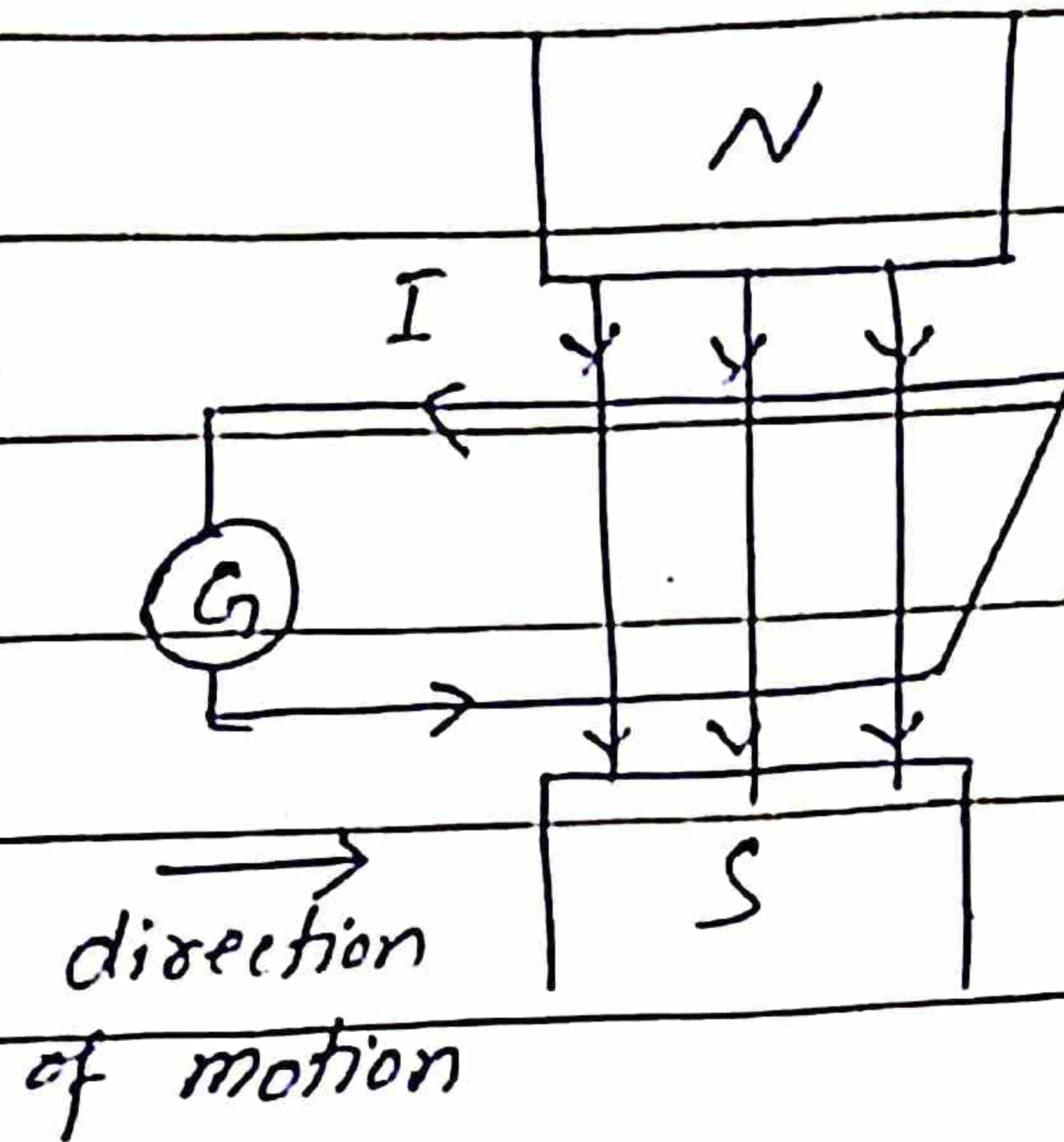
Induced current:

When a closed loop or coil is moved in the magnetic field or the magnet is moved facing the loop then an emf and current will be induced due to change in magnetic flux. This induced current depends upon the following factors:

- i- The strength of magnetic field
- ii- The speed of the loop/coil.
- iii- The number of turns of the coil.

Direction of current:

The direction of current flowing in the loop depends upon the direction



of motion of the loop. If the current flows anti-clockwise due to the right side movement of loop then the current will be clockwise due to left side movement of loop.

Motional emf

Definition:

The emf induced by the motion of a conductor across a magnetic field is called motional emf.

Explanation:

Consider the conducting rails on which a conducting rod of length L



is placed and the whole apparatus is in the magnetic field (B) as shown in the figure. The galvanometer is connected between the points c and d in this way a complete loop $abcd a$ is formed. There will be no current in the loop until the conductor ab is moved.

If we move the conducting rod towards right, a magnetic force will act on the charges present in the loop given by:

$$\vec{F}_b = qv(\vec{v} \times \vec{B})$$

$$F_b = qvB \sin \theta$$

the angle between $\vec{v}$ and $\vec{B}$ is 90° . So,

$$F_b = qvB \sin 90^\circ$$

$$= qvB(1)$$

$$F_b = qvB$$



From the right hand rule, we can see that the magnetic force is directed upward along the rod ab . So, charges move towards point b and a high concentration is formed there. While there will be low concentration of charges at point a . In this way, an electric field is set up from point b to point a along the rod. An equilibrium state will be achieved when these two forces i.e. electric force and magnetic force will be balanced.

$$F_e = F_b$$

$$qE_0 = qvB$$

$$E_o = vB \rightarrow (1)$$

We know that negative of the potential gradient is equal to the electric intensity.

$$E_o = - \frac{\Delta V}{\Delta x}$$

Here $\Delta x = L$

So,

$$E_o = - \frac{\Delta V}{L} \rightarrow (2)$$

Comparing eq. (1) and eq. (2)

$$- \frac{\Delta V}{L} = vB$$



$$-\Delta V = LvB$$

$$\Delta V = -vBL$$

Here ΔV is the potential difference $V_b - V_a$ which is equal to the motional emf.

$$\mathcal{E} = -vBL$$

If there is angle θ between v and B . Then

$$\mathcal{E} = -vBL \sin \theta$$

Due to this motional emf the charge will continuously move in the circuit. When

the charge reaches at point. a it is deflected towards point. b and again starts moving in the circuit.



Faraday's Law

statement:

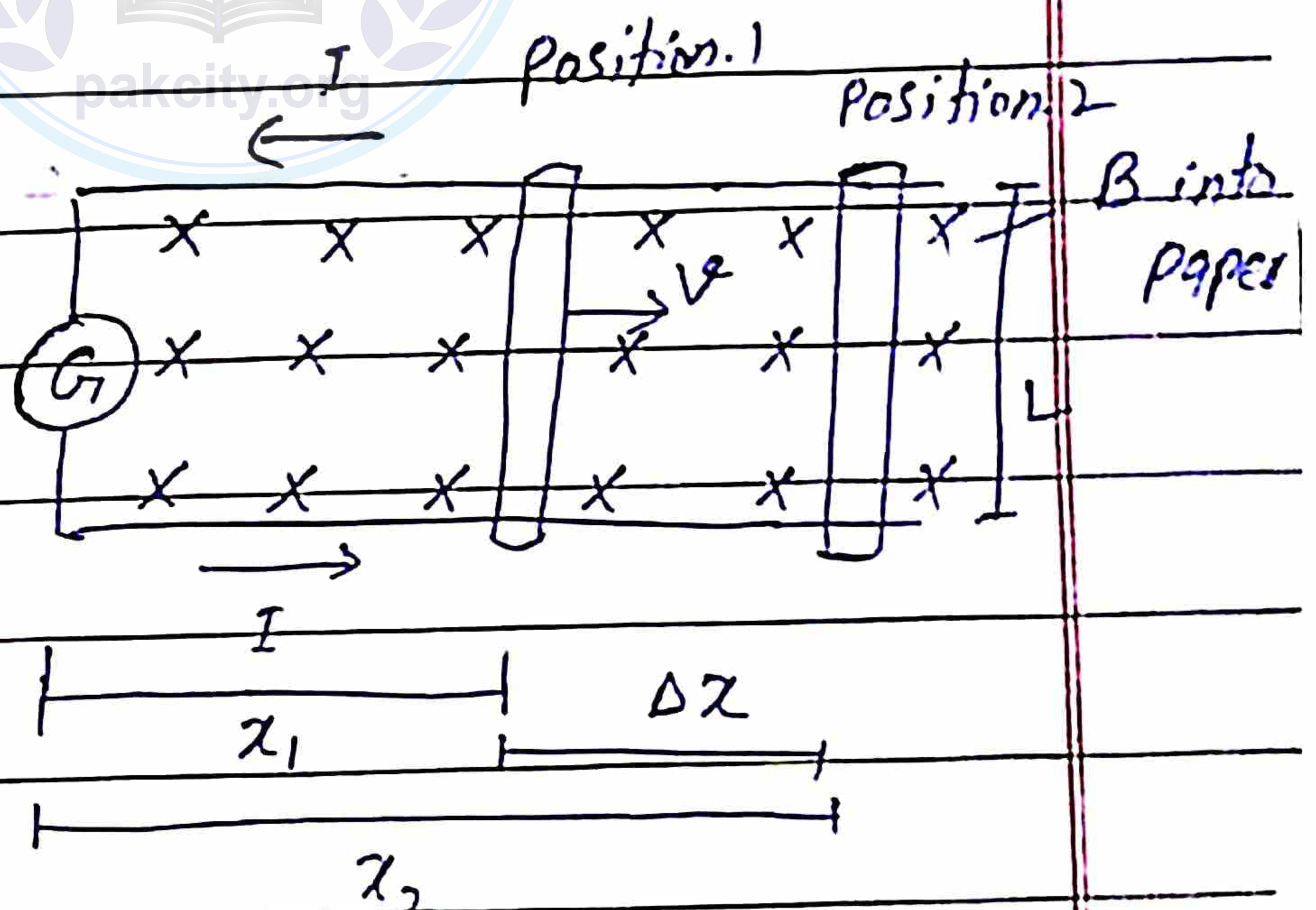
The average emf induced in the conducting coil of N loops is equal to negative of the rate at which the magnetic flux through the coil is changing with time.

Explanation:

Consider the conducting rail on which a conductor

of length " L "

is placed. The whole arrangement is placed in the magnetic field as shown in the figure.



The galvanometer is attached to the conducting rails. When the conductor is moved from position.1 to position.2 with velocity v , then current flows in the anti-clock wise direction. The motional emf will be:

$$\mathcal{E} = -vBL$$

The distance between position.1 and position.2 is Δx moved in time Δt . So,

$$v = \frac{\Delta x}{\Delta t}$$



So,

$$\mathcal{E} = - \frac{\Delta x}{\Delta t} BL \rightarrow (1)$$

The magnetic flux is the dot product of magnetic field intensity B and vector area.

$$\text{So, } \Delta \Phi = B \Delta A$$

$$= B (\text{length} \times \text{width})$$

$$\Delta \Phi = B \Delta x L$$

Now eq. (1) can be written as

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

If a coil of N loops is used instead of a single loop. Then:

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

This is the mathematical expression for Faraday's law.

Lenz's Law

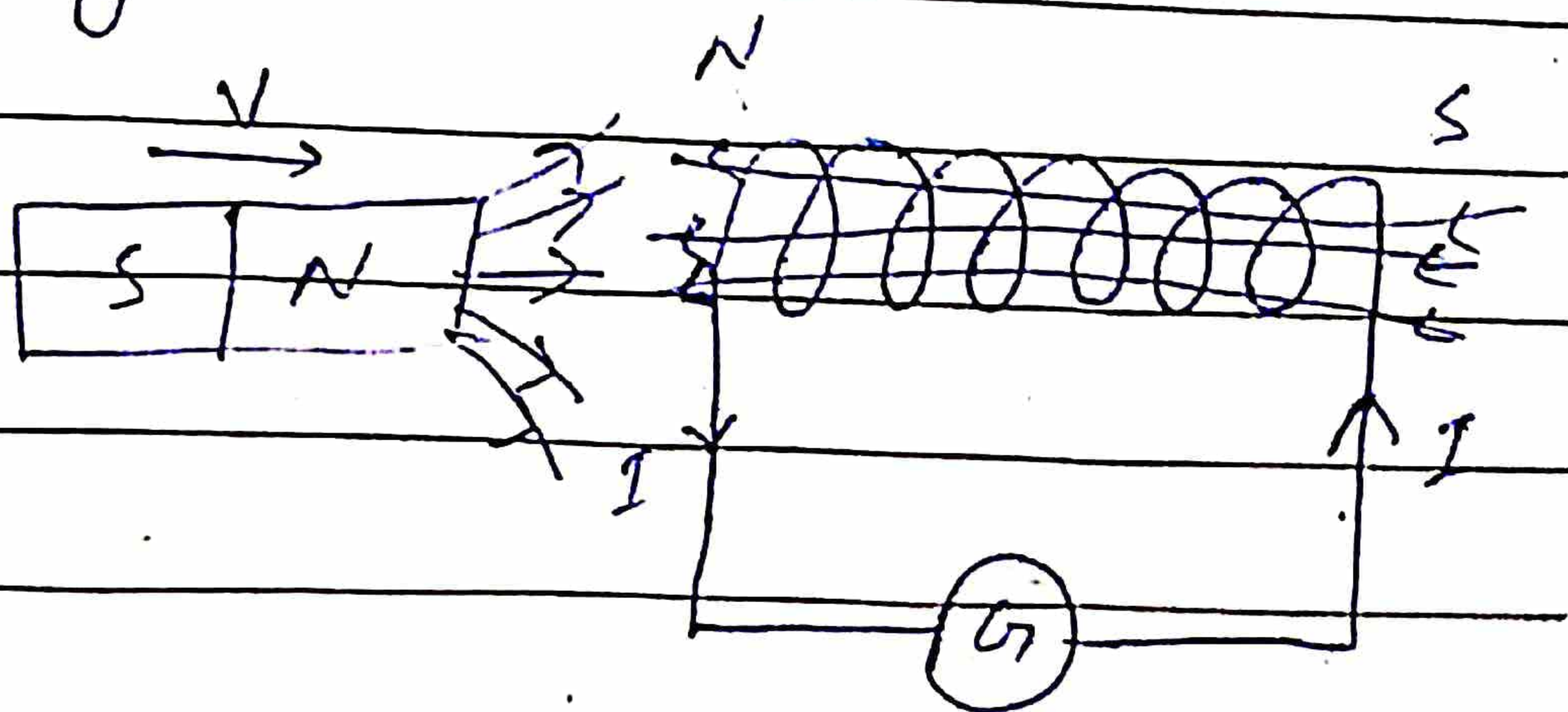
Statement: The direction of induced current is always so as to oppose the change which cause the current.

Explanation: Lenz's law explains the -ve sign in the expression of Faraday's law.

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

Lenz's law was made by Russian Physicist Heinrich Lenz in 1834. Lenz's law explains the direction of induced current that always opposes the cause that produces the current.

Consider a coil and a magnet.

