ELECTROMAGNETIC INDUCTION AND
ALTERNATING CURRENT

Abstract

This Unit carries 08 marks, and is divided into two chapters ELECTROMAGNETIC INDUCTION and ALTERNATING CURRENTS both are equally important, marks wise.

INTRODUCTION: Electricity and magnetism are related, we had seen in the last chapter that moving charges (electric current) produces magnetic field, in this chapter we see the converse i.e. how magnetic field can be made to produce electric current.

Magnetic Flux $\phi_B$: The magnetic flux linked with a surface held in a magnetic field is defined as the number of magnetic field lines crossing the surface normally and is measured as the product of the component of the magnetic field normal to the surface ($B \cos \theta$) and the surface area ($A$). Magnetic flux through a plane of area $A$ placed in a uniform magnetic field ($B$) (Fig 1) can expressed as

$$\phi_B = \vec{B}.\vec{A} = BA \cos \theta$$ (1)

where $\theta$ is the angle between $\vec{B}$ and $\vec{A}$.

Figure 1: magnetic flux definition

If the magnetic field has different magnitudes and directions at various parts of a surface as shown in Fig 2., then the magnetic flux through the surface is given by

Figure 2: Flux when $\vec{B}$ varies in magnitude and direction at different parts of the surface
\[
\phi_B = \vec{B}_1 \cdot \Delta \vec{A}_1 + \vec{B}_2 \cdot \Delta \vec{A}_2 + \vec{B}_3 \cdot \Delta \vec{A}_3 \ldots \vec{B}_i \cdot \Delta \vec{A}_i = \sum_{all} \vec{B}_i \cdot \Delta \vec{A}_i
\]  \hspace{1cm} (2)

where \textit{all} stands for summation over all the area elements \(\Delta \vec{A}_i\) comprising the surface and \(\vec{B}_i\) is the magnetic field at the area element \(\Delta \vec{A}_i\). If we consider the area elements to be infinitesimally small then the flux can be written in the integral form as:

\[
\phi_B = \oint \vec{B} \cdot d\vec{A} = \oint B \, dA \cos \theta
\]  \hspace{1cm} (3)

**UNITS OF FLUX**

Flux is a scalar quantity and the SI unit of magnetic flux is \textit{weber (Wb)} or \textit{tesla meter squared (Tm}^2\).**

**FARADAY’S EXPERIMENTS:**

**EXPERIMENT 1:**

- When a bar magnet is pushed toward \(s\) a coil, the pointer in the galvanometer G deflects as shown in fig 3.

![Diagram](image)

Figure 3: \textit{An emf is induced in the coil when a magnet is pushed toward s the coil}

The following were observed from the experiment:-

1. The pointer in the galvanometer deflects, indicating the presence of electric current in the coil.
2. The deflection lasts as long as the bar magnet is in motion. The galvanometer does not show any deflection when the magnet is held stationary.
3. When the magnet is pulled away from the coil, the galvanometer shows deflection in the opposite direction, which indicates reversal of the currents direction.
4. When the South-pole of the bar magnet is moved toward \(s\) or away from the coil, the deflections in the galvanometer are opposite to that observed with the North-pole for similar movements.
5. The deflection (and hence current) is found to be larger when the magnet is pushed toward \(s\) or pulled away from the coil faster.
6. All the above observations were true even if the magnet is held stationary and the coil was moved, this shows that it is the relative motion between the magnet and the coil that is responsible for generation (induction) of electric current in the coil.

**EXPERIMENT 2**
If two coils (with one connected to a battery and the other to a galvanometer) are moved relative to each other then the galvanometer shows deflection as shown in fig 4. It is the relative motion between the coils that induces the electric current.

