PRACTICAL CENTRE

PHYSICS

UNIT # 19

PRODUCTION OF ELECTRICITY BY MAGNETISM

2024-25

PRODUCTION OF ELECTRICITY BY MAGNETISM 19

S. No.	CONTENTS	Page#

19.1 ELECTROMAGNETIC INDUCTION:

The generation of electromotive force (emf) in a conductor due to change of magnetic flux through it is called the phenomenon of Electromagnetic Induction. The current thus produced is called the Induced current and the emf produced is called Induced emf.

Induced Electromotive Force (EMF)

An emf generated in a coil or conductor due to change of magnetic flux is called induced emf, denoted by ξ or V.

Induced electromotive force (emf) can be generated in following two primary ways:

(i) By Relative Movement (The Generator Effect)

In this way an emf is induced in a conductor when it experiences a change in magnetic flux. The generator effect also known as motional emf, occurs when there is a relative motion between a conductor and a magnetic field.

Example:

In a simple electrical generator, a coil of wire rotates within a magnetic field. This induced emf drives an electric current through an external circuit.

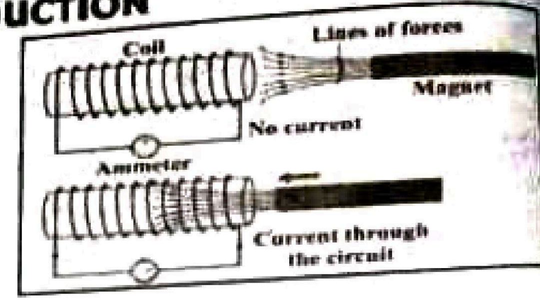
(ii) By Changing a Magnetic Field (The Transformer Effect)

In this way emf induced due to changing magnetic field around a stationary conductor.

Example:
In a transformer, an alternating current in the primary coil creates a changing magnetic field. This is the basis for how transformers transfer electrical energy between circuits at different voltages.

FARADAY'S LAWS OF ELECTROMAGNETIC INDUCTION

Faraday's Laws of electromagnetic induction is a fundamental principle in electromagnetism that describe the relationship between a changing magnetic field and the induced electromotive force (emf) or voltage in a closed circuit.



These laws are given below:

First Law:

"An emf is induced in a coil through which the magnetic flux is changing. The emf lasts so long as the change of flux is in progress and becomes zero as soon as the flux through the coil becomes constant."

Second Law:

"The electromotive force (emf) induced in a closed circuit is directly proportional to the rate of change of magnetic flux passing through the circuit." Mathematically it can written as:

Induced emf α rate of change of magnatic flux

$$\xi \alpha \frac{\Delta\phi}{\Delta t}$$

$$\xi = (\text{constant})\frac{\Delta\phi}{\Delta t}$$

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

From Lenz's law

$$\boxed{\xi = -N\frac{\Delta\phi}{\Delta t}}$$

Where N is the number of turns of coil, and the negative sign arises from lenz's law.

Factors affecting the magnitude of the induced emf:

1. **Magnetic Flux Change:** Magnitude of induced emf depends upon change of Magnetic flux.

   It becomes larger if change of flux is increases and it becomes smaller if change of magnetic flux is decreases.

2. **Numbers of turns in the Coil:** Magnitude of induced emf is directly proportional to the numbers of turns in the coil.

3. **Area of the Coil:** Magnitude of induced emf is directly proportional to the area of cross-sectional area of coil.

4. **Angle between magnetic field and Coil:** Magnitude of induced emf is minimum if magnetic field is perpendicular the coil's plane ($\theta = 90^o$) and emf is maximum if field line are parallel to the coil's plane ($\theta = 0^o$).

4. **External Factors:** Magnitude of induced emf also depends upon external factors, such as temperature, pressure, material property and other environmental condition.

LENZ'S LAW:

The direction of induced current was carefully studied by H.E.F Lenz a German scientist and the results were generalized most elegantly into a rule in 1835 called Lenz's Law. The Law states that:

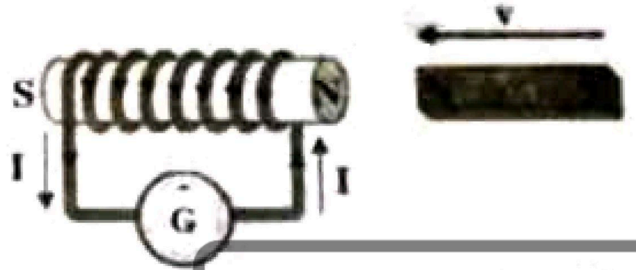
"The induced current always flows in such a direction so as to oppose the cause which gives rise to it."