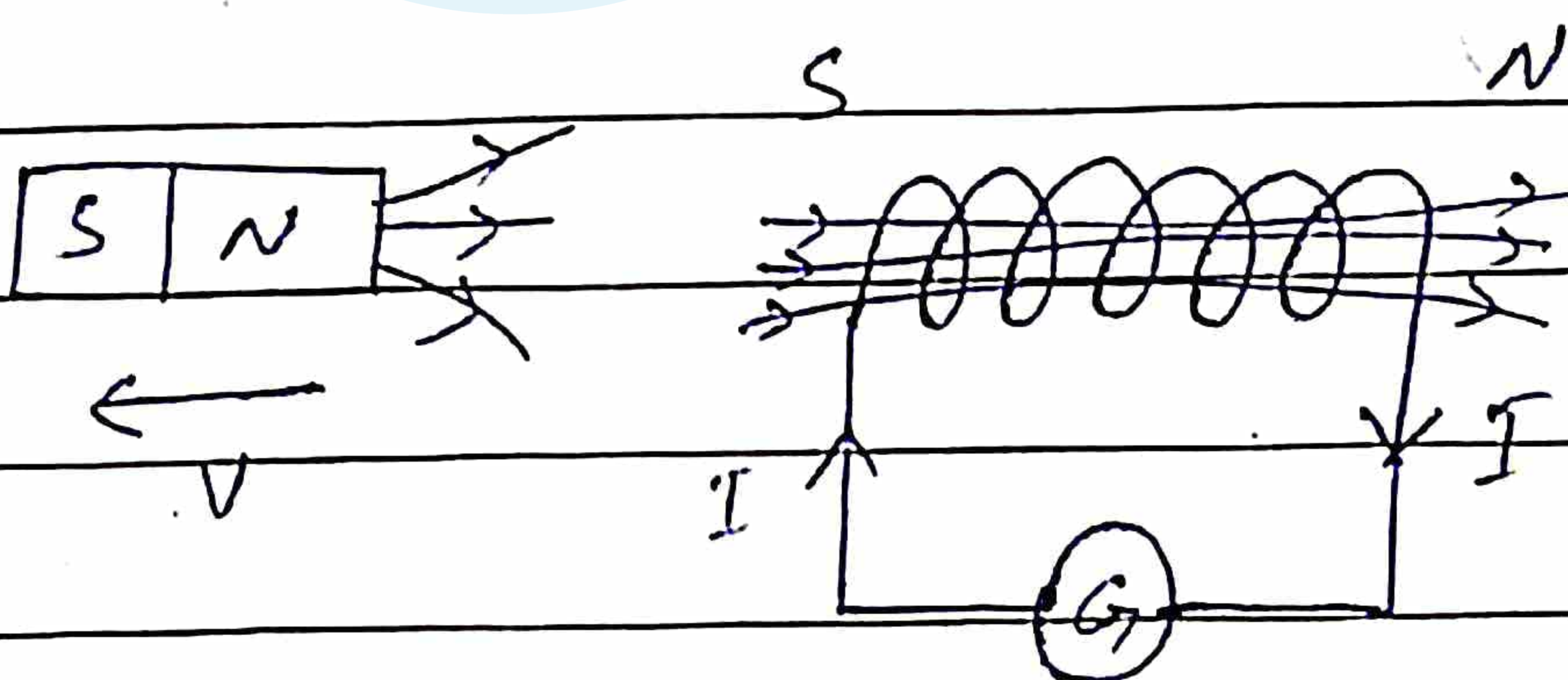


when the magnet is moved towards the coil, the magnetic flux through the coil changes.

As a result, current is induced due to which magnetic field is produced.

The coil acts as bar-magnet.

The direction of current and magnetic field will be so as to repel the magnet. So, the near end will become north and by right hand rule the current will be anti-clockwise.



If the magnet is moved away from the coil. Then the induced current and magnetic field in the coil will act to attract the

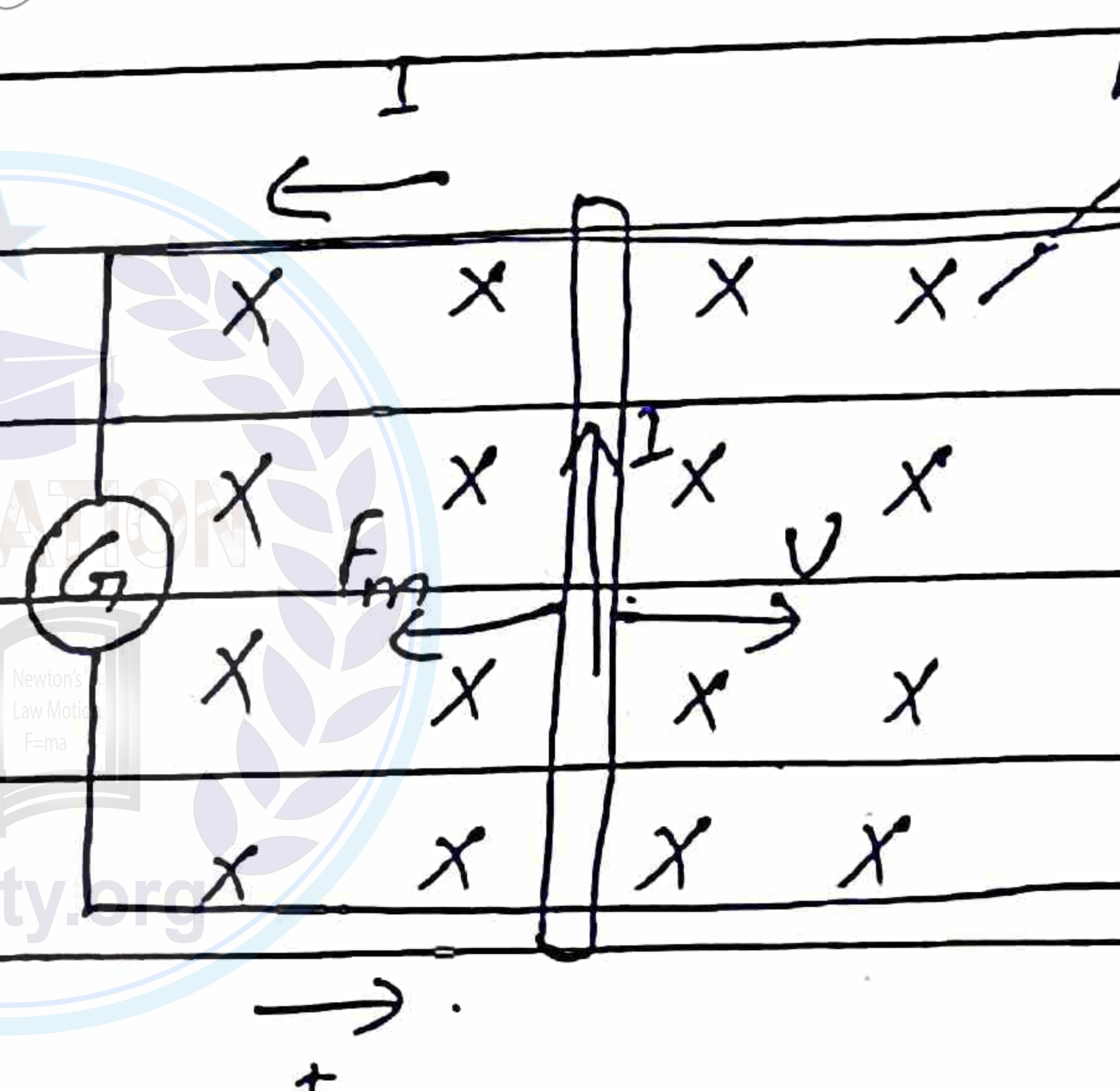
magnet. So, the current will flow in clock-wise direction.



Lenz's law and law of conservation of energy:

Lenz's law satisfies the law of conservation of energy.

Consider the conducting rail on which a conductor is moved towards right side.

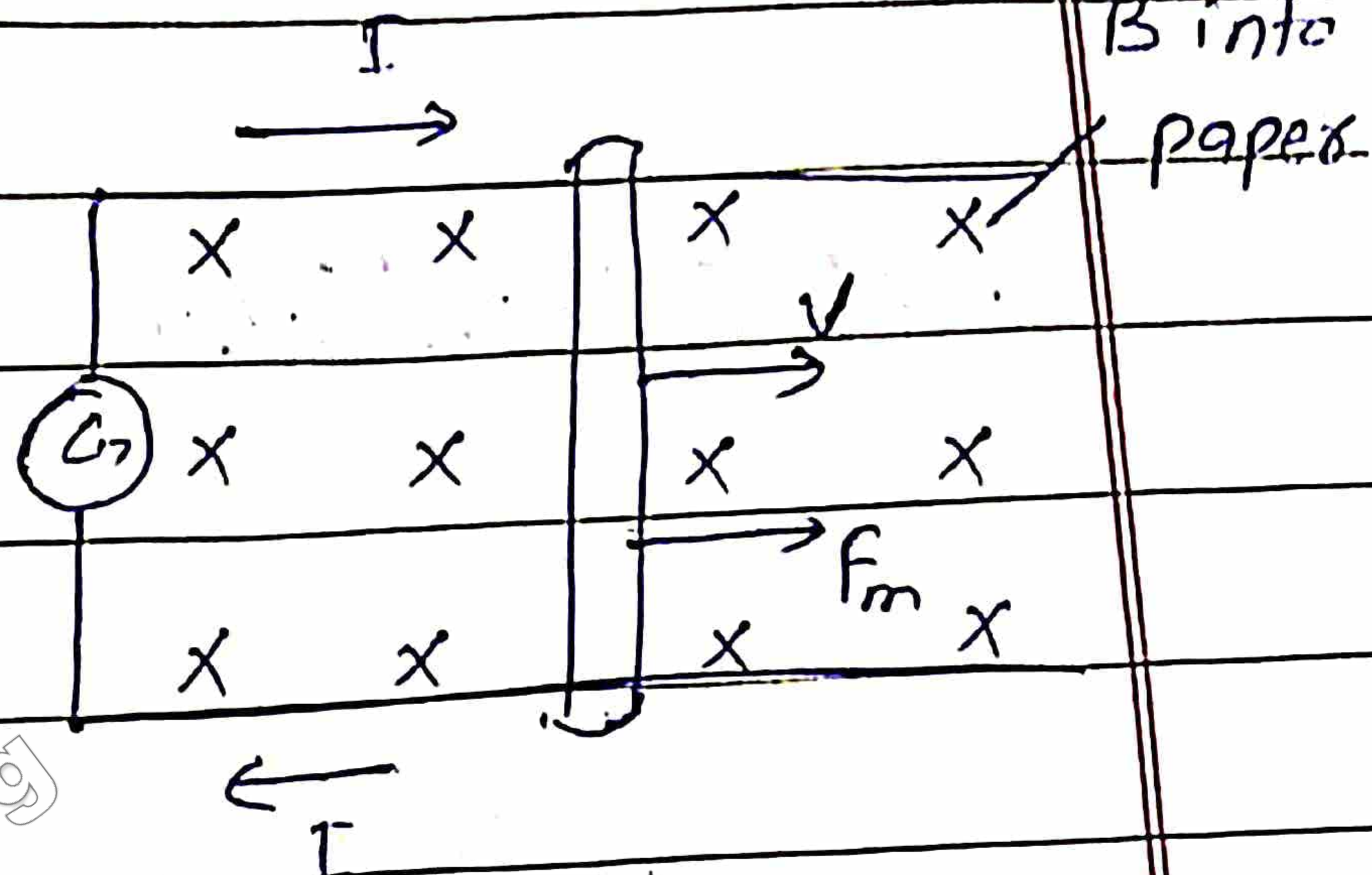


The whole apparatus

is placed in the magnetic field acting into the paper. Due to the movement of conductor induced current flows in the anti-clockwise direction. Due to this current, magnetic force acts towards the left side. This force is in accordance

to the law of conservation of energy. To conserve this opposing force the conductor has to be moved towards right side.

If we consider the clock-wise direction of current. Then



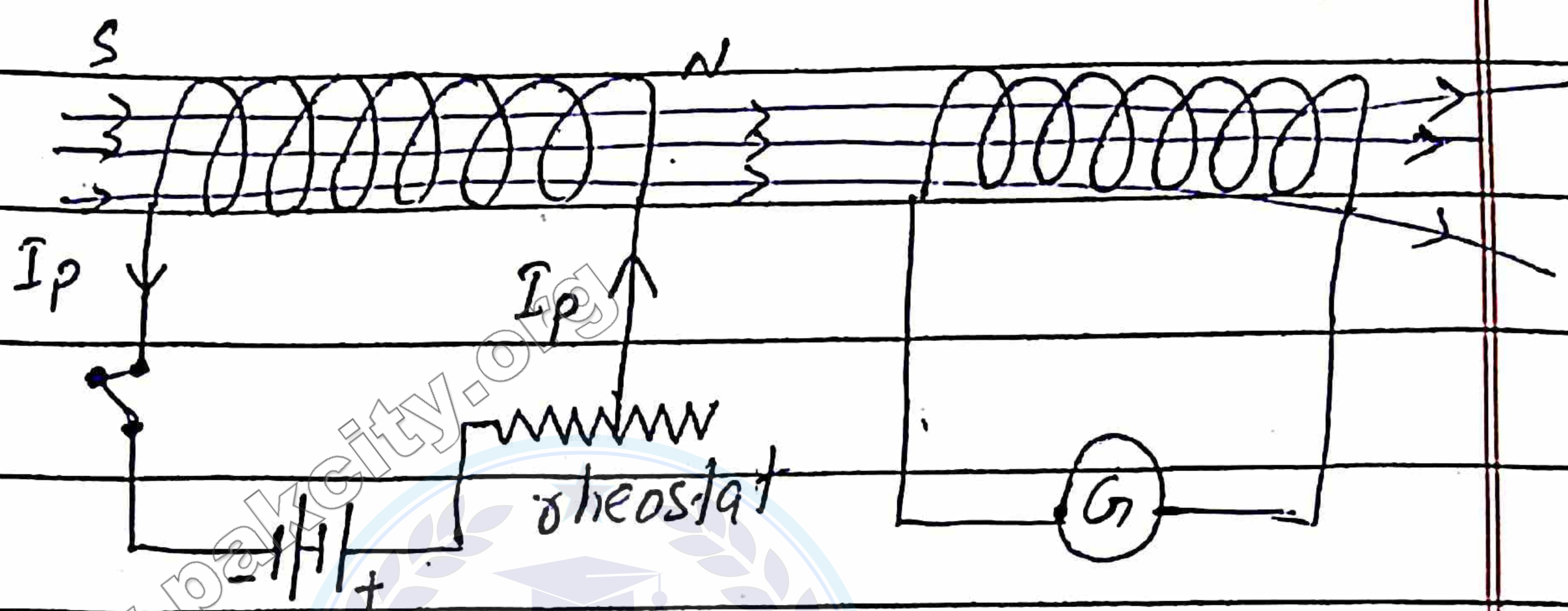
the magnetic force will also act towards right same as the direction of motion of the conductor.

In this way, it will become a self moving system that is against the law of conservation of energy.

Mutual Induction

Defination: The Phenomena in which the changing current in one coil induces an emf in another coil is called the mutual induction.

Construction:



Primary coil Secondary coil

The apparatus used for mutual induction consists of two coils. One is called primary coil which is connected to the switch, battery and rheostat. While other coil is called secondary coil connected to the galvanometer.

Working principle:

Mutual induction works on the principle of Faraday's law. When the current flowing in the primary coil is changed with the help of rheostat then the changing magnetic field reaches to the secondary coil and induces current in it.



Mathematical expression:

Consider the current flowing in the primary coil is I_p , number of turns of the secondary coil is N_s and magnetic flux through secondary is Φ_s . Then the flux in the secondary is directly proportional to the current in the primary coil.

$$N_s \Phi_s \propto I_p$$

$$N_s \Phi_s = M I_p \rightarrow (1)$$

Here M is the

proportionality constant called mutual inductance.

According to the magnitude of Faraday's law, the emf induced in the secondary coil is given by:

$$\mathcal{E}_s = -N_s \frac{\Delta \Phi_s}{\Delta t}$$

$$\mathcal{E}_s = - \frac{\Delta N_s \Phi_s}{\Delta t}$$

By using eq. (1)

$$\mathcal{E}_s = - \frac{\Delta M I_p}{\Delta t}$$

$$\mathcal{E}_s = M \frac{\Delta I_p}{\Delta t}$$

$$\mathcal{E}_s = -M \frac{\Delta I_p}{\Delta t}$$

This is the mathematical expression for mutual induction. It shows that the emf induced in the secondary coil is proportional to the rate of change of current in the primary coil. -ve sign

indicates that the emf in the secondary coil will oppose the current in the primary coil.

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Mutual inductance: For mutual inductance, we ignore negative sign.

$$M = \frac{E_s}{\frac{\Delta I_p}{\Delta t}}$$

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Mutual inductance is the ratio of emf induced in the secondary coil to the rate of change of current in the primary coil.

Dependence: It depends upon the no. of turns of coil, their area of cross section, their closeness together, and the nature of core material upon which two coils are wound.