EXPERIMENT 3

![Figure 4: the coil on the right behaves like a magnet(solenoid)](image)

Fig 5 shows two coils $C_1$ and $C_2$ both held stationary. Coil $C_1$ is connected to a galvanometer G while the second coil $C_2$ is connected to a battery through a tapping key K. The following were observed from the experiment

![Figure 5: The process of switching on and off induces current in the coil $C_1$](image)

1. The galvanometer shows a momentary deflection when the tapping key K is pressed, the pointer in the galvanometer returns to zero immediately.
2. After the initial deflection even if the key is held pressed continuously, there is no deflection in the galvanometer.
3. When the key is released, a momentary deflection is observed again, but in the opposite direction.
4. It is also observed that the deflection increases dramatically when an iron rod is inserted into the coils along their axis.
THE SERIES OF EXPERIMENTS CARRIED OUT BY FARADAY, CAN BE EXPLAINED USING FARADAY’S LAWS.

FARADAY’S LAW OF INDUCTION

Faraday’s Law of electromagnetic Induction states that:- The magnitude of the induced emf in a circuit is equal to the time rate of change of magnetic flux through the circuit. Mathematically, the induced emf is given by

\[ E = -\frac{d\phi_B}{dt} \]  

(4)

The negative sign indicates the direction of current in a closed loop. (This will be discussed in detail using conservation of energy later.) In the case of a closely wound coil of N turns, change of flux associated with each turn, is the same. Therefore, the expression for the total induced emf is given by

\[ E = -N\frac{d\phi_B}{dt} \]  

(5)

EXPLANATION FOR FARADAY’S EXPERIMENT USING FARADAY’S LAWS

Flux is given by \[ \phi_B = BA \cos \theta \] Changing \( B, A, \text{or } \theta \) can change the flux which will induce an emf. This is the basic concept of Faraday’s law using this Faraday’s experiments can be explained.

Explanation for EXPERIMENT 1 and 2

The motion of a magnet toward s or away from coil \( C_1 \) in Experiment 1 and moving a current-carrying coil \( C_2 \) toward s or away from coil \( C_1 \) in Experiment 2, change the magnetic flux associated with coil \( C_1 \) this is because \( B \) changes with distance \( B \) is more when the magnet / coil is closer and less when away. The change in magnetic flux induces emf in coil \( C_1 \). It was this induced emf which caused electric current to flow in coil \( C_1 \) and through the galvanometer.

Explanation for EXPERIMENT 3

When the tapping key K is pressed, the current in coil \( C_2 \) (and the resulting magnetic field) rises from zero to a maximum value in a short time. Consequently, the magnetic flux through the neighboring coil \( C_1 \) also increases. It is the change in magnetic flux through coil \( C_1 \) that produces an induced emf in coil \( C_1 \). When the key is held pressed, current in coil \( C_2 \) is constant (hence \( d\phi_B/dt = 0 \)). Therefore, there is no change in the magnetic flux through coil \( C_1 \) and the induced current in coil \( C_1 \) drops to zero. When the key is released, the current in \( C_2 \) and the resulting magnetic field decreases from the maximum value to zero in a short time. This results in a decrease in magnetic flux through coil \( C_1 \) and hence again induces an electric current in coil \( C_1 \).

LENZ’S LAW:

The polarity of induced emf is such that it tends to produce a current which opposes the change in magnetic flux that produced it. The negative sign shown Faraday’s Law (Equan. (4)) represents this effect.

LENZ’S LAW AND CONSERVATION OF ENERGY (Explanation for the negative sign in Faraday’s law)

Lenz’s law is a consequence of the law of conservation of energy (i.e., energy can neither be created or destroyed but can only be transferred from one form to another). For example when the north pole or the south pole of a magnet is pushed or pulled toward s or away from a coil an emf is induced in the coil this induced emf will produce a magnetic field which will oppose the motion of the magnet that is to induce an emf in the coil work has to be done against the force exerted by the magnetic field created by the induced emf (in the coil) against the magnet. Thus mechanical work has to be done to produce electrical energy (i.e., electrical energy is not created but transformed from mechanical energy).