OR

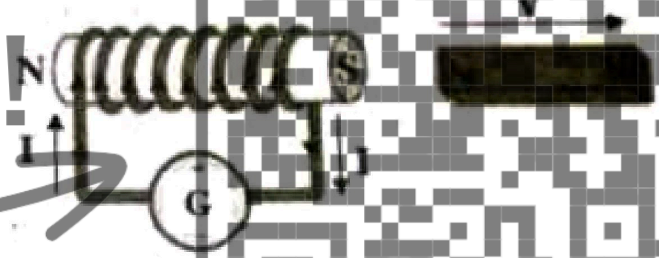
"The direction of induced emf in a circuit is always such that it opposes the cause which produces it."

For Example:

a) When the North Pole of the bar magnet is moving towards the face of the coil it becomes a North face by the induction of current in anticlockwise direction to oppose forward motion of the magnet as shown.



b) When the North Pole of the bar magnet is moving away from the face of the coil it becomes a South face by the induction of current in clockwise direction to oppose the backward motion of the magnet as shown.

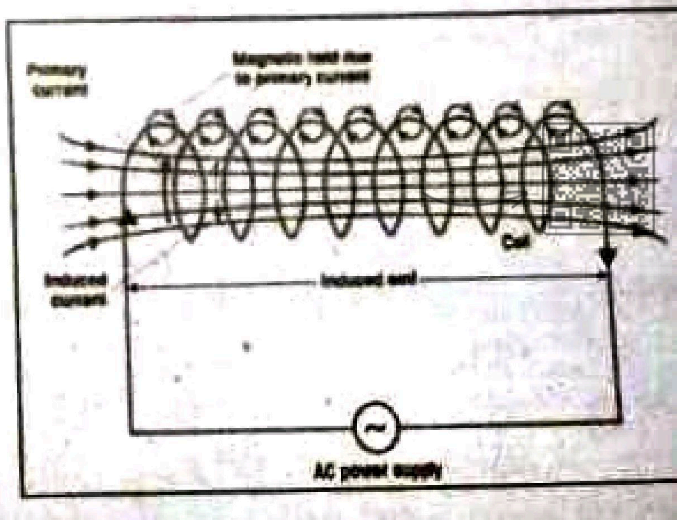


LENZ'S LAW AND ENERGY CONSERVATION:

Lenz's law is also directly related with the law of conservation of energy. When we drag the wire across the magnetic field we do work against the magnetic field arising from the interaction of the original magnetic field and that of the induced current and in doing so we impart energy to the loop. This energy is the source of induced current. The electromagnetic induction is exactly according to the law of conservation of energy.

19.2 SELF INDUCTION:

The change in the magnetic flux in a coil may be due to the relative motion of the coil and the magnetic field or due to the change of current in the coil itself. ***Phenomenon of inducing emf in the coil due to change of current in coil itself is called self Induction.***



Let us consider a coil of N turns with a battery, a galvanometer and a rheostat in its circuit. If current in the coil is changed with the help of rheostat, then the change of magnetic flux would also be felt by the coil itself, thereby inducing an emf in it.

The induced emf in the coil is

$$\xi \propto \frac{\Delta I}{\Delta t}$$

$$\xi = (\text{constant})\frac{\Delta I}{\Delta t}$$

Where this constant is called self inductance, denoted by L therefore,

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

From Lenz's Law

$$\xi = -L\frac{\Delta I}{\Delta t} \quad \text{.......................................} \quad (1)$$

According to Faraday's Law of electromagnetic induction

$$\xi = -N\frac{\Delta \varphi}{\Delta t} \quad \text{.......................................} \quad (2)$$

By equating equation (1) and (2), we get

$$-L\frac{\Delta I}{\Delta t} = -N\frac{\Delta \varphi}{\Delta t}$$

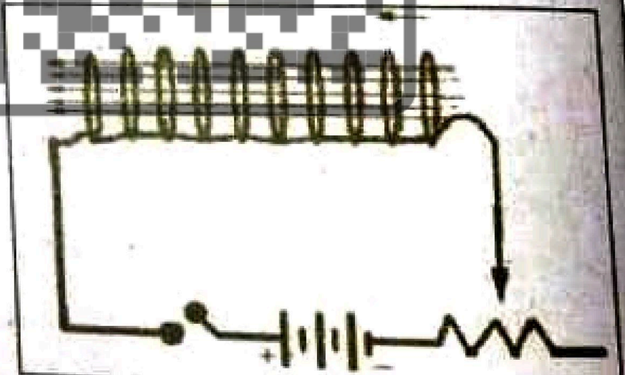
$$\boxed{L\Delta I = \Delta N\phi}$$

Where L is the constant called as self induction. The S.I. Unit of self-induction is Henry.