Henry: The SI unit of mutual inductance is henry (H) named after Joseph Henry.

$$1H = \frac{1V}{\frac{1A}{1s}}$$

Defination of Henry:

One Henry is the mutual inductance of the pair of coils in which the rate of change of current of one ampere per second in the primary causes an induced emf of one volt in the secondary.

Self Induction

Defination: The phenomena in which the changing current in a coil induces an emf in itself called self induction.

Construction:

The

apparatus

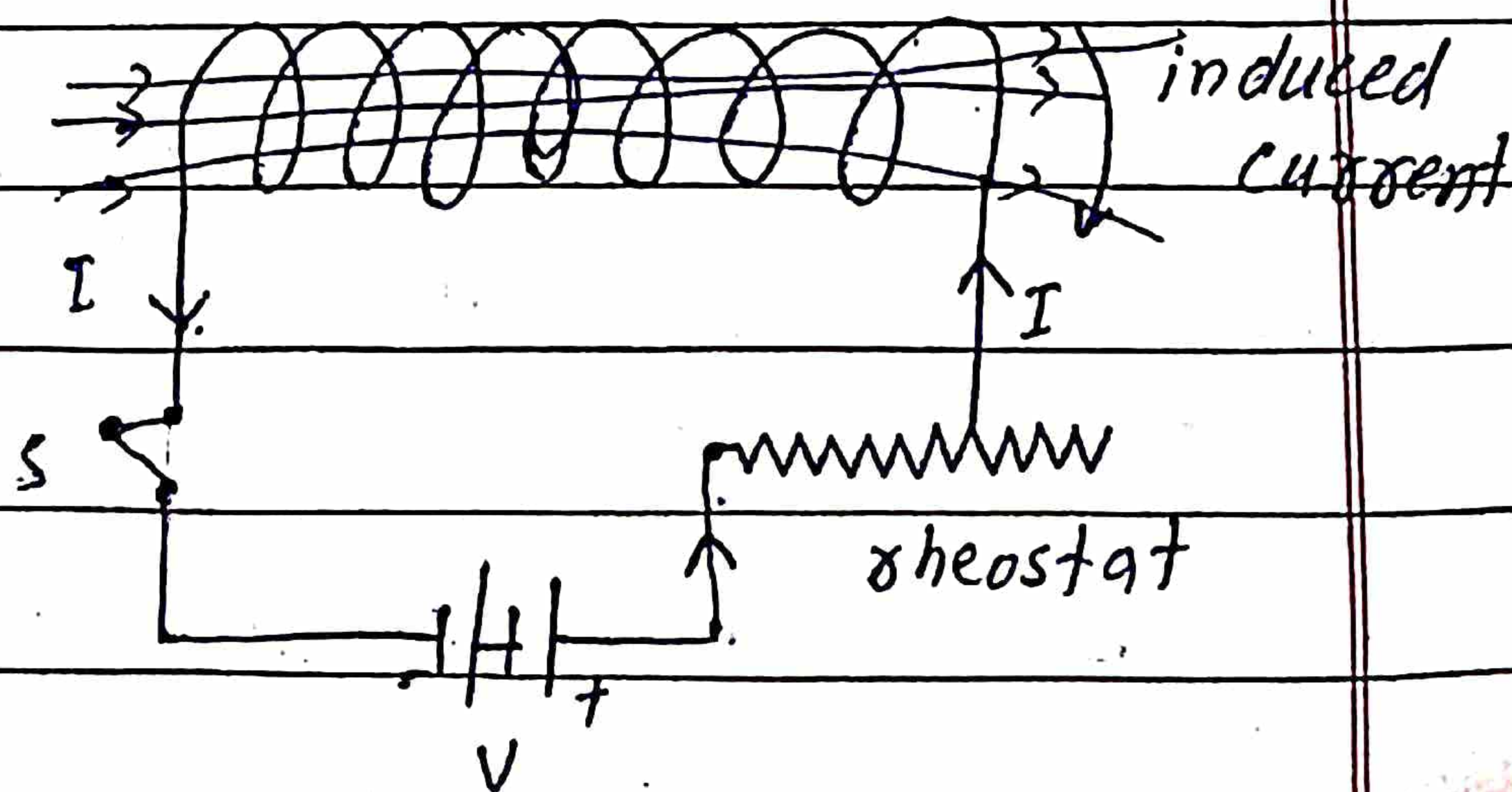
used for

self

induction

consists

of one coil only. The coil



is connected to the switch, battery and rheostat as shown in the figure



* Working principle:

Self induction works on the principle of Faraday's law. When the current flowing in the coil changes with the help of rheostat, the magnetic field also changes.

This changing magnetic field when passes again through the coil, it induces current and emf. The emf induced in this way is called back emf.

Mathematical expression:

Consider the current flowing in the coil is I , number of turns of the coil is N , the magnetic flux through the coil is ϕ and flux is directly proportional

to the current.

$$N\Phi \propto I$$

$$N\Phi = LI \rightarrow (1)$$

Here L is the proportionality constant called self inductance.

According to Faraday's law, the emf induced in the coil is given by:

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

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



By using eq. (1)

$$\mathcal{E}_L = - \frac{\Delta LI}{\Delta t}$$

$$\mathcal{E}_L = -L \frac{\Delta I}{\Delta t}$$

This is the mathematical expression for the emf induced in the coil. It shows that the induced emf is directly proportional to the

rate of change of current in the coil. Negative sign shows that the induced emf will oppose the current flowing in the coil due to the battery.



Self Inductance:

For self inductance we ignore the negative sign.

$$L = \frac{\mathcal{E}_L}{\Delta I / \Delta t}$$

Self inductance is the ratio of emf induced in the coil to the rate of change of current in that coil.

Dependence:

- It depends upon the:
- Number of turns of coil
 - Cross-sectional area
 - Nature of Core Material

Henry:

The SI unit of self inductance is Henry named after Joseph Henry.

$$1H = \frac{1V}{1A/sec.}$$

One Henry is the self inductance of coil in which the rate of change of current in one Ampere per second induces the emf of one volt in that coil.

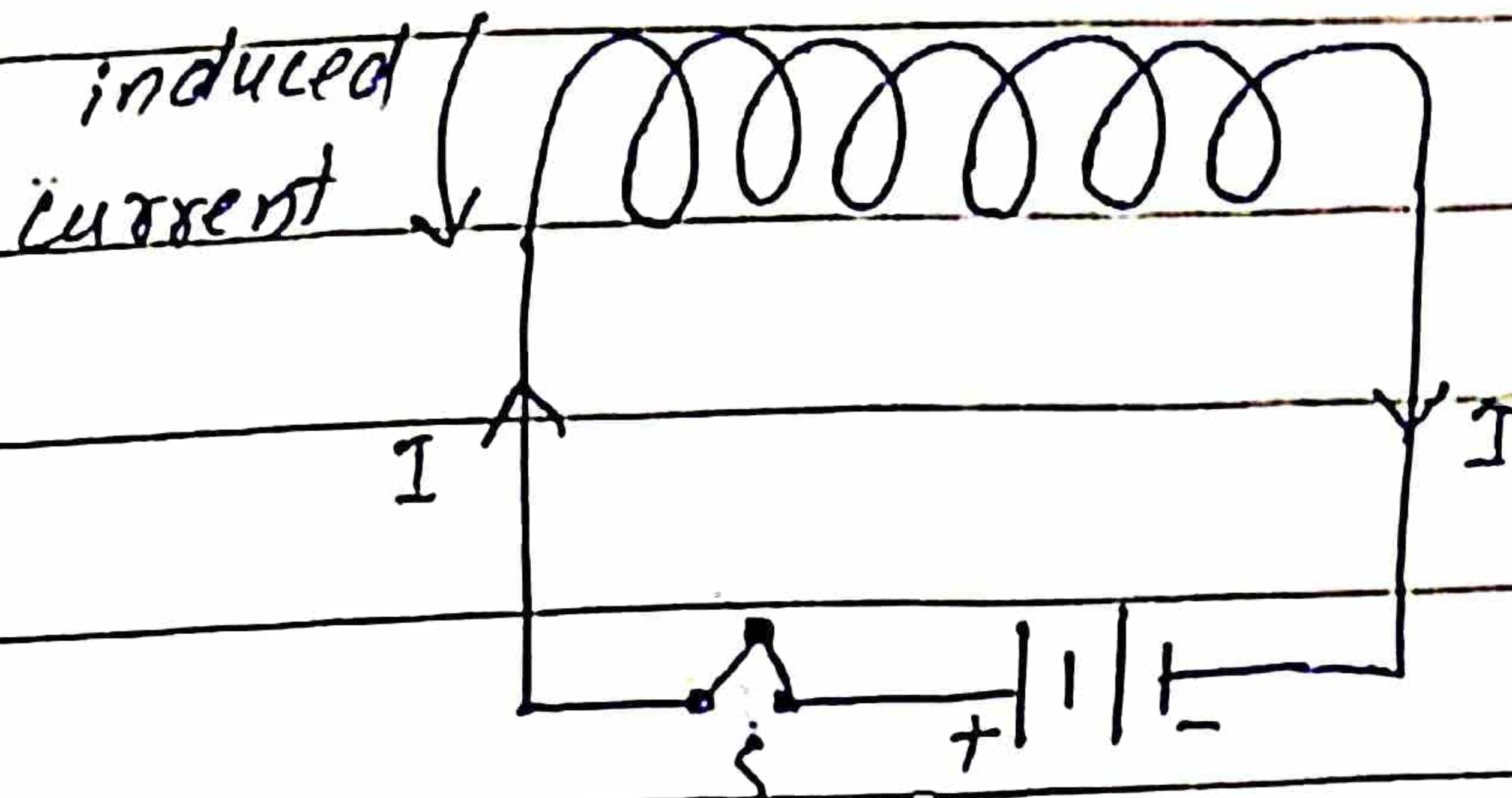
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✓ Energy Stored In An Inductor

Introduction: The energy is stored in the form of electric field for a capacitor. In the same way energy is stored in the form of

magnetic field for an inductor.

Explanation: Consider a coil



having N number of turns and length l connected to a switch and battery. When the current flows through the coil, a magnetic field is produced. This changing magnetic field induces the current and emf in the coil. This emf is called back emf. The work done by the battery in moving a charge Δq is:

$$W = \Delta q V_E$$

According to the self induction, magnitude of induced emf is:

$$E_L = L \frac{\Delta I}{\Delta t}$$

So,
$$W = \Delta q \cdot L \frac{\Delta I}{\Delta t}$$

$$W = L \left(\frac{\Delta q}{\Delta t} \right) (\Delta I) \rightarrow (1)$$

When the switch is closed, the current changes from zero to its maximum value I . So,

$$\text{average current} = \frac{\Delta q}{\Delta t} = \frac{0 + I}{2}$$

$$\frac{\Delta q}{\Delta t} = \frac{I}{2}$$

$$\text{change in current} = \Delta I = I - 0$$

$$\Delta I = I$$

Now eq. (1) can be written as:

$$W = L \left(\frac{I}{2} \right) (I)$$

$$W = \frac{1}{2} L I^2$$

This work done appears as the electric potential energy stored in the inductor.

$$U_m = \frac{1}{2} L I^2 \rightarrow (2)$$

for the self induction:

$$N \Phi = L I$$

$$\frac{N \Phi}{I} = L$$

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$$L = \frac{N \Phi}{I}$$

But magnetic flux is:

$$\Phi = B A$$

So,

$$L = \frac{N B A}{I}$$

for a coil / solenoid:

$$B = \mu_0 n I$$

So,

$$L = \frac{N \mu_0 n I A}{I}$$

$$L = N \mu_0 n A$$

we know that n is the number of turns per unit length:

$$n = \frac{N}{l}$$

$$\Rightarrow n l = N$$

So,

$$L = n^2 \mu_0 n A$$

$$L = \mu_0 n^2 A l$$

and

$$I = \frac{B}{\mu_0 n}$$

Put these values of L and I in eq. (2)

$$U_m = \frac{1}{2} (\mu_0 n^2 A l) \left(\frac{B}{\mu_0 n} \right)^2$$

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$$= \frac{1}{2} (\mu_0 n^2 A l) \left(\frac{B^2}{\mu_0 n^2} \right)$$

$$U_m = \frac{1}{2} \frac{B^2}{\mu_0} (A l)$$

$$\text{Energy} = \frac{1}{2} \frac{B^2}{\mu_0} (A l)$$

$$= \frac{1}{2} \frac{B^2}{\mu_0} (\text{Volume})$$

$$\frac{\text{Energy}}{\text{Volume}} = \frac{1}{2} \frac{B^2}{\mu_0}$$

$$\text{Energy density} = \frac{1}{2} \frac{B^2}{\mu_0}$$

Here B is magnetic field strength and μ_0 is permeability of

free space. Its value is
 $4\pi \times 10^{-7} \text{ Wb A}^{-1} \text{ m}^{-1}$

Alternating Current Generator

Definition:

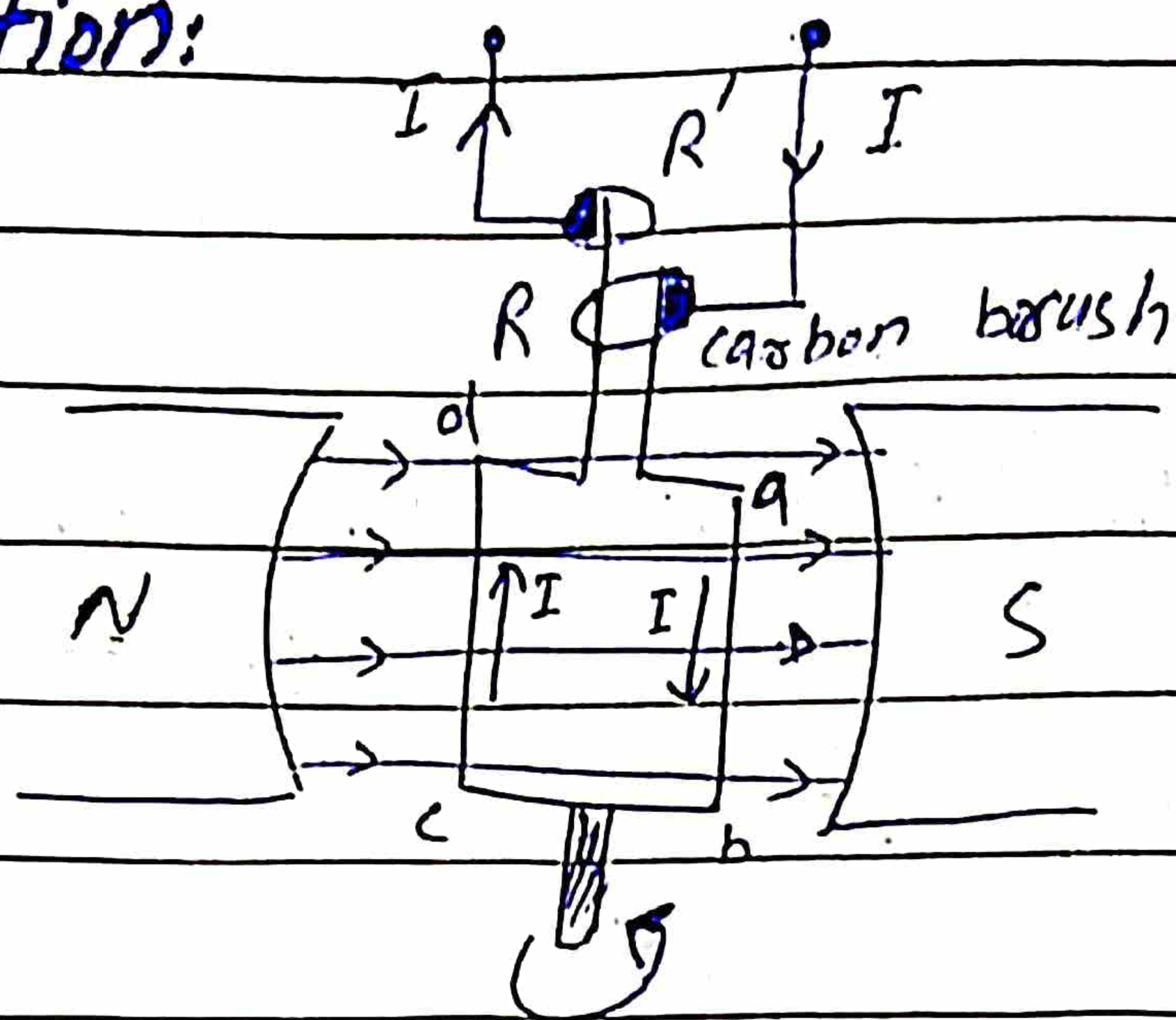
Alternating current generator is a device that converts mechanical energy to electrical energy.