Application of LENZ’S LAW

We can understand Lenz’s law by examining the following examples

(i) NORTH POLE OF MAGNET IS MOVED TOWARDS A CONDUCTING LOOP
In the figure below (fig. 6) the North-pole of a bar magnet is being pushed toward s the closed coil. As the North-pole of the bar magnet moves toward s the coil, the magnetic flux through the coil increases. Hence current is induced in the coil in such a direction that it opposes the increase in flux (Lenz’s Law). This induced current produces its own magnetic field with the magnetic field oriented in such a direction as to oppose the motion of the magnet, this can happen only if the face of the loop facing North pole of the magnet behaves like the north pole (so that north pole north pole repel). The current carrying loop which is the equivalent of of a magnetic dipole behaves as the north pole only if the current flows anti-clock wise.

Figure 6: Direction of current in the current loop using Lenz’s law

(ii) NORTH POLE OF MAGNET MOVES AWAY FROM A CONDUCTING LOOP

If the North pole of the magnet is being withdrawn from the coil (fig 6), the magnetic flux through the coil will decrease, hence an emf is induced. To counter this decrease in magnetic flux, the induced current in the coil flows in clockwise direction and its South pole faces the receding North-pole of the bar magnet. This would result in an attractive force which opposes the motion of the magnet and the corresponding decrease in flux.

Figure 7: the loop with current flowing clockwise

(iii) INDUCTION IN COILS

Consider two coils kept near each other as shown in figure 8. When the switch (key) in coil \( C_2 \) is switched on or off there is a momentary deflection in the galvanometer (after the switch is closed or after the switch is opened there is no deflection-the deflection or the flow of current in the coil exists only during the process of switching on or off.) When the current is switched on in \( C_2 \) the current in \( C_2 \) grows there by the magnetic field in \( C_2 \) grows. The induced current in \( C_1 \) will be in such a direction as to reduce the growth of the magnetic field in \( C_2 \) i.e to oppose the magnetic field of \( C_2 \). The field due to \( C_1 \) and \( C_2 \) are oppositely directed so as to reduce the growth of the magnetic field during switching.

When the current in the coil \( C_2 \) is switched off the current decays and hence the magnetic field also decays, the induced current in \( C_1 \) will be in such a way as to oppose the decay.
MOTIONAL ELECTROMOTIVE FORCE
Consider a straight conductor moving in a uniform magnetic field, shown in Figure 10. A rectangular conductor PQRS in which the conductor PQ is free to move. The rod PQ is moved toward the left with a constant velocity v as shown in the figure. Assume that there is no loss of energy due to friction. PQRS forms a closed circuit enclosing an area that changes as PQ moves. It is placed in a uniform magnetic field B which is perpendicular to the plane of this system. If the length RQ = x and RS = l, the magnetic flux \( \phi_B \) enclosed by the loop PQRS is given by:

\[
\phi_B = B A \cos \theta
\]

\[
\theta = 0
\]
\[ A = lx \]
\[ \therefore \phi_B = BA = Blx \]

Since \( x \) is changing with time, the rate of change of flux \( \phi_B \) will induce an emf given by using Faraday's Law:

\[ E = -\frac{d\phi_B}{dt} = -Blx \frac{dx}{dt} \]
\[ E = -Blx \frac{dx}{dt} = Blv \] \( \text{(6)} \)

where \( \frac{dx}{dt} = -v \) which is the speed of the conductor PQ. The induced emf \( Blv \) is called **motional emf**. The induced emf is produced by moving a conductor instead of varying the magnetic field.

**MOTIONAL EMF IN TERMS OF LORENTZ FORCE**

Consider any arbitrary charge \( q \) in the conductor PQ. When the rod moves with speed \( v \), the charge will also be moving with speed \( v \) in the magnetic field \( B \). The **Lorentz force** on this charge is \( qvB \) in magnitude, and its direction is toward the point Q. All charges experience the same force, in magnitude and direction, irrespective of their position in the rod PQ.

The work done in moving the charge from P to Q is,

\[ W = qvBl \]

Since emf is the work done per unit charge,

\[ E = \frac{W}{q} \]

hence

\[ E = Blv \] \( \text{(7)} \)

**Direction of MOTIONAL EMF-FLEMINGS RIGHT HAND RULE (optional)**

The Flemings **Right hand rule** gives the direction of the induced current in the case of motional emf.