Energy Produced in Self Induction

An inductor stores energy in its magnetic field when it carries a direct current (DC). This energy remains stored as long as the inductor continues to carry the current. When the current in the inductor increases, the stored energy also increases; conversely, it decreases when the current is reduced.

Consider an inductor connected to a DC power source through a switch. When the switch is closed, the current in the inductor gradually rises until it reaches its maximum value, denoted as I. This changing current leads to a corresponding change in the magnetic flux within the coil, causing an induced electromotive force (emf) to establish itself in the coil. Consequently, an induced current is generated in the circuit, which works to minimize the current produced by the battery in accordance with Lenz's law.



As a result, the battery must perform work on the charges to build up the current I. This work is mathematically expressed as follows:

$W = \Delta V\, \Delta q$.........(1)

As the induced emf is produced in the inductor, we have

$\Delta V = \varepsilon_L = L\,(\Delta I/\Delta t)$,

And equation (1) can be rewritten as:

$E = L\,(\Delta I/\Delta t)\,\Delta q$

$E = (\Delta q/\Delta t)\,\Delta I$............ (2)

Since $\Delta q/\Delta t$ is average current, which is given by

$\Delta q/\Delta t = (0 + I)/2 = I/2$

Put in (2) becomes:

$$E = (1/2)\, LI^2$$

Where:

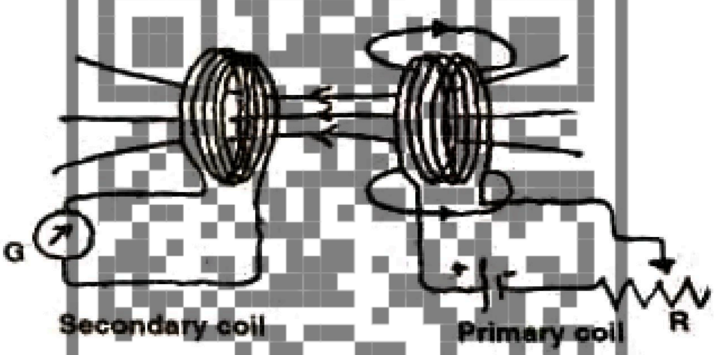
- E is the energy stored in joules (J).
- L is the self-inductance of the inductor in Henri (H).
- I is the current flowing through the inductor in amperes (A).

This formula indicates that the energy stored in an inductor is directly proportional to the square of the current passing through it and is also dependent on the inductance of the inductor itself. As the current increases, the energy stored in the inductor increases, and as the current decreases, the stored energy decreases.

19.3 MUTUAL INDUCTION:

If the two coils are placed close together, then a changing current in one coil (the primary) sets up a changing magnetic field in the other (the secondary) and so induce an e.m.f. in the second coil. This effect is known as ***mutual induction*** and can be defined ***as "The phenomenon of inducing e.m.f. in the secondary coil by changing the magnetic flux of the primary coil with the help of a varying current through it is called Mutual induction."***

Consider two coils located near each other. The coil with the battery circuit is called the primary coil and the coil joined with the galvanometer circuit is called the secondary coil. The secondary coil is within the magnetic field of the current carrying primary coil. The current in the primary coil can be changed with the help of rheostat.



If the current is changed in the primary coil, the magnetic flux through the secondary coil due to primary coil also changes. So, an e.m.f. is induced in the secondary coil.

$$\xi_S \propto -\frac{\Delta I_P}{\Delta t}$$

$$\xi_S = -\frac{M\Delta I_P}{\Delta t} \qquad \text{.......................} \qquad (1)$$

Where M is the constant of proportionality called a Mutual induction and negative sign arises due to Lenz's Law.

According to the Faraday's Law of electromagnetic induction

$$\xi_S = \frac{-N_s\Delta\phi}{\Delta t} \qquad \text{..................................} \qquad (2)$$

By equating equation (1) and (2), we get

$$\frac{-M\Delta I_P}{\Delta t} = \frac{-N_s\Delta\phi}{\Delta t}$$

$$\boxed{M\Delta I_p = N_s\Delta\phi}$$

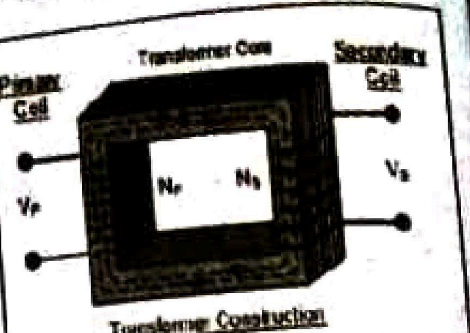
The S.I unit of self induction is Henry.