Working principle:



Alternating current generator works on the principle of Faraday's law. When the coil rotates in the magnetic field with the help of some mechanical means. Then due to the changing magnetic field, emf and current is induced in the coil.

Construction:



Alternating current generator consists of the following parts:

- i- A magnet. Between its north and south pole loop is placed.
- ii- A rectangular loop $abcd$
- iii- Slip rings R and R' that rotate with the loop.
- iv- Carbon brushes that provide the connection between the loop and external circuit.

Working:

When the rectangular loop $abcd$ rotates by some mechanical means, the magnetic field passing through it changes that induces the

current. The slip rings rotate with the rotation of the loop. Current is provided to the external circuit with the help of carbon brushes.



Mathematical expression:

We know that when a conductor moves in the magnetic field emf is induced given by:

$$\epsilon = vBL \sin \theta$$

Here v is the speed of the loop, B is strength of magnetic field, L is the length of loop and θ is the angle between v and B .

For the sides bc and da magnetic field is either parallel or anti-parallel for the sides. So,

$$\epsilon_{bc} = \epsilon_{da} = 0$$

while the induced emf along the sides ab and cd

will be:

$$\mathcal{E}_{ab} = \mathcal{E}_{cd} = vBL \sin \theta$$

$$\mathcal{E}_{ab} = \mathcal{E}_{cd} = vBL \sin \theta$$

The total emf induced in the loop is:

$$\mathcal{E} = \mathcal{E}_{ab} + \mathcal{E}_{bc} + \mathcal{E}_{cd} + \mathcal{E}_{da}$$

$$= vBL \sin \theta + 0 + vBL \sin \theta + 0$$

$$\mathcal{E} = 2vBL \sin \theta$$

For a coil having N number of turns.

$$\mathcal{E} = 2NvBL \sin \theta$$

The linear velocity and angular velocity are related as

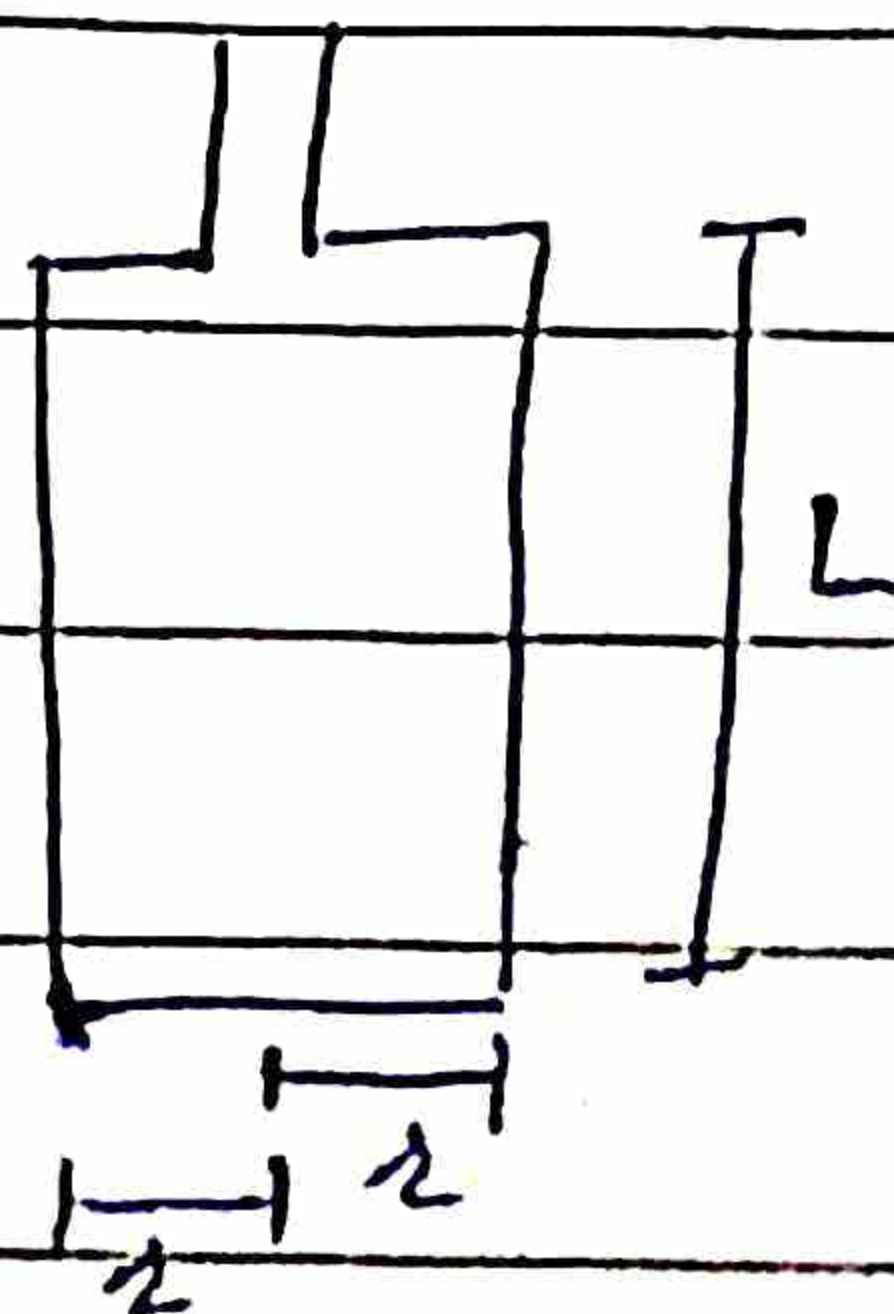
$$v = r\omega$$

So,

$$\mathcal{E} = 2N r \omega BL \sin \theta$$

The area of the coil can be found as:

$$\text{Area} = \text{length} \times \text{width}$$



$$A = (L)(2r)$$

$$A = 2rL$$

Now expression for induced emf will be:

$$\mathcal{E} = N W (2rL) B \sin \theta$$

$$\mathcal{E} = N W A B \sin \theta$$

This is the expression for the induced emf in the coil of AC generator.

For maximum emf $\theta = 90^\circ$

$$\mathcal{E}_0 = N W A B \sin 90^\circ$$

$$= N W A B (1)$$

$$\mathcal{E}_0 = N W A B$$

So,

$$\mathcal{E} = \mathcal{E}_0 \sin \theta$$

The induced current can be determined as:

$$I = \frac{\mathcal{E}}{R}$$



$$I = \frac{\mathcal{E}_0 \sin \theta}{R}$$

$$I = I_0 \sin \theta$$

Also $\theta = \omega t$

$$I = I_0 \sin \omega t$$

and $\omega = 2\pi f$

So,

$$I = I_0 \sin (2\pi f t)$$



This is the mathematical expression for the alternating current induced in the alternating current generator.

Variation in current:

The expression for alternating current is:

$$I = I_0 \sin \theta$$

The value of alternating current depends upon the angle " θ ". Now we will discuss the variation in current for different angles.

i- For $\theta = 0^\circ$

$$I = I_0 \sin 0^\circ = I_0 (0)$$

$I = 0$ So, current is zero.

ii- For $\theta = 90^\circ$

$$I = I_0 \sin 90^\circ = I_0 (1)$$

$$I = I_0$$

so, current is maximum.

iii- For $\theta = 180^\circ$

$$I = I_0 \sin 180^\circ = I_0 (0)$$

$$I = 0$$

so, current is zero

iv- For $\theta = 270^\circ$

$$I = I_0 \sin 270^\circ = I_0 (-1)$$

$$I = -I_0$$

so, current is maximum but in negative.