*If we stretch our first finger, central finger and thumb of our right hand in a mutually perpendicular directions such that the first finger points along the direction of the magnetic field, the thumb along the direction of motion of the conductor, then the central finger would give the direction of the induced current.*
EMF INDUCED WHEN THE MAGNETIC FIELD IS CHANGING-USING LORENTZ FORCE

An emf is induced when a conductor is stationary and the magnetic field is changing (a fact which Faraday verified by numerous experiments.) In the case of a stationary conductor, the force on its charges is given by the Lorentz equation:

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

since $v = 0$ (the conductor is stationary)$\vec{F} = q\vec{E}$ Thus, any force on the charge arises from the electric field term E alone. In this case The cause of induced emf or induced current, is that a time-varying magnetic field generates an electric field. A bar magnet in motion (or more generally, a changing magnetic field) can exert a force on the stationary charge. This is the fundamental significance of the Faradays discovery. Electricity and magnetism are related.

ENERGY IN MOTIONAL EMF

Let r be the resistance of movable arm PQ of the rectangular conductor shown in Fig. 10. We assume that the remaining arms QR, RS and SP have negligible resistances compared to r. The current I in the loop is given by

$$I = \frac{E}{r} = \frac{Blv}{r} \quad (8)$$

Where $E$ is the motional emf.

Due to the presence of the magnetic field there will be a force on the current carrying conductor given by:-

$$F = BIl$$

using equan (8) in the above equation we get

$$F = \frac{B^2l^2v}{r} \quad (9)$$

This force arises due to drift velocity of charges (responsible for current) along the rod. The arm PQ is being pushed with a constant speed v, the power required to do this is,

$$P = Fv$$

Using equan (9)

$$P = \frac{B^2l^2v^2}{r}$$

This energy, which is mechanical is dissipated in the form of Joule heat

$$P_j = I^2r$$

substituting equan. (8) we get

$$P_j = \frac{B^2l^2v^2}{r}$$

Which proves that mechanical energy is converted to heat energy (conservation of energy)

EMF INDUCED DUE TO THE ROTATION OF A CONDUCTING ROD IN A MAGNETIC FIELD

Consider a metallic rod of length $l$ is rotated with an angular frequency of $\omega$, with one end hinged at the centre and the other end at the circumference of a circular metallic ring of radius $l$, about an axis passing through the centre and perpendicular to the plane of the ring (Fig. 12). A constant and uniform magnetic field B parallel to the axis is present everywhere, then the emf induce across the can be calculated as follows:-
Let P and Q be two points on the circular ring let \( \theta \) be the angle between the radius and the rod at the point Q as the rod rotates \( \theta \) changes with time hence \( \theta \) is a function of time. As the rod moves there is a change in area swept by the rod, and hence the flux changes and as per Faraday’s law there is an induced emf hence the magnitude induced emf \( E \) is given by

\[
E = \frac{d\Phi_B}{dt} = B \frac{dA}{dt} \quad \text{(10)}
\]

where \( A \) is the area of the sector OPQ. Area of the sector OPQ \( A \) is given by

\[
A = \pi r^2 \frac{\theta(t)}{2\pi} = \frac{1}{2} r^2 \theta(t)
\]

Substituting for \( A \) in equan. (10) and differentiating we get

\[
E = B \frac{d}{dt} \left( \frac{1}{2} r^2 \theta(t) \right) = \frac{1}{2} Bl^2 \frac{d\theta(t)}{dt} \quad \text{but}
\]

\[
\frac{d\theta(t)}{dt} = \omega
\]

\[
\therefore E = Bl^2 \omega
\]

**METHOD II (using the concept of motional emf)**

Consider a small element of length \( dr \) in the rod then the *emf* induced in the element \( dE \) is given by (using \( E = Blv \))

\[
dE = Bdrv
\]

\[
v = r\omega
\]

Hence

\[
dE = B\omega rdr
\]

Integrating between the limits 0 to 1 we get

\[
E = \frac{Bl^2 \omega}{2}
\]
EDDY CURRENTS

Eddy currents are induced currents produced when bulk pieces of conductors are subjected to changing magnetic flux. These eddy currents are in the form of eddies or whirlpools