19.4 TRANSFORMER:

Transformer is the device which is used to change the voltage of an alternating current to a desired value.

PRINCIPLE:

The principle of transformer is "The Mutual Induction.", ***i.e. the rate of change of current in the primary coil induced emf in the secondary coil.***



Transformer Construction

CONSTRUCTION:

A transformer consists of two coils, one of them acts as primary coil and the other as secondary. These coils are wound on the same rectangular or circular soft iron core which is in the form of sheets and are insulated by some means.

WORKING:

A changing current in the primary coil induces an emf in the secondary coil. On supplying voltage V_p to the primary coil with N_p turns, the resulting current I causes a varying flux in the iron core according to the Faraday's Law. The magnitude of induced emf V_s in the secondary coil, having "N_s" turns is given by.

$$V_s = -\frac{N_s \Delta\phi}{\Delta t} \quad \text{.............................} \quad (1)$$

As the varying flux in the iron core induces emf in the secondary coil, it also induces emf in the primary coil. According to the Faraday's Law.

$$V_p = -\frac{N_p \Delta\varphi}{\Delta t} \quad \text{.............................} \quad (2)$$

Dividing equation ⇒(1) by equation ⇒(2)

$$\frac{V_s}{V_p} = -\frac{N_s \Delta\varphi}{\Delta t} \div -\frac{N_p \varphi}{\Delta t}$$

$$\frac{V_s}{V_p} = -\frac{N_s \Delta\varphi}{\Delta t} \times -\frac{\Delta t}{N_p \Delta\varphi}$$

$$\boxed{\frac{V_s}{V_p} = \frac{N_s}{N_p}} \quad \text{.............................} \quad (3)$$

This result shows that for a step up transformer, i.e. for $V_s > V_p$, there should be $N_s > N_p$ and for step down transformer, i.e. for $V_s < V_p$ there should be $N_s < N_p$.

From the energy conservation principle, power input in primary coil = power output from secondary coil:

$$V_p I_p = V_s I_s$$

OR

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

i.e. in step-up transformer the current at secondary coil decreases, and in step-down transformer the current in secondary coil increases. The efficiency of a transformer is given by:

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

TYPES OF TRANSFORMER:

Transformer can be classified as follows:

(i) STEP UP TRANSFORMER:

The transformer which raises the input voltage, i.e. voltage of primary coil at the output, i.e. voltage on secondary coil.

(ii) STEP DOWN TRANSFORMER:

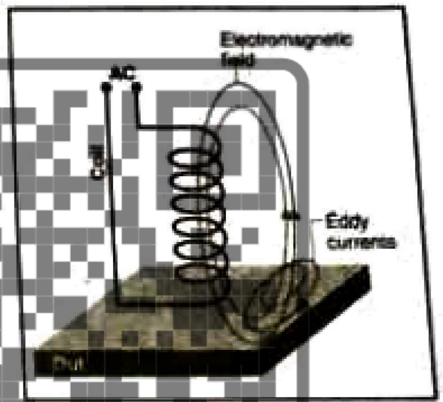
The transformer which decreases the input voltage, i.e. voltage of primary coil at the out put, i.e. voltage on secondary coil.

(iii) CENTER TAPPED TRANSFORMER (stabilizer):

The transformer which maintains the output voltage, i.e. the voltage of secondary coil at some particular desired value.

19.5 EDDY CURRENTS:

Eddy currents are circular currents generated in conductors when exposed to changing magnetic fields. They have significant magnetic and heating effects in various electromagnetic systems.



Eddy Currents Produced:

Eddy currents form according to Faraday's Law of Electromagnetic Induction. When a changing magnetic field passes through a conductor (like a metal plate or coil), the magnetic flux changes, inducing an electromotive force (emf) and generating eddy currents.

Magnetic Effects of Eddy Currents

Two key magnetic effects of eddy currents are:

1. **Counteracting Magnetic Field:**
   Eddy currents produce their own magnetic fields, opposing the original magnetic field that induced them. This counteraction reduces the net magnetic field.
2. **Magnetic Damping:**
   Intentionally induced eddy currents create magnetic resistance, opposing motion. This effect is utilized in applications like electromagnetic brakes and magnetic dampers to control and slow down movement.

Heating Effects and Reduction of Eddy Currents

Joule Heating

Eddy currents flowing through conductors encounter resistance, converting electrical energy into heat, as described by Joule's law. This heating effect can be beneficial in applications like induction heating for metal processing or cookware. However, in many electrical systems, eddy currents lead to undesirable energy loss.