v- For $\theta = 360^\circ$

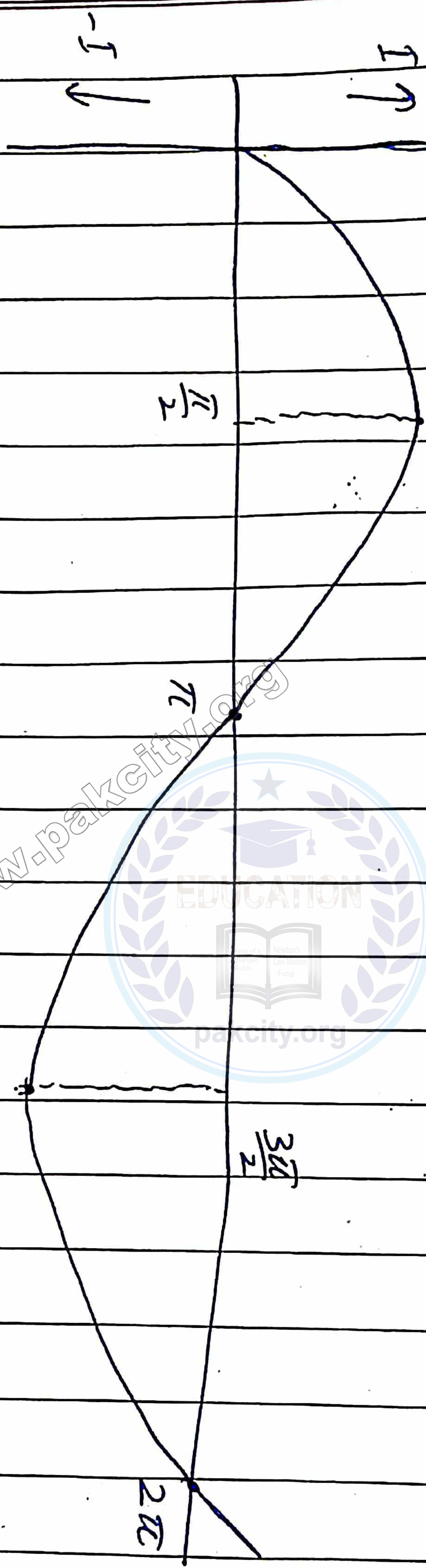
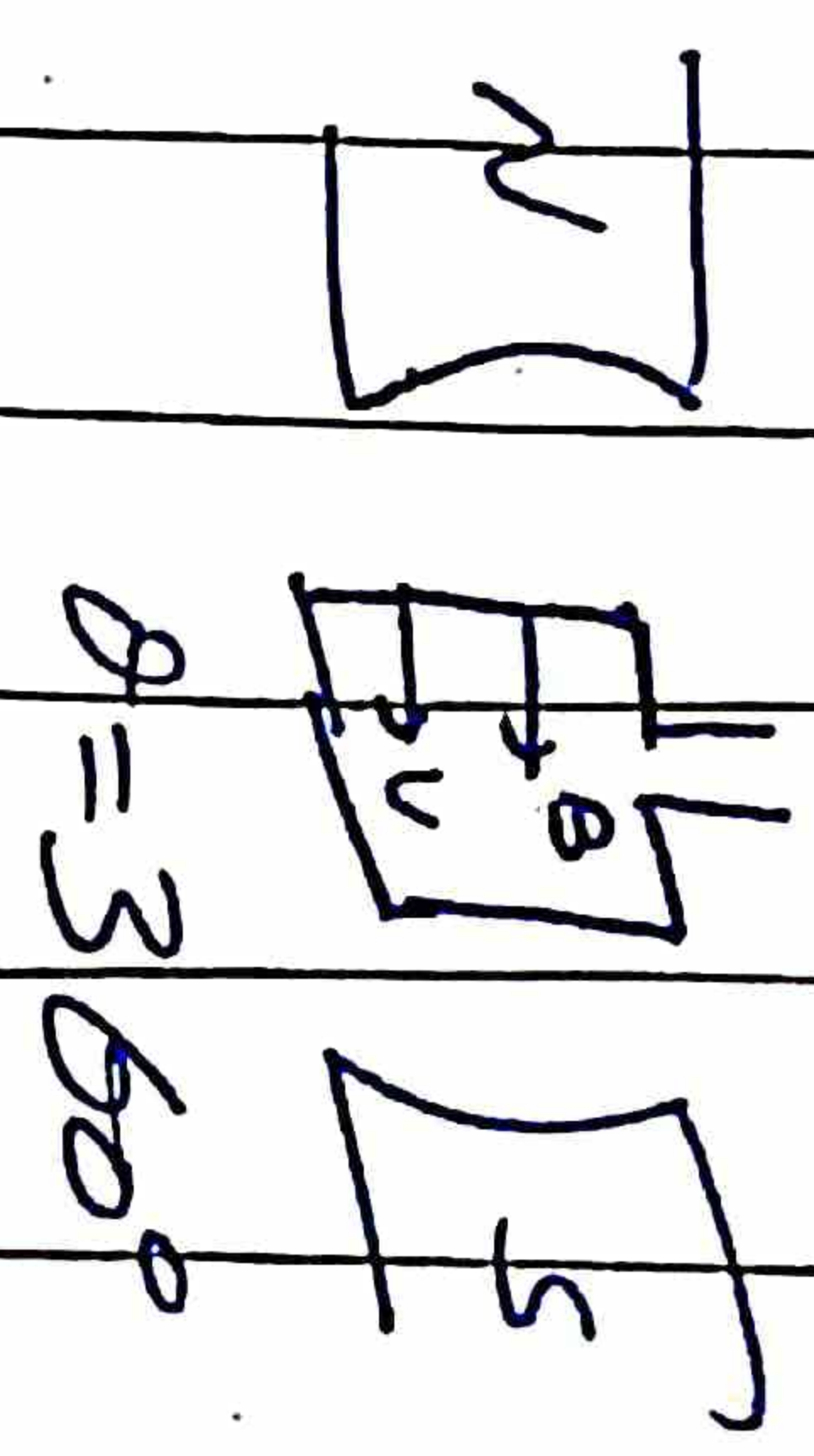
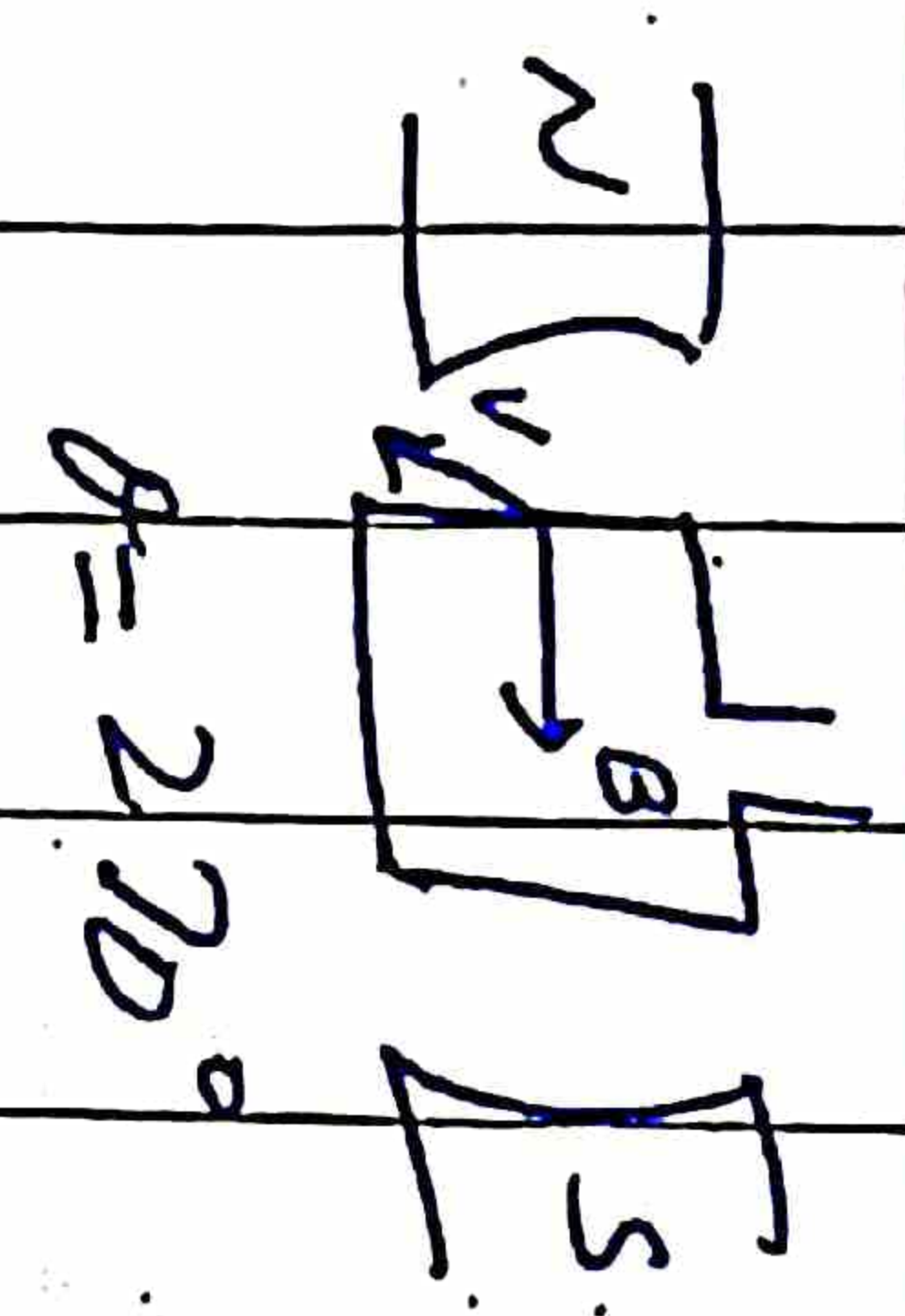
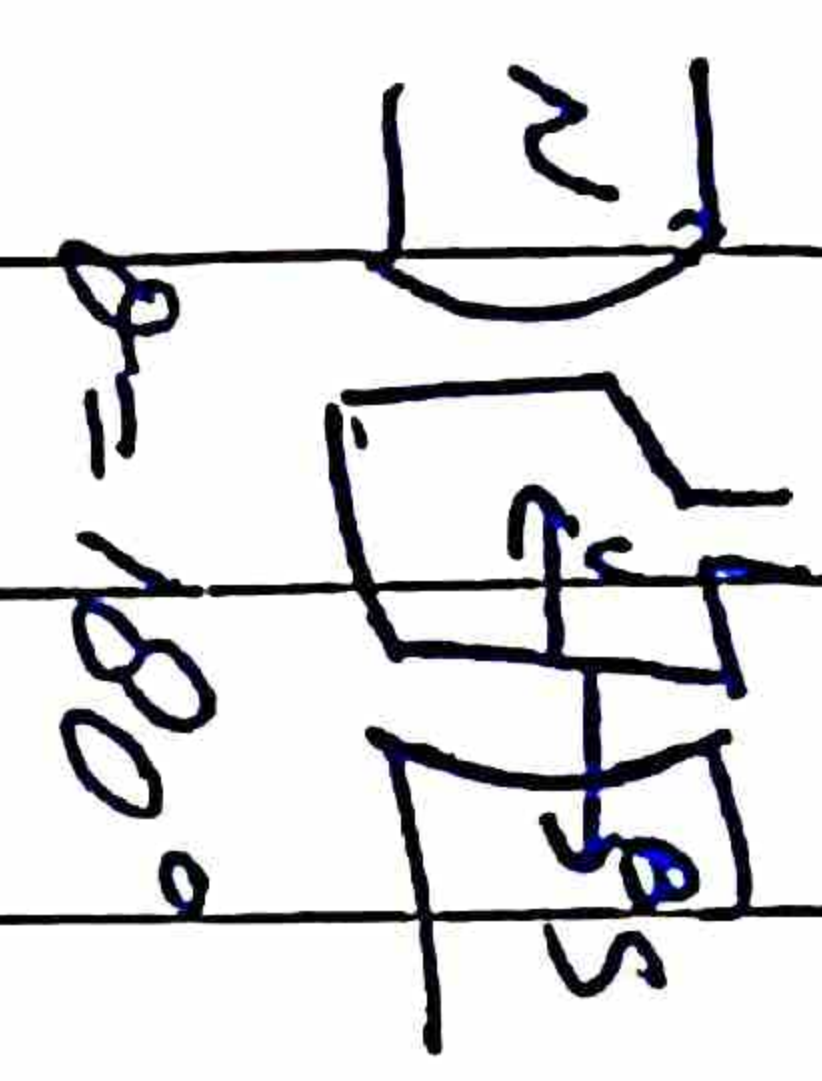
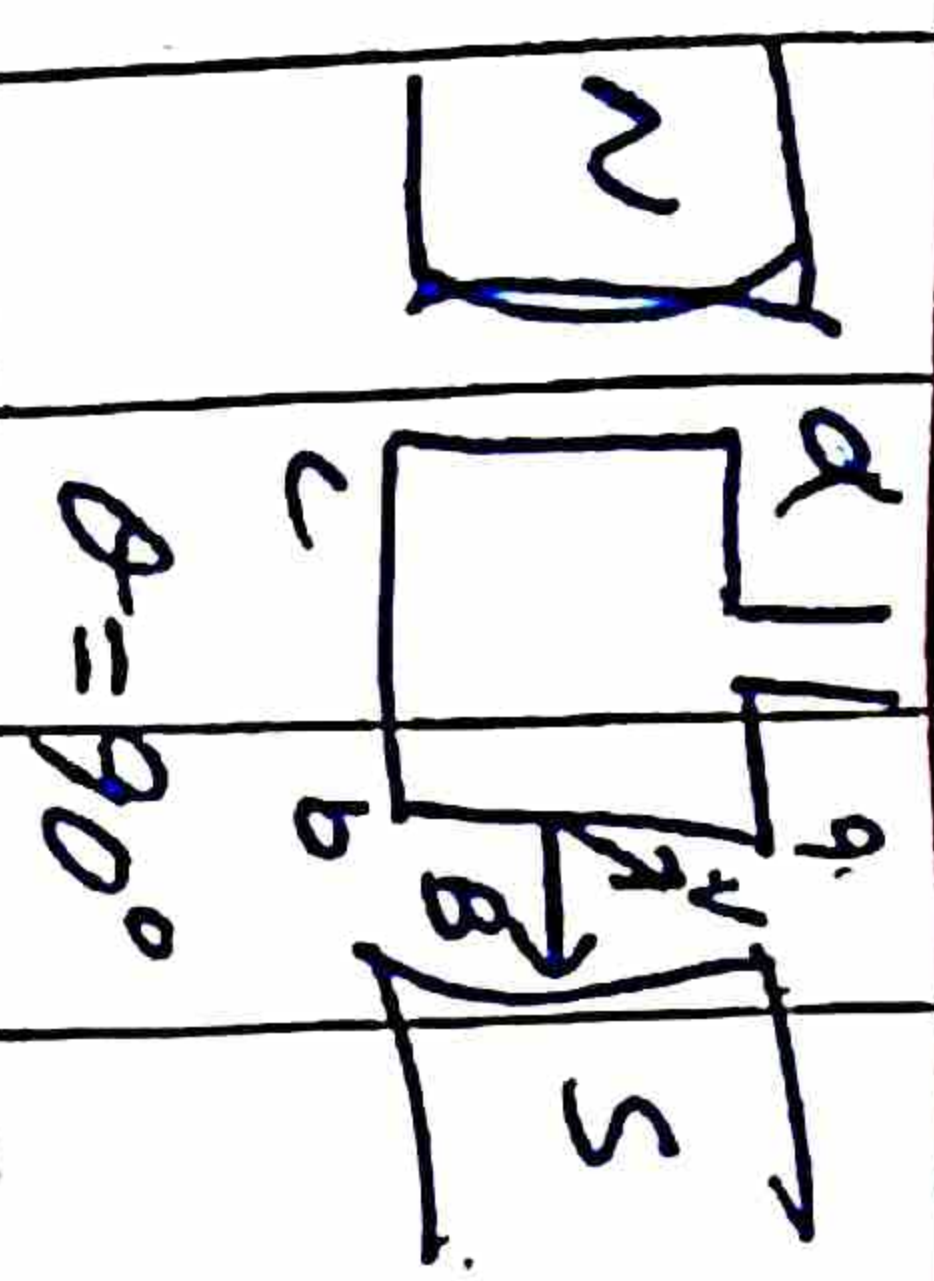
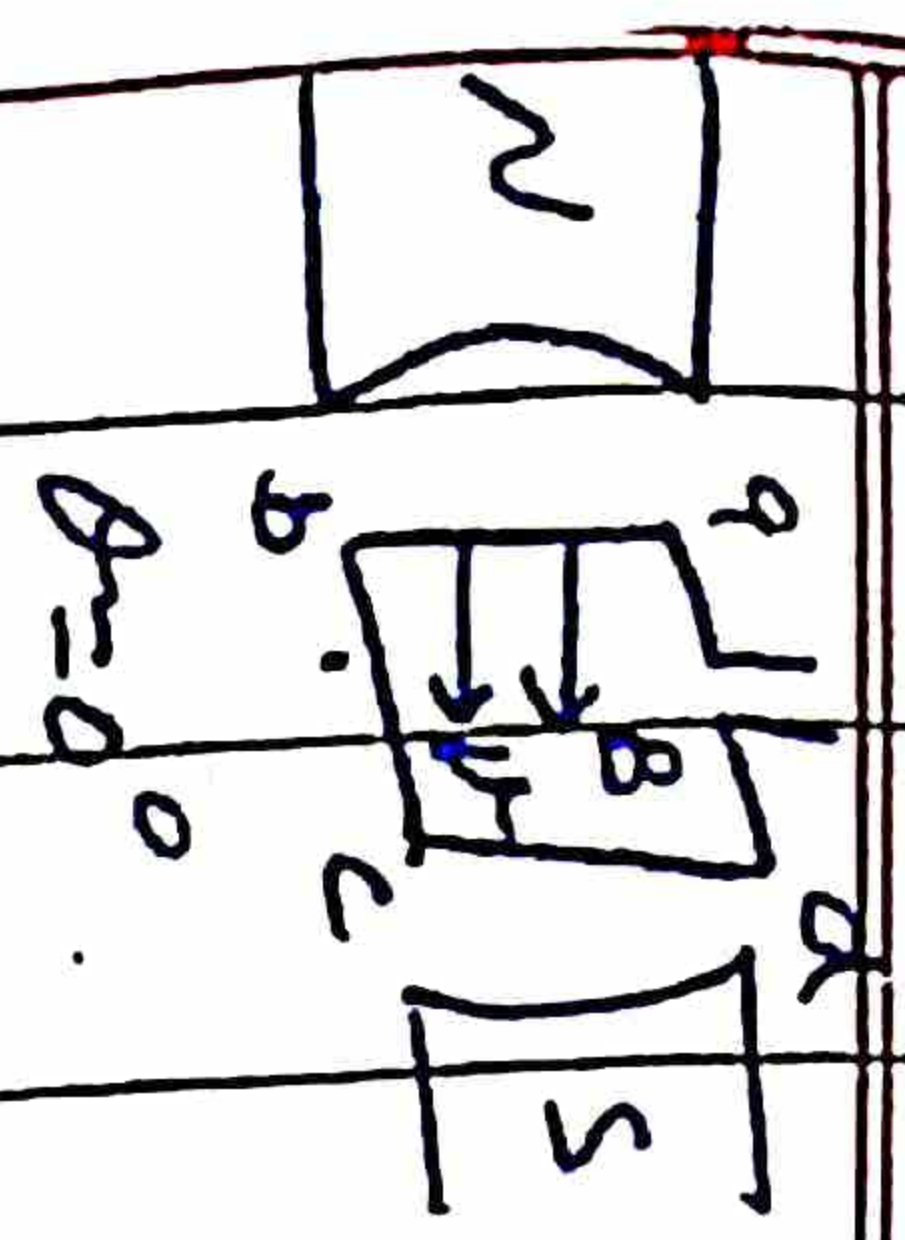
$$I = I_0 \sin 360^\circ = I_0 (0)$$

$$I = 0$$

so, current is zero.

Armature:

A number of the coil that are wound on an iron cylinder which is rotated in the magnetic field is Armature.



Commutator:

In 1834 William Sturgeon invented a device that is used in DC generator to prevent the current from changing its direction that is known as commutator. It is simply split rings that changes their location as the coil is rotated and the output current remains in the same direction.



How fluctuations of the output for DC generator can be reduced?

The fluctuations of the output can significantly reduced by using many coils rather than a single one. Multiple coils are wound around a cylindrical core form the armature. Each coil is connected to a separate commutator and the output of every coil is tapped only as it reaches

its peak emf. Thus the emf in the outer circuit is almost constant.

Load: The device in the circuit that consume electrical energy are known as the load. The greater the load, the larger the current is supplied by the generator. When the circuit is open the generator does not supply electrical energy and a very little force is needed to rotate the coil.

✓ Back motor effect in generator:

When the coil of the generator is rotated by some mechanical means in the external magnetic field. Due to changing magnetic flux current is induced in the coil. This induced current produces its own magnetic field due to which a counter current is produced in the coil. This effect is

called back motor effect in generator. The larger the current draw, the greater is the counter torque produced.



DC motor:

A motor is a device which converts electrical energy into mechanical energy.

When current flows through the armature coil, the force on the conductor produces a torque that rotates the armature. The amount of this force depends upon the current, the strength of magnetic field, the area of the coil and the number of turns of coil.

How can jerks be reduced in DC motor?

Torque vanishes each time the current changes its direction. This creates jerks.

in the smooth running of the armature. However the problem is overcome by using more than one coil wrapped around the soft-iron core. This results in producing a more steady torque.

Field coils:



The magnetic field in the motor, is provided by a permanent magnet or an electromagnet. The windings of the electromagnet are usually called the field coils. The field coil may be in series or in parallel to the armature coils.

Back emf in motor:

When The coil of the motor rotate across The magnetic field by The applied potential difference and emf is induced in it. The induced emf is in such a direction that opposes The emf running The motor due to this reason the induced emf is called back emf of The motor. The magnitude of the back emf increases with the speed of motor.

Since V and E are opposite in polarity. The net emf in The circuit is $V - E$. If R is The Resistance of The coil and I is The current drawn from the motor. Acc. to ohm's law:

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

$$V = E + IR.$$

Variation of back emf effect in motor:

1- When The motor is just started back emf is almost zero since a large current passes through a coil.

2- When The motor speed up The back emf increases and The current become smaller and smaller.

3- If The motor is overloaded it slows down consequently The back emf decreases and allow The motor to draw more current.

4- If The motor is overloaded beyond its limits the current could be so high that it may burn out The motor.

Transformer

Defination: It is an electrical device used to Change a given alternating emf in to a larger or smaller alternating emf.

Working principle:

It works on the Principle of Mutual induction between two coils.