Minimizing Eddy Current Losses

To reduce energy losses, laminated cores are used in transformers, electric motors, and generators. These devices are exposed to alternating magnetic fields, which induce eddy currents in solid cores, causing inefficiency.

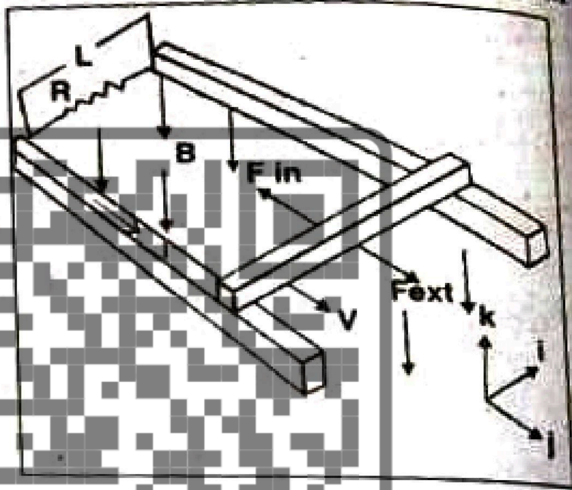
Benefits of Laminated Cores

1. **Improve Efficiency:**
   Reduce eddy current losses, minimizing energy waste as heat and enabling devices to operate more efficiently.
2. **Mitigate Vibration and Noise:**
   Decrease vibrations and noise levels by reducing eddy currents, making devices quieter and mechanically stable.
3. **Enhance Cooling and Thermal Management:**
   Lower heat generation enables more efficient cooling, leading to longer operational lifetimes and improved reliability.

19.6 MOTIONAL EMF:

If a conductor is moved in a region where magnetic flux is changing then an emf is induced in the conductor, called as Motional emf.

Consider the situation as shown in figure, where a conductor of length L is sliding with velocity v along fixed conducting rails in a region of uniform magnetic field B, which is perpendicular to the plane of the rails and the conductor. An external force pulls the bar along the rails at a constant speed v. if a positive charge q moves within the moving conductor, then it will experience a force in magnetic region in the j-direction, given by:



$$F_{mag} = qvB\,Sin\theta$$

OR

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

As the velocity of the conductor is perpendicular to the direction of magnetic lines, therefore,

$$F_{mag} = qvB \quad \text{.................................} \quad (1)$$

The external force that pulls the sliding conductor provides the work required to move the charges around the circuit through the length "l" of the conductor,

$$W = F_{mag}\, l$$

$$W = qvBl$$

As emf is the work done on the charge, given by

$$emf = \frac{work}{charge}$$

OR

$$V = \frac{qvBl}{q}$$

$$V = vBl$$

Where V is the motional emf. If the direction of velocity of conductor and magnetic lines are at angle θ with each other, then

$$\boxed{V = vBl\,Sin\theta}$$

19.7 ALTERNATING CURRENT GENERATOR:

A device which converts mechanical energy into electrical energy is called generator. A generator which produces alternating voltage and current is called A.C generator.

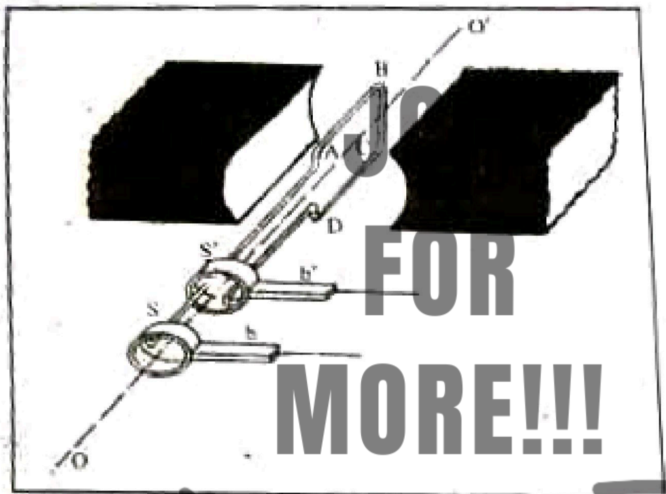
PRINCIPLE:

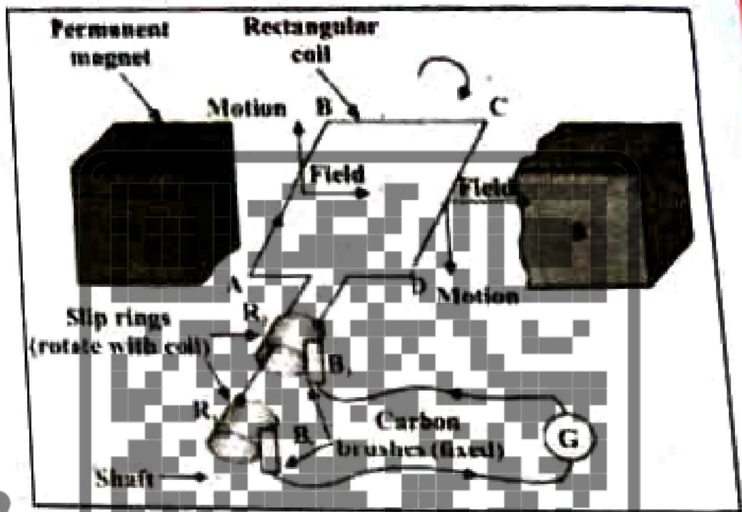
Its principle based upon Farady Law when coil rotates by any means in a magnetic field, the magnetic flux changes and induced emf is produced.

CONSTRUCTION:

The main parts of an A.C generator are

(i) **Field Magnet:**
It is a strong permanent magnet which produces a strong and uniform magnetic field between it poles. (In commercial generator electromagnet is used).





(ii) **Armature:**
A rectangular coil ABCD of N turns closely wound on a iron cylinder (core) rotates about as axis oo′ which is perpendicular to the magnetic field. The assembly (coil + cylinder) is called armature.

(iii) **Slip Rings:**
S and S′ are the two copper circular rings called slip rings which are connected to the ends of the coil the slip rings rotate with coil.

(iv) **Carbon Burshes:**
b and b′ are the two carbon brushes slide-over the slip ring (SS′) and connected the coil to the external circuit.

WORKING:

When the coil ABCD is made to rotate by any means in the magnetic field about an axis oo′ The magnetic flux through the coil changes.

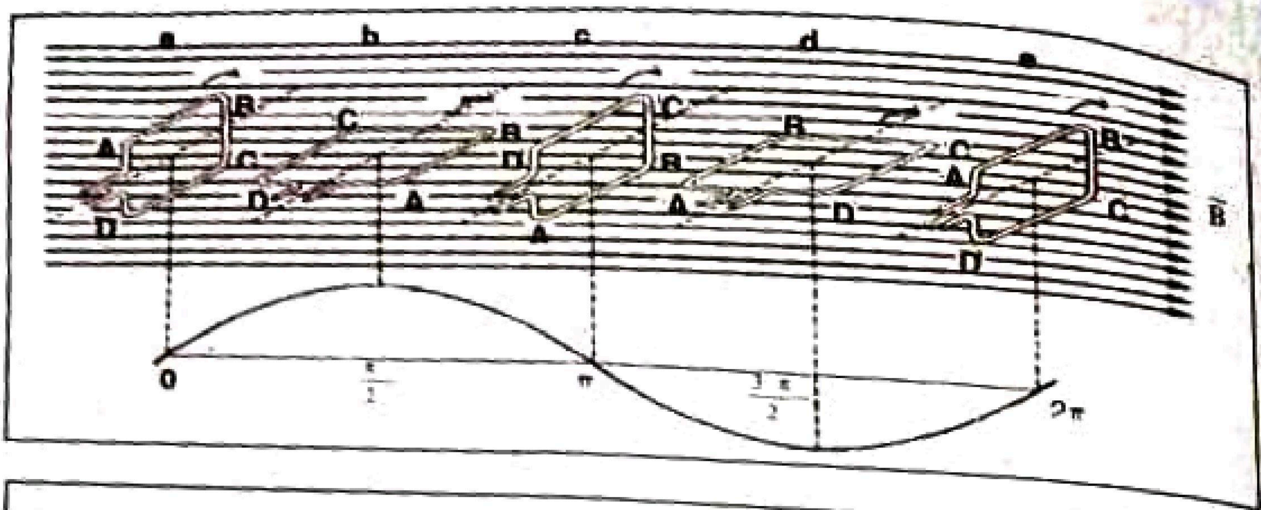
According to Faraday's Law induced current or emf is produced is it. Consider different position of the coil during one rotation as shown in the figure.