Construction:

The transformer Consist of two coils of Copper,

electrically insulated

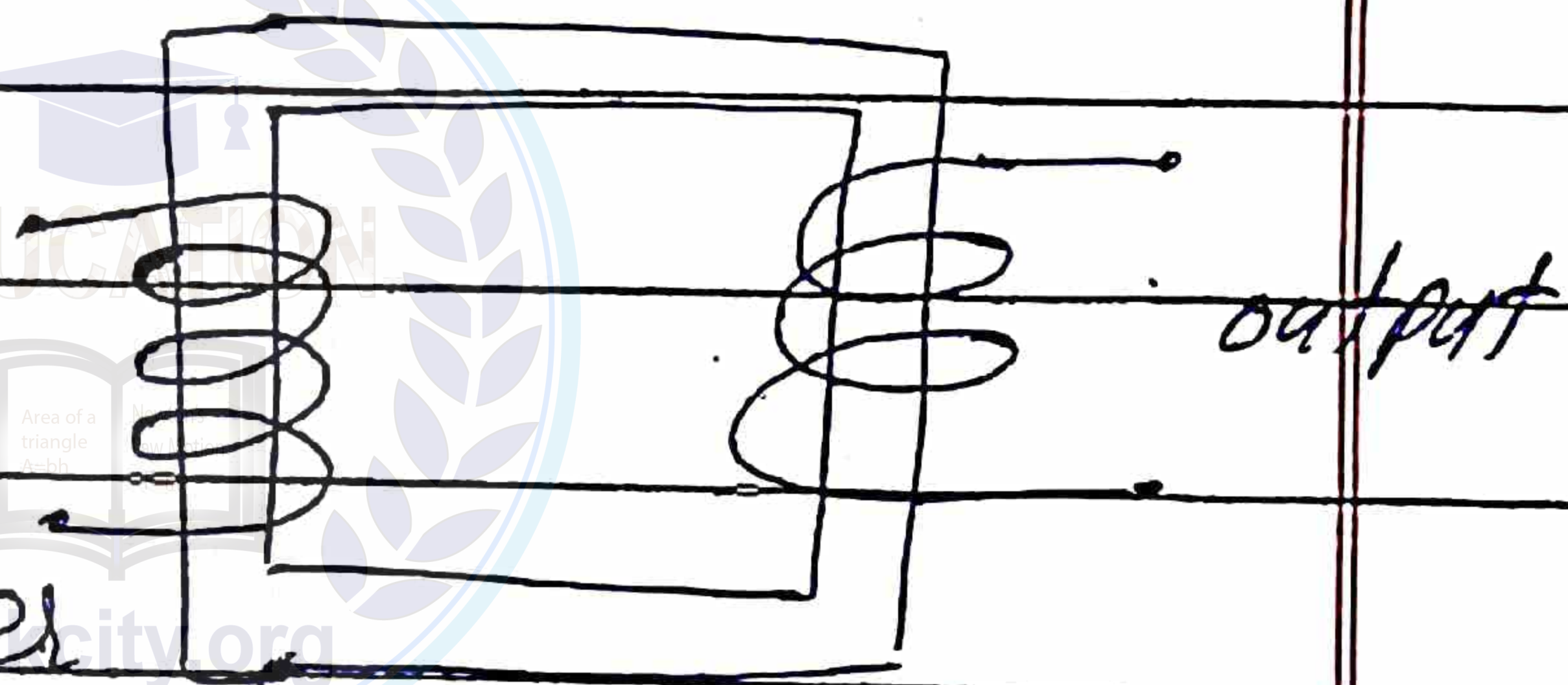
from each other

wound on the same iron

core. The coil to which A.C power is supplied is called

primary and that from which power is delivered to the circuit is called secondary coil.

It should be noted that there is no electrical connection between two coils but they are magnetically linked.



Working: When the emf is provided at the primary coil, magnetic field is produced and due to changing magnetic field back emf is also induced. If $\Delta\phi$ is the change in magnetic flux and N_p is the number of turns of primary coil.

$$\text{self induced emf} = -N_p \frac{\Delta\phi}{\Delta t}$$

The ^{back} emf is equal and opposite to the provided emf.

$$V_p = -\text{back emf} = -(-N_p \frac{\Delta\phi}{\Delta t})$$

$$V_p = N_p \frac{\Delta\phi}{\Delta t}$$

This emf induces emf in the secondary coil due to mutual induction. The emf induced in secondary coil is:

$$V_s = N_s \frac{\Delta\phi}{\Delta t}$$

here N_s is the number

of turns of secondary coil.

By dividing the above equations:

$$\frac{V_s}{V_p} = \frac{N_s \frac{d\phi}{dt}}{N_p \frac{d\phi}{dt}}$$

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

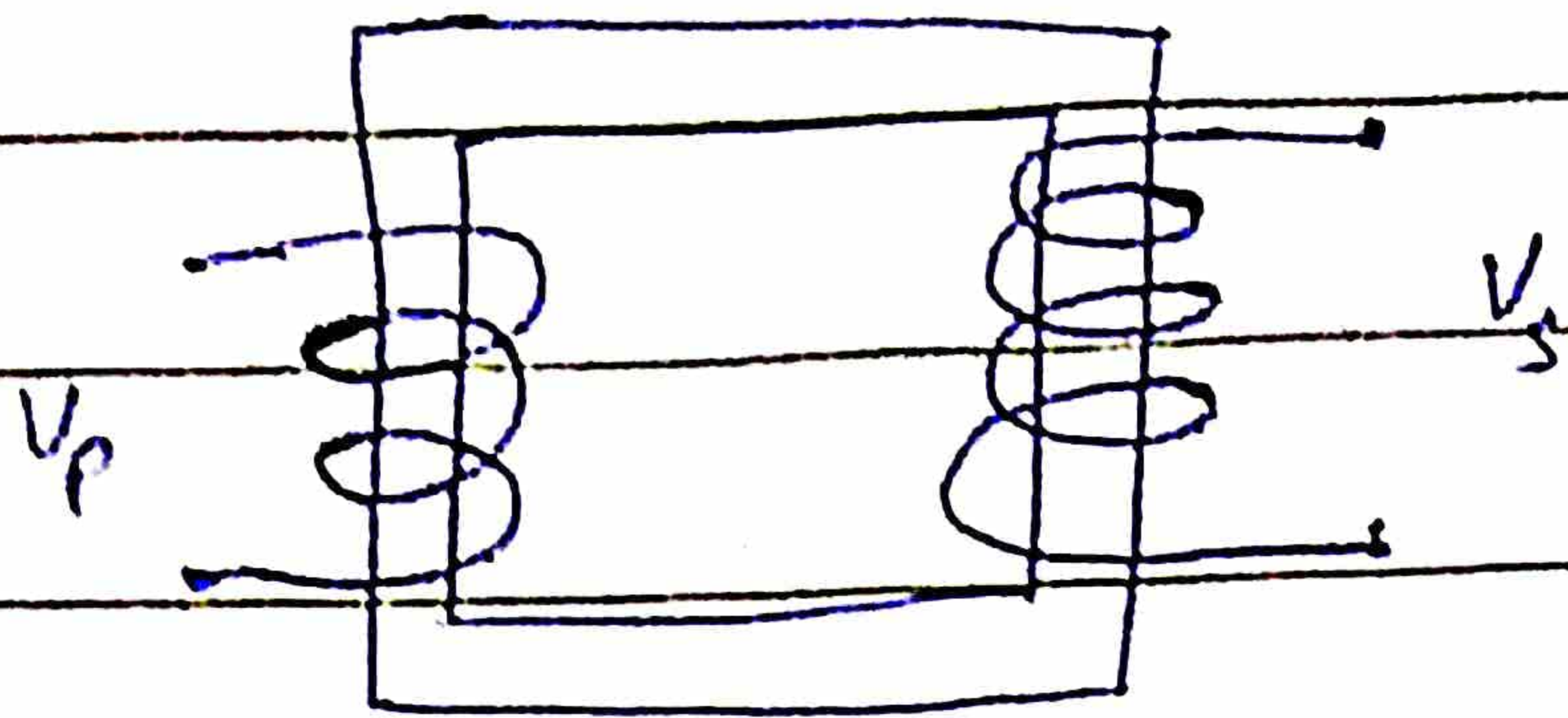
So, the ratio of emf in the coils is equal to the ratio of number of turns of the coils.

Types: There are two types of transformers:

i- Step-up transformer:

The transformer in which number of turns of secondary coil are greater than number of turns of the primary coil is called step-up transformer. For this transformer the output voltage of secondary is greater than

input voltage
of
primary.



$$N_s > N_p$$

$$V_s > V_p$$

$$N_p < N_s$$

$$V_p < V_s$$

ii- Step-down transformer:

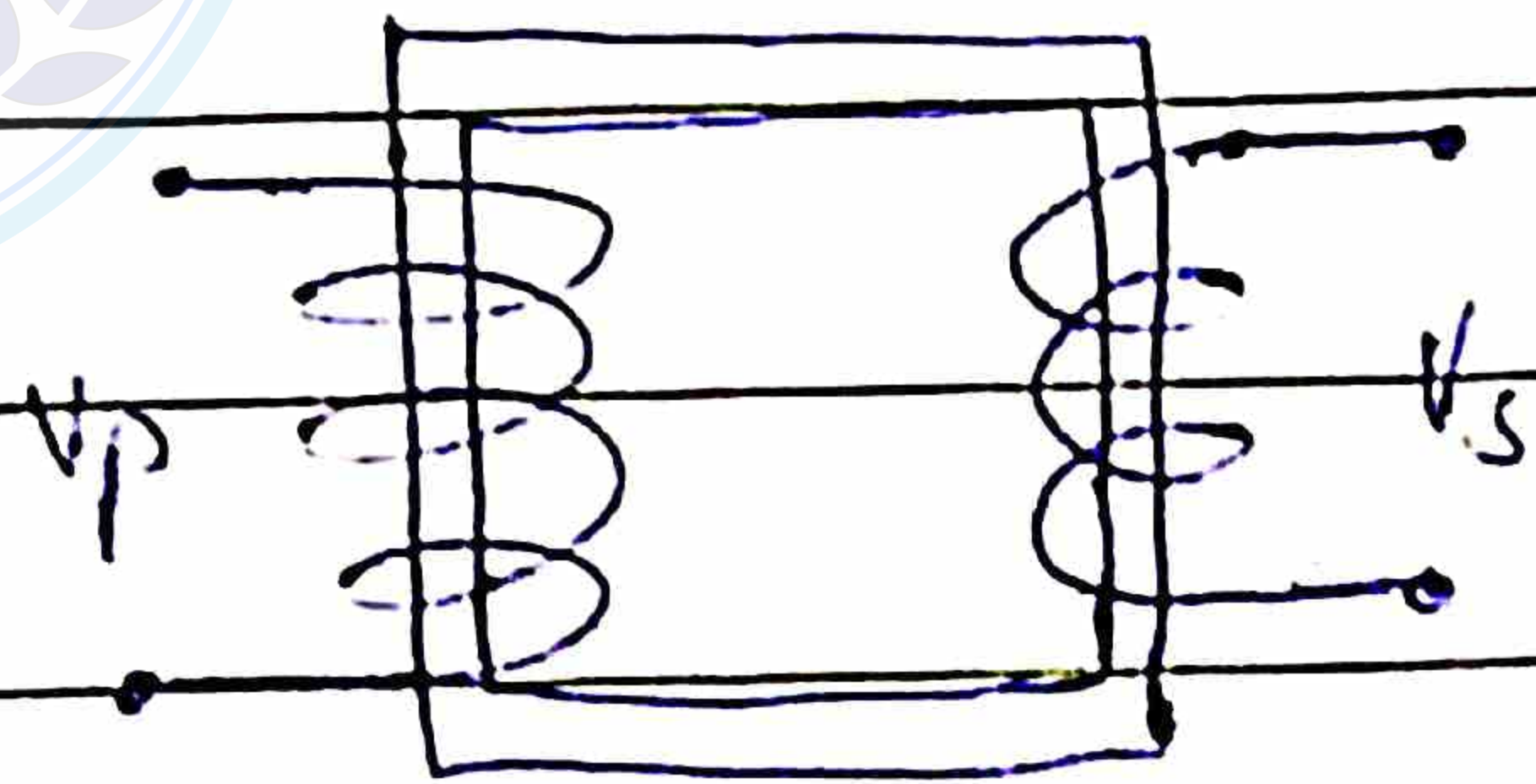
The transformer in which the number of turns of secondary coil is less than the number of turns of primary coil is called step-down transformer.

For this

transformer the output voltage of secondary

is less than the

input voltage of primary.



$$V_p > V_s$$

$$N_p > N_s$$

$$V_s < V_p$$

$$N_s < N_p$$

Ideal transformer:

For an ideal transformer the input power should be equal to output power.

Input power = Output power

$$V_p I_p = V_s I_s$$

$$\frac{V_p}{V_s} = \frac{I_s}{I_p}$$

For the transformer, voltage and current are inversely proportional as shown by the above relation.

Power loss during transmission:

When the current is transmitted from the power station to our homes then during its flow some power is lost due to the resistance due to atoms of the wire, this is named as power loss during transmission. Mathematically,

$$\text{Power loss} = I^2 R$$

Method to reduce power loss:

To reduce the power loss during transmission, two methods can be adopted:

i- The resistance of the transmission ^{wire} would be reduced.

But for minimum resistance more thick wire should be used. But this is an expensive method.

ii- Second method is suitable to reduce the current. So, by using step-up transformer at the power station we increase the voltage to reduce the current. By decreasing the current power loss also decreases.

Power loss within the transformer:

There are two main reasons of the power loss in the transformer. Due to these power losses the output power reduces from input power practically.

i- Eddy current:

When the magnetic field lines produced by the primary coil reach to secondary coil due to changing flux output emf is induced. But some of the magnetic field lines pass through the iron core of the transformer and induce current in it. This current is called eddy current. This eddy current is the cause of power dissipation and heating of core material.

To minimize the eddy current, the core should be laminated with insulation in between ~~between~~ layers of lamination.

ii- Hysteresis loss:

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Hysteresis loss is the energy expended to magnetize and demagnetize the core material in each cycle of the A.C.

Efficiency of transformer:

The ratio of the output power to input power of a transformer is called its efficiency.

$$E = \frac{\text{output power}}{\text{input power}} \times 100$$

Due to the power losses of eddy current and hysteresis loss transformer can not be ideal.

Methods to improve efficiency:



→ Core should be assembled from the laminated sheets of a material whose hysteresis loop area is very small.

→ The insulation between lamination sheets should be perfect so as to stop the flow of eddy currents.

→ The resistance of primary and secondary coil should be kept to minimum.

→ As power transfer from primary to secondary takes place through flux linkage. So, the primary and secondary coil should be wound in such a way that flux coupling between them is maximum.

15.1: No, induced emf in a circuit does not depend on the resistance of the circuit. mathematically,

$$\mathcal{E} = vBL \sin \theta \quad \text{and} \quad \mathcal{E} = -N \frac{\Delta \Phi}{\Delta t}$$

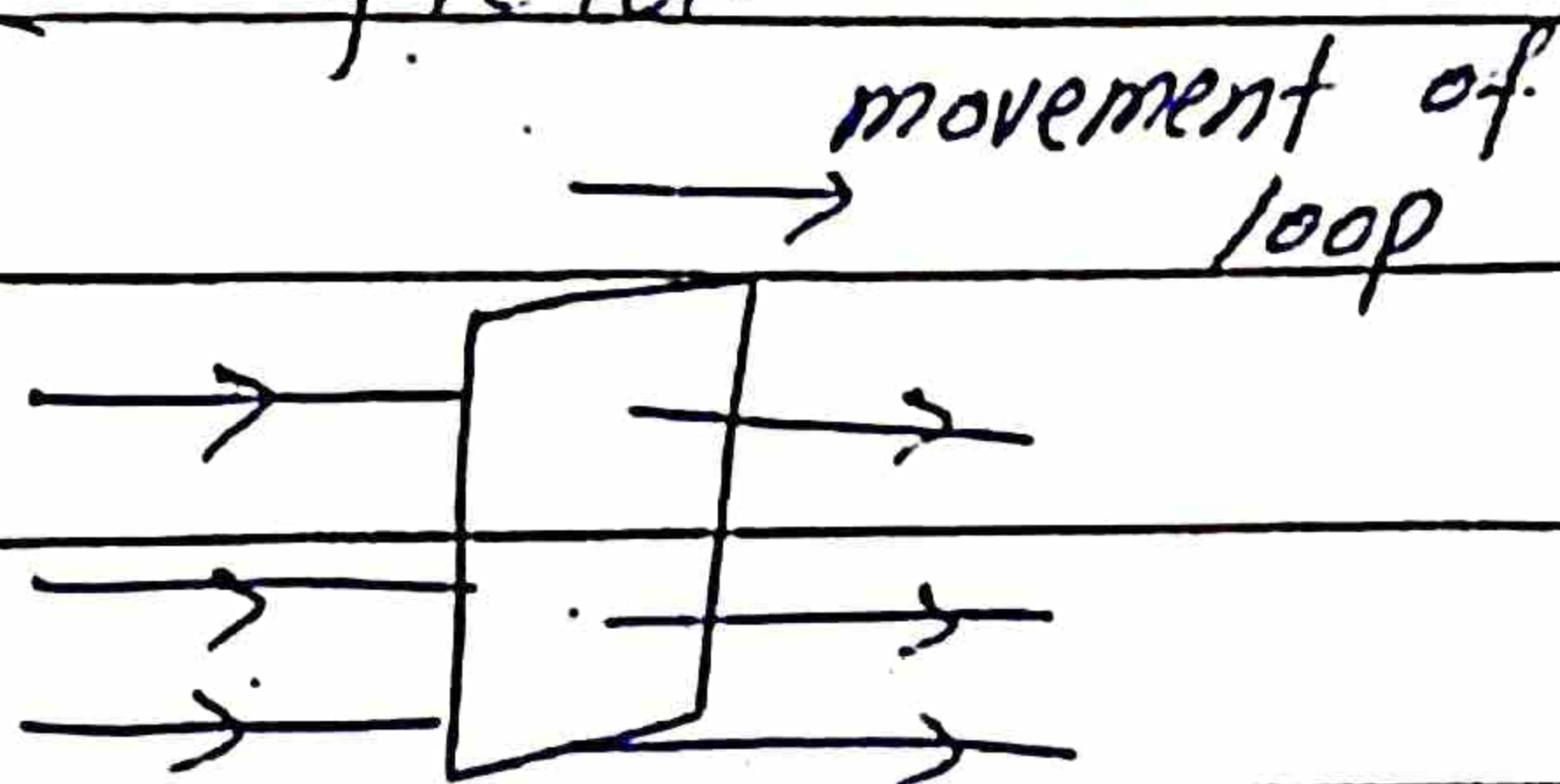
Yes, induced current depends on the resistance of the circuit. mathematically,

$$I = \frac{\mathcal{E}}{R}$$

15.2 No, emf will not be induced in the loop when a square loop of wire is moving through a uniform magnetic field and normal to the loop is oriented parallel to the magnetic field.