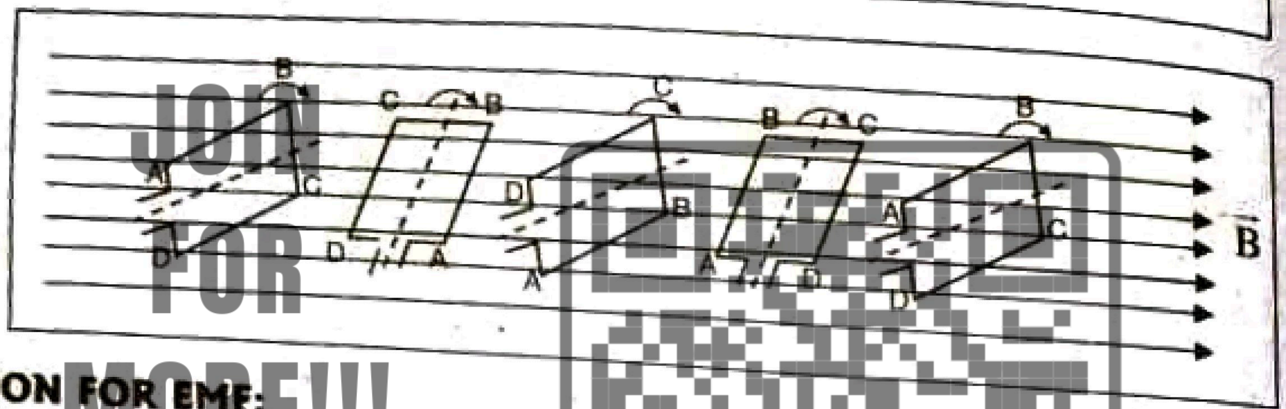
When the coil rotates from 0° to 90° the flux decreases from maximum to zero and induce current increases and becomes maximum.

During rotation from 90° to 180°, the flux increases from zero to maximum the induce current decreases from maximum to zero.

During rotation from 180° to 270°, the flux decreases from maximum to zero and induce current increases and becomes maximum but in opposite direction.

During rotation from 270° to 360°





EXPRESSION FOR EMF:

As we know that the induced e.m.f in a conductor of length "L" moving in a magnetic field of strength B with velocity v is given by:

$$V = BvL\ Sin\theta$$

During the first half rotation, which is positive

$$V_+ = BvL\ Sin\theta$$

During the second half rotation which is negative

$$V_- = -BvL\ Sin\theta$$

Total emf in one cycle is

$$V = V_+ - V_-$$

$$V = BvL\ Sin\theta - (-BvL\ Sin\theta)$$

$$V = 2BvL\ Sin\theta$$

If the coil has N turns or loops

$$V = 2BvNL\ Sin\theta \qquad \text{.............................(1)}$$

As

$$v = r\omega$$

Where 'r' here is the half of width of coil

$$r = \frac{b}{2}$$

$$\therefore \quad v = \frac{b}{2}\omega$$

equation (1) ⇒ $V = 2B\frac{b}{2}\omega NL\sin\theta$

OR $V = LbBN\omega\sin\theta$

But $Lb = A;$ (the area of coil)

$V = ABN\omega\sin\theta$

As $\theta = \omega t$

∴ $V = ABN\omega\sin\omega t$

And $\omega = 2\pi f$

∴ $V = ABN\omega\sin 2\pi ft$ .... (2)

for maximum emf putting $\sin 2\pi ft = 1$

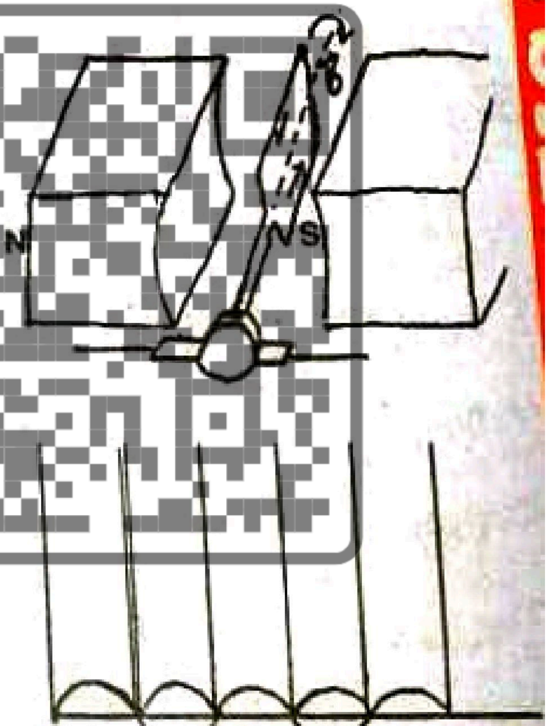
$V_{max} = ABN\omega$

Equation (2) ⇒ or $V = V_{max}\sin 2\pi ft$

$$\boxed{V = V_o\sin 2\pi ft}$$

D.C GENERATOR:

The current induced in the coil of A.C. Generator is passed to the external circuit by the two carbon brushes, pressed against copper slip rings. As the coil rotates, the emf is induced in the coil. In one rotation the vertical position of coil reverses, so the emf cycle also alters and thus the current produced is called alternating current. But if the slip rings are replaced by a simple split called commutator or split rings, the alternations in the cycle can be eliminated, because during the reversion of vertical position of coil, the two halves of the split rings exchange contact with the brushes and thus the direction of induced emf in the circuit remains unaltered.. This emf increase from zero to a maximum and then falls to zero when the coil is back to the initial vertical position. A generator modified for this function is called a D.C generator and the current so obtained is called a D.C current.

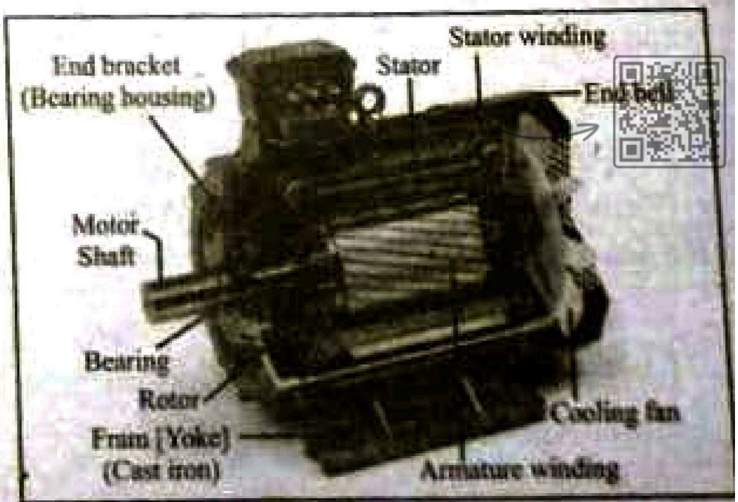


Pulsuating current

19.8 A.C MOTOR FUNDAMENTALS

AC Motor:

An AC (Alternating Current) motor converts electrical energy into mechanical energy using alternating current.



AC Motor Components and Their Functions

Although AC motors vary in design, their primary components share consistent features. The main components and their roles are:

1. **Stator:**
   Stationary part
   Contains primary windings
   Produces rotating magnetic field
2. **Rotor:**
   Rotating part
   Interacts with stator's magnetic field
   Experience torque, causing rotation
3. **Bearings:**
   Support rotor
   Reduce friction
   Enable smooth operation
4. **Shaft:**
   Connected to rotor
   Transfer mechanical energy
   Performs useful work
5. **Cooling System:**
   Dissipates heat
   Prevents overheating
   Prolongs motor lifespan

These components work together to enable the AC motor's operation.

AC Motor Operation

- AC voltage applied to stator windings creates rotating magnetic field
- Rotor rotates due to torque
- Mechanical work performed

AC Motor Performance

- Depends on design, quality, load, and operating conditions
- Proper maintenance and control optimize performance

Production of Back EMF

Back EMF is produced through electromagnetic induction, following Faraday's Law:

1. **Rotating Magnetic Field:**
   When an AC motor rotates, its magnetic field rotates with it.
2. **Changing Magnetic Flux:**
   The rotating magnetic field creates a changing magnetic flux through the motor's windings.
3. **Induced Voltage:**
   According to Faraday's Law, the changing magnetic flux induces a voltage in the windings.
4. **Direction:**
   The induced voltage opposes the original applied voltage (Lenz's Law).
5. **Back EMF:**
   This induced voltage is known as Back EMF.

Factors Affecting Back EMF

1. **Speed**: Back EMF increases with motor speed.
2. **Magnetic Field Strength**: Stronger magnetic fields produce higher Back EMF.
3. **Number of Turns**: More turns in the winding increase Back EMF.

Effects of Back EMF

1. **Reduces Current**: Back EMF opposes applied voltage, reducing current flow.
2. **Increases Efficiency**: By reducing current, Back EMF helps minimize energy losses.
3. **Motor Speed Regulation**: Back EMF helps regulate motor speed.

Current Regulation through Back EMF

Back EMF plays a vital role in motor operation by regulating current flow.

How it Works

1. As motor speed increases, back EMF also increases.
2. Higher back EMF reduces net voltage across motor windings.
3. Decreased net voltage leads to decreased current flow.

Benefits

1. Prevents excessive current draw.
2. Avoids overheating.
3. Protects motor from potential damage.

Motor Speed Regulation

Back EMF and motor speed have an direct relationship.

1. Higher speed → Higher back EMF → Reduced current.
2. Lower speed or increased load → Lower back EMF → Increased current.

Consequence

The dynamic interplay between back EMF and motor speed;

1. Maintains consistent speed.
2. Provides necessary torque to overcome loads.