Because the magnetic flux through the

loop will not change.



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

As $\Delta \Phi = 0$

So,

$$\mathcal{E} = 0$$



15.3: The current will flow clock wise in the ring.

when the ring is released from

above it will induce current

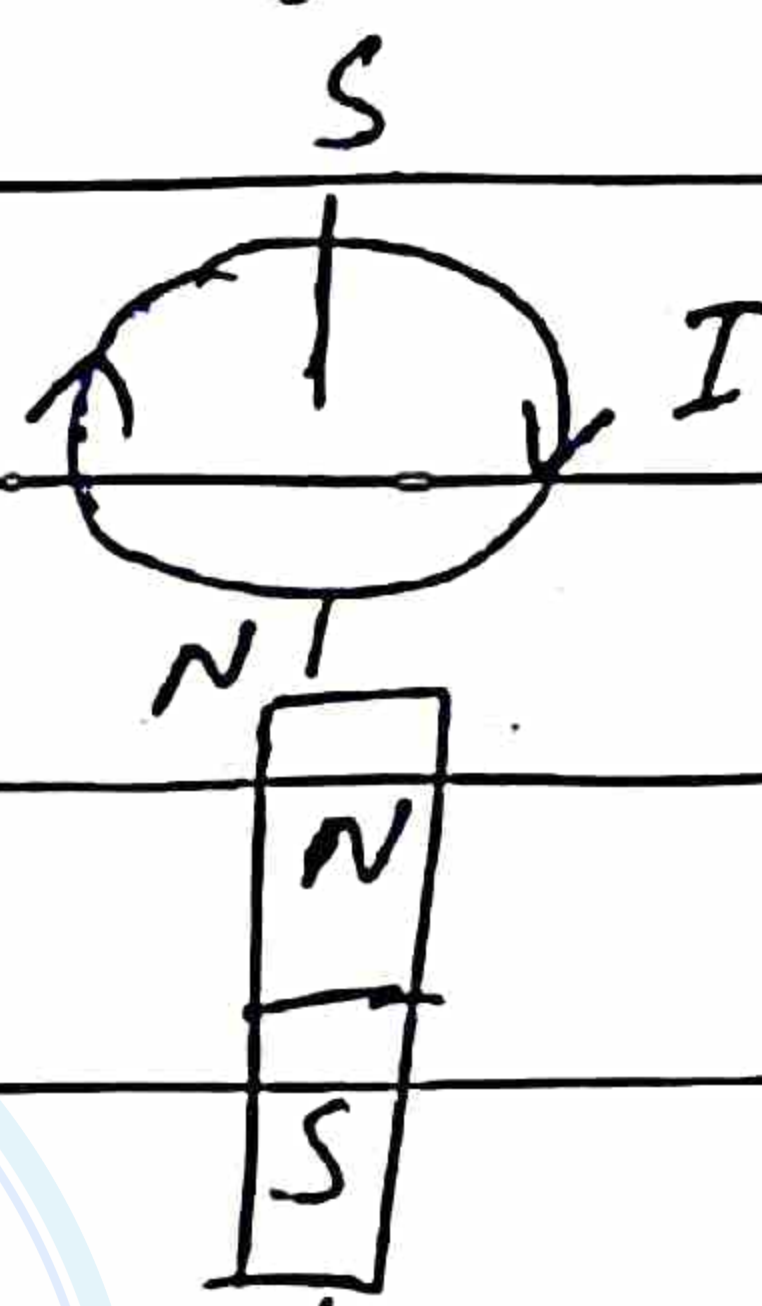
in such a way that the lower

end will behave - as north and upper end as south. So, by

right hand rule we see

that current flows in

clock wise direction.



15.5: No, the induced emf does not always act to decrease the magnetic flux through a circuit.

Induced emf opposes

the change in magnetic flux.

If magnetic flux is increasing induced emf will act to decrease it but if magnetic flux is decreasing, induced emf will act to increase it.

15.8: When the flat loop of wire is placed parallel in a changing magnetic field then no emf will be induced because there will be no change in magnetic flux.

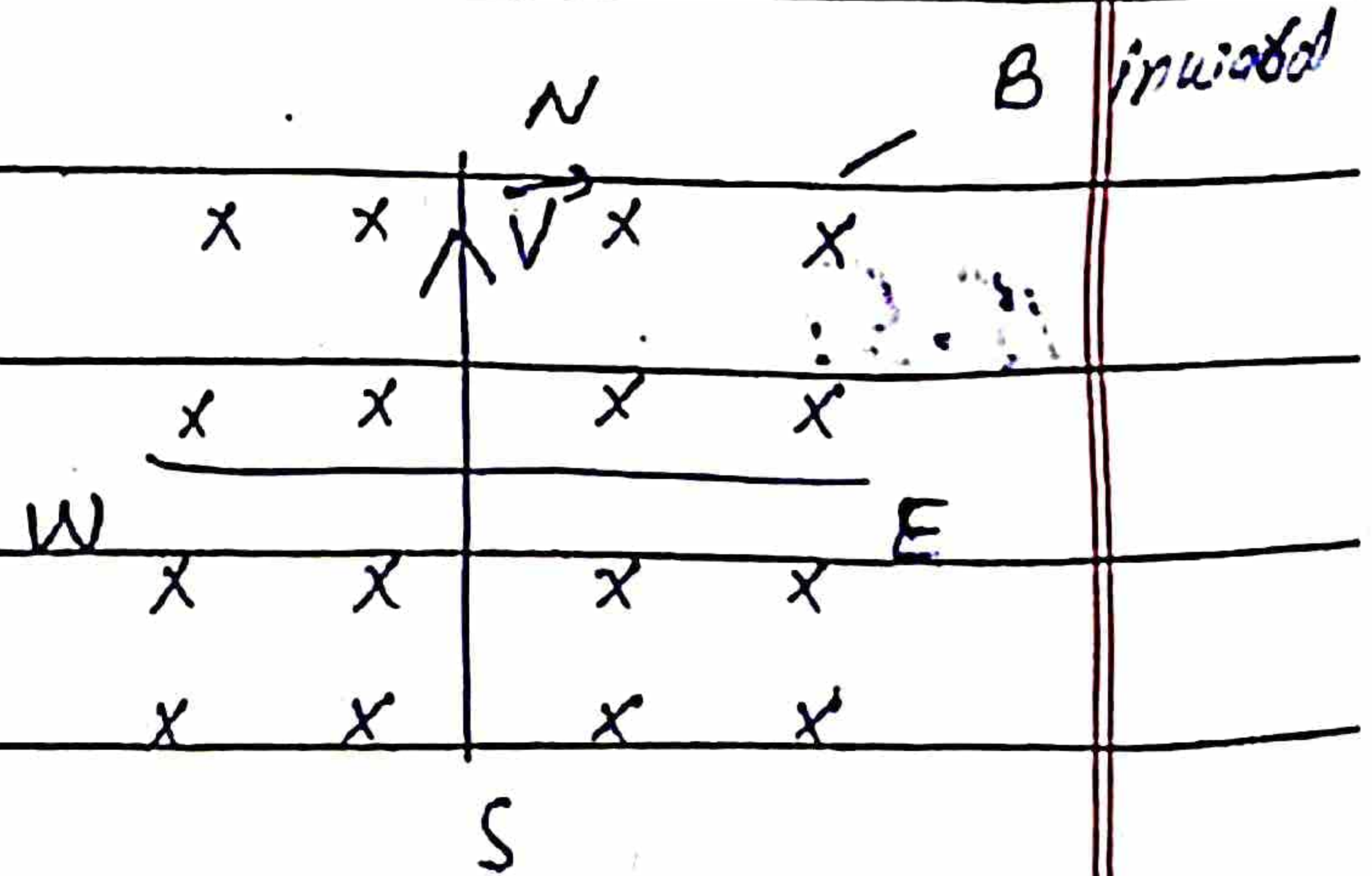
$$\mathcal{E} = -N \frac{\Delta \Phi}{\Delta t}$$

here $\Delta \Phi = 0$

so,

$$\mathcal{E} = 0$$

15.9: In a certain region the earth's magnetic field points vertically down and plane flies due



north. Then according to right hand rule west wingtip is positively charged.

$$\vec{F} = q(\vec{v} \times \vec{B})$$

curl fingers of right hand from $\vec{v}$ to $\vec{B}$ then force is acting towards ~~north~~ west.



15.10:

The unit of ϵ is Volt.

now

$$\frac{\Delta \phi}{\Delta t} = \frac{B \Delta A}{\Delta t}$$

unit

$$\frac{T m^2}{s} = \frac{N A^{-1} m^{-1} m^2}{s}$$

$$= \frac{Nm}{As} = \frac{J}{C} = \text{Volt}$$

So, ϵ and $\frac{\Delta \phi}{\Delta t}$ have same units.

15.11: Yes, when an electric motor such as an electric drill is being used, it also act as a generator. Because the coil of the motor is rotating in the magnetic field and due to changing magnetic flux, emf will be induced.

This emf is called back emf.

⇒ When The motor is just started back emf is always zero. Since a large current passes through a coil.

⇒ When The motor speed up The back emf increases and current become smaller.

⇒ If The motor is overloaded it slows down The back emf decreases The motor draw more current.

⇒ If The motor is overloaded beyond its limit The current could be so high so, it may burn out the motor.

15.12: Yes. A DC motor can be turned into a DC generator. Following changes should be done to do this:

i- The magnetic field should be made through a permanent magnet.

ii- The coil should be rotated through some external source.

15.13: Yes, it is possible to change both the area of the loop and the magnetic field passing through the loop and still not have an induced emf in the loop. It may be possible if magnetic field and area change but their product remains constant.

$$\Phi = \Delta B \Delta A$$

$$\Phi = \text{constant}$$

$$\text{Then } \Delta \Phi = 0$$

and

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

$$\text{So, } \mathcal{E} = 0$$

15.14: No, it is not possible that an electric motor be used to drive an electric generator with the output from the generator being used to operate the motor. Because it is against the law of conservation of energy.

Moreover, the output of any motor can not be equal to input, there are always some power losses due to friction.

15.15: A suspended magnet is oscillating freely in a horizontal plane. The oscillation are strongly damped when a metal plate is placed under the magnet because due to changing magnetic flux through the metal plate current is induced. This induced current, according to Lenz's law, opposes the cause that

produces it.

15.16: If four unmarked wires emerge from a transformer then first of all we will determine the primary and secondary wires with the help of Ohm-meter. Then we will measure the primary voltage V_p and secondary voltage V_s by voltmeter. Then the ratio of secondary to primary voltage will give the ratio of number of turns.

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

15.17:

(a) No, a step-up transformer can not increase the power level. It increase the emf due to greater number of turns in secondary coil. For an ideal transformer the

power remains same and practically it reduces due to power losses.

(b) In a transformer, there is no transfer of charge from primary to secondary but due to magnetic field the power is transferred.

Transformer follows the principle of mutual induction.

15.18:

(a) When the primary of a transformer is connected to AC mains the current in it is very small if the secondary circuit is open.

Because there is no output used and then input will also be very small.

(b) When The primary of the transformer is connected to AC mains the current

in it is ~~very~~ increases
when the secondary circuit
is closed. Because the
output is ^{now} being used and
the input will increase.

15.1 Data



$$\text{emf} = \mathcal{E}_1 = 0.45 \text{ V}$$

$$\text{magnetic field} = B_1 = 0.22 \text{ T}$$

$$\text{2nd magnetic field} = B_2 = ?$$

$$\text{2nd emf} = \mathcal{E}_2 = 1.5 \text{ V}$$

Solution:

$$\mathcal{E} = v B L \sin \theta$$

$$\mathcal{E}_1 = v B_1 L \sin \theta$$

$$\mathcal{E}_2 = v B_2 L \sin \theta$$

$$\frac{\mathcal{E}_1}{B_1} = v L \sin \theta$$

$$\frac{\mathcal{E}_2}{B_2} = v L \sin \theta$$

Comparing the above equations

$$\frac{\mathcal{E}_1}{B_1} = \frac{\mathcal{E}_2}{B_2}$$

$$\mathcal{E}_1 B_2 = \mathcal{E}_2 B_1$$

$$B_2 = \frac{\mathcal{E}_2 B_1}{\mathcal{E}_1} = \frac{(1.5)(0.22)}{0.45}$$

$$B_2 = 0.73 \text{ T}$$

15.2 Data

$$\text{flux density} = B = 0.5 \text{ Wb m}^{-2}$$

$$\text{induced emf} = \mathcal{E} = ?$$

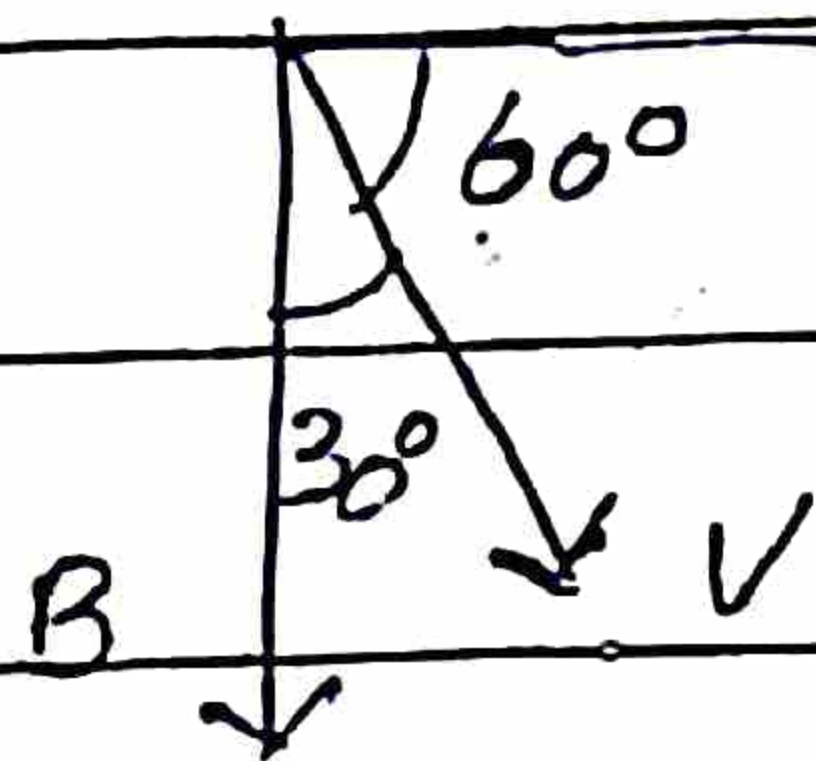
$$\text{length of wire} = L = 5 \text{ cm}$$

$$L = \frac{5}{100} \text{ m} = 0.05 \text{ m}$$

angle between

$$v \text{ and } B = 90^\circ - 60^\circ$$

$$\theta = 30^\circ$$



$$\text{speed} = v = 100 \text{ cm s}^{-1}$$

$$v = \frac{100}{100} \text{ m s}^{-1}$$

$$v = 1 \text{ m s}^{-1}$$

Solution:

$$\mathcal{E} = vBL \sin \theta$$

$$\mathcal{E} = (1)(0.5)(0.05) \sin 30^\circ$$

$$\mathcal{E} = 0.0125 \text{ V}$$

$$\mathcal{E} = 1.25 \times 10^{-2} \text{ V}$$

15.3 Data

$$\text{number of loops} = N = 10$$

$$\text{Area of loop} = A = 1.5 \times 10^{-3} \text{ m}^2$$

$$B_1 = 0.05 \text{ T}, B_2 = 0.06 \text{ T}$$

$$\text{change in magnetic field} = \Delta B$$

$$\Delta B = 0.06 - 0.05 = 0.01 \text{ T}$$

$$\text{time} = \Delta t = 0.1 \text{ s}$$

$$\text{emf} = \mathcal{E} = ?$$

Solution:

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

$$= -N \frac{\Delta B A}{\Delta t}$$

$$= - \frac{(10)(0.01)(1.5 \times 10^{-3})}{0.1}$$

$$\mathcal{E} = -1.5 \times 10^{-3} \text{ V}$$

-ve sign shows the direction of emf.

$$\boxed{\mathcal{E} = 1.5 \times 10^{-3} \text{ V}}$$

15.4 Data

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$$\text{Number of turns} = N = 15$$

$$\text{radius} = r = 2 \text{ cm} = \frac{2}{100} \text{ m}$$

$$r = 0.02 \text{ m}$$

$$\text{angle with plane of coil} = \theta' = 40^\circ$$

$$\text{angle with vector area} = \theta = 90^\circ - 40^\circ$$

$$\theta = 50^\circ$$

$$\text{magnetic field} = B_1 = 0.2 \text{ T}, B_2 = 0.5 \text{ T}$$

$$\text{change in magnetic field} = \Delta B = 0.5 - 0.2 = 0.3 \text{ T}$$

$$\text{time} = \Delta t = 0.2 \text{ s}$$

$$\text{induced emf} = \mathcal{E} = ?$$

Solution: $\mathcal{E} = N \frac{\Delta \phi}{\Delta t}$

$$\mathcal{E} = N \frac{\Delta B A \cos \theta}{\Delta t}$$

$$= N \frac{\Delta B (\pi r^2) \cos \theta}{\Delta t}$$

$$= \frac{(15)(0.3)(\pi)(0.02)^2 \cos 50^\circ}{0.2}$$

$$\mathcal{E} = 0.018 \text{ V}$$

$$\mathcal{E} = 1.8 \times 10^{-2} \text{ V}$$

15.5 Data

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$$\text{secondary emf} = \mathcal{E}_s = 0.8 \text{ V}$$

$$\text{change in current} = \frac{\Delta I_p}{\Delta t} = 200 \text{ A s}^{-1}$$

$$\text{mutual inductance} = M = ?$$

Solution: $M = \frac{\mathcal{E}_s}{\frac{\Delta I_p}{\Delta t}}$

$$M = \frac{0.8}{200} = 4 \times 10^{-3} \text{ H}$$

$$M = 4 \text{ mH}$$

15.6 Data

mutual inductance = $M = 0.75 \text{ H}$

change in current = $\Delta I = 10 - 0$

$$\Delta I = 10 \text{ A}$$

time = $\Delta t = 0.025 \text{ s}$

secondary emf = $\mathcal{E}_s = ?$

change in flux = $\Delta \Phi = ?$

number of turns of secondary = $N_s = 500$

Solution:

$$\begin{aligned}\mathcal{E}_s &= M \frac{\Delta I_p}{\Delta t} \\ &= \frac{(0.75)(10)}{0.025}\end{aligned}$$

$$\boxed{\mathcal{E}_s = 300 \text{ V}}$$

now

$$\mathcal{E}_s = N_s \frac{\Delta \Phi}{\Delta t}$$

$$\mathcal{E}_s \Delta t = N_s \Delta \Phi$$

$$\frac{\mathcal{E}_s \Delta t}{N_s} = \Delta \Phi$$

$$\Delta \Phi = \frac{(300)(0.025)}{500}$$

$$\Delta \Phi = 0.015 \text{ wb}$$

$$\Delta\phi = 1.5 \times 10^{-2} \text{ Wb}$$

15.7 Data

number of turns = $N = 250$

self inductance = $L = 2.4 \text{ mH}$

$$L = 2.4 \times 10^{-3} \text{ H}$$

magnetic flux = $\phi = ?$

current = $I = 2 \text{ A}$

induced emf = $\mathcal{E} = ?$

change in current = $\frac{\Delta I}{\Delta t} = 20 \text{ A s}^{-1}$

Solution:

$$N\phi = LI$$

$$\phi = \frac{LI}{N}$$

$$= \frac{(2.4 \times 10^{-3})(2)}{250}$$

$$\phi = 1.92 \times 10^{-5} \text{ Wb}$$

NOW

$$\mathcal{E} = L \frac{\Delta I}{\Delta t}$$

$$= (2.4 \times 10^{-3})(20)$$

$$\mathcal{E} = 0.048 \text{ V}$$

$$\mathcal{E} = 48 \times 10^{-3} \text{ V}$$

$$\mathcal{E} = 48 \text{ mV}$$

15.8 Data

length of solenoid = $l = 8 \text{ cm}$

$$l = \frac{8}{100} \text{ m} = 0.08 \text{ m}$$

$$\text{area} = A = 0.5 \text{ cm}^2 = \frac{0.5}{100 \times 100} \text{ m}^2$$

$$A = 5 \times 10^{-5} \text{ m}^2$$

number of turns = $N = 520$

self inductance = $L = ?$

current = $\Delta I = 1.5 \text{ A}$

time = $\Delta t = 0.2 \text{ s}$

induced emf = $\mathcal{E} = ?$

$$\mu_0 = 4\pi \times 10^{-7} \text{ Wb A}^{-1} \text{ m}^{-1}$$

Solution:

$$L = \mu_0 n^2 A l$$

$$L = \mu_0 \left(\frac{N}{l}\right)^2 A l$$

$$= \frac{\mu_0 N^2 A l}{l^2}$$

$$= \frac{\mu_0 N^2 A}{l}$$

$$= \frac{(4\pi \times 10^{-7}) (520)^2 (5 \times 10^{-5})}{0.08}$$

$$L = 2.12 \times 10^{-4} \text{ H}$$

$$\mathcal{E} = L \frac{\Delta I}{\Delta t}$$

$$= \frac{(2.12 \times 10^{-4})(1.5)}{0.2}$$

$$\mathcal{E} = 1.6 \times 10^{-3} \text{ V}$$



15.9 Data:

$$I_1 = 100 \text{ mA} = 100 \times 10^{-3} \text{ A} = 10^{-1} \text{ A} = 0.1 \text{ A}$$

$$I_2 = 200 \text{ mA} = 200 \times 10^{-3} \text{ A} = 0.2 \text{ A}$$

$$\text{change in current} = \Delta I = 0.2 - 0.1$$

$$\Delta I = 0.1 \text{ A}$$

$$\text{time} = \Delta t = 0.005 \text{ s}$$

$$\text{induced emf} = \mathcal{E} = 40 \text{ mV}$$

$$\mathcal{E} = 40 \times 10^{-3} \text{ V}$$

$$\text{self inductance} = L = ?$$

$$\text{increase in energy} = ?$$

Solution:

$$\mathcal{E} = L \frac{\Delta I}{\Delta t}$$

$$\mathcal{E} \Delta t = L \Delta I$$

$$\frac{\mathcal{E} \Delta t}{\Delta I} = L$$

$$L = \frac{(40 \times 10^{-3})(0.005)}{0.1}$$

$$L = 0.002 \text{ H}$$

$$= 2 \times 10^{-3} \text{ H}$$

$$L = 2 \text{ mH}$$

$$\text{increase in energy} = \frac{1}{2} L I_2^2 - \frac{1}{2} L I_1^2$$

$$= \frac{1}{2} L (I_2^2 - I_1^2)$$

$$= \frac{1}{2} (2 \times 10^{-3}) (0.2^2 - 0.1^2)$$

$$= 3 \times 10^{-5} \text{ J}$$

$$= 3 \times 10^{-2} \times 10^{-3} \text{ J}$$

$$\text{increase in } E = 0.03 \text{ mJ}$$

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15.10 Data

magnetic energy = $U_m = ?$

magnetic field strength = $B = 7 \times 10^{-5} \text{ T}$

Area = $A = 10 \times 10^8 \text{ m}^2$

$A = 10^9 \text{ m}^2$

height = $l = 750 \text{ m}$

$\mu_0 = 4\pi \times 10^{-7} \text{ wb A}^{-1} \text{ m}^{-1}$

Solution:

$$U_m = \frac{1}{2} \frac{B^2}{\mu_0} (A l)$$

$$= \frac{(7 \times 10^{-5})^2 (10^9) (750)}{2 (4\pi \times 10^{-7})}$$

$$U_m = 1.46 \times 10^9 \text{ J}$$

15.11 Data

side of square coil = $l = 18 \text{ cm}$

$$l = \frac{18}{100} \text{ m} = 0.18 \text{ m}$$

$$\text{Area} = A = (l)(l)$$

$$= (0.18)(0.18)$$

$$A = 0.0324 \text{ m}^2$$

number of turns = $N = 200$

magnetic field = $B = 0.05 \text{ T}$

peak emf = $\mathcal{E}_0 = 12 \text{ V}$

angular velocity = $\omega = ?$

Solution:

$$\mathcal{E}_0 = N\omega AB$$

$$\frac{\mathcal{E}_0}{NAB} = \omega$$

$$\omega = \frac{12}{(200)(0.0324)(0.05)}$$

$$\omega = 47 \text{ rad. s}^{-1}$$

15.12 Datanumber of turns = $N = 360$ angular velocity = $\omega = 420 \text{ rev. min}^{-1}$

$$\omega = \frac{420 \text{ rev.}}{\text{min.}} = \frac{420 \times 2\pi \text{ rad}}{60 \text{ s}}$$

$$\omega = 43.98 \text{ rad. s}^{-1}$$

~~the~~ magnetic field = $B = 0.14 \text{ T}$ peak emf = $\mathcal{E}_0 = 50 \text{ V}$ width of coil = $b = 5 \text{ cm}$

$$b = \frac{5}{100} \text{ m} = 0.05 \text{ m}$$

length of coil = $l = ?$ Solution:

$$\mathcal{E}_0 = N \omega A B$$

$$\mathcal{E}_0 = N \omega l b B$$

$$\frac{\mathcal{E}_0}{N \omega b B} = l$$

$$l = \frac{50}{(360)(43.98)(0.05)(0.14)}$$

$$l = 0.45 \text{ m}$$

$$= (0.45)(100) \text{ cm}$$

$$l = 45 \text{ cm}$$

15.13 Data

maximum emf = $\mathcal{E}_0 = 5 \text{ kV}$

$$\mathcal{E}_0 = 5000 \text{ V}$$

frequency = $f = 50 \text{ Hz}$

$$\text{Area} = A = 1 \text{ m}^2$$

number of turns = $N = 200$

magnetic field = $B = ?$

Solution:



$$\mathcal{E}_0 = N \omega A B$$

$$\mathcal{E}_0 = N (2\pi f) A B$$

$$\frac{\mathcal{E}_0}{2\pi f N A} = B$$

$$B = \frac{5000}{2\pi(50)(200)(1)}$$

$$B = 0.08 \text{ T}$$

15.14 Data

back emf = $\mathcal{E} = 120 \text{ V}$

angular velocity = $\omega = 1680 \text{ rev. per min.}$

$$\omega = \frac{1680 \text{ rev.}}{\text{min}} = \frac{1680 \times 2\pi \text{ rad}}{60 \text{ s}}$$

$$\omega = 176 \text{ rad. s}^{-1}$$

second back emf = $\mathcal{E}' = ?$

angular velocity = $\omega' = 3360 \text{ rev. per min}$

$$\omega' = \frac{3360 \text{ rev}}{\text{min}} = \frac{3360 \times 2\pi \text{ rad}}{60 \text{ s}}$$

$$\omega' = 352 \text{ rad. s}^{-1}$$

Solution: $\mathcal{E} = N\omega AB$

and

$$\mathcal{E} = N\omega AB, \quad \mathcal{E}' = N\omega' AB$$

$$\frac{\mathcal{E}}{\omega} = NAB, \quad \frac{\mathcal{E}'}{\omega'} = NAB$$

comparing both equations

$$\frac{\mathcal{E}}{\omega} = \frac{\mathcal{E}'}{\omega'}$$

$$\frac{\mathcal{E}\omega'}{\omega} = \mathcal{E}'$$

$$\mathcal{E}' = \frac{(120)(352)}{176}$$

$$\boxed{\mathcal{E}' = 240 \text{ V}}$$

15.15 Data

$$\text{voltage} = V = 240 \text{ V}$$

$$\text{resistance} = R = 0.5 \Omega$$

$$\text{current} = I = 15 \text{ A}$$

$$\text{back emf} = \mathcal{E} = ?$$

Solution:

$$\mathcal{E} = V - IR$$

$$= 240 - (15)(0.5)$$

$$\mathcal{E} = 232.5 \text{ V}$$

15.16 Data

$$\text{radius} = r = 4 \text{ cm} = \frac{4}{100} \text{ m}$$

$$r = 0.04 \text{ m}$$

$$\text{resistance} = R = 1 \text{ m}\Omega$$

$$R = 10^{-3} \Omega$$

$$\text{increase in magnetic field} = \Delta B$$

$$\Delta B = 0.4 - 0.2$$

$$\Delta B = 0.2 \text{ T}$$

$$\text{time} = \Delta t = 5 \times 10^{-3} \text{ s}$$

$$\text{current} = I = ?$$

$$\text{for copper ring} = N = 1$$

Solution:

$$\varepsilon = N \frac{\Delta \phi}{\Delta t}$$

$$= N \frac{\Delta B A}{\Delta t}$$

$$= N \frac{\Delta B (\pi r^2)}{\Delta t}$$

$$= \frac{(1)(0.2)(\pi)(0.04)^2}{5 \times 10^{-3}}$$

$$\varepsilon = 0.201 \text{ V}$$

Now

$$I = \frac{\varepsilon}{R}$$

$$= \frac{0.201}{10^{-3}}$$

$$I = 201 \text{ A}$$

15.17 Data

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number of turns = $N = 10$

area = $A = 35 \text{ cm}^2$

$$A = \frac{35}{100 \times 100} \text{ m}^2 = 35 \times 10^{-4} \text{ m}^2$$

magnetic field = $\Delta B = 0.5 \text{ T}$

time = $\Delta t = 1 \text{ s}$

induced emf = $\varepsilon = ?$

Solution:

$$\begin{aligned}
 \mathcal{E} &= N \frac{\Delta \Phi}{\Delta t} \\
 &= N \frac{\Delta B A}{\Delta t} \\
 &= \frac{(10)(0.5)(35 \times 10^{-4})}{1}
 \end{aligned}$$

$$\mathcal{E} = 0.0175 \text{ V}$$

$$\mathcal{E} = 1.75 \times 10^{-2} \text{ V}$$


15.18 Data

input voltage = $V_p = 240 \text{ V}$

output voltage = $V_s = 12 \text{ V}$

power = $P_s = 30 \text{ W}$

primary current = $I_p = ?$

transformation ratio = $\frac{N_s}{N_p} = ?$

Solution: For ideal transformer

input Power = output power

$$V_p I_p = P_s$$

$$I_p = \frac{P_s}{V_p} = \frac{30}{240}$$

M T W T F S

Date:

$$I_p = 0.125 A$$

now

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

$$= \frac{12}{240}$$

$$\frac{N_s}{N_p} = \frac{1}{20}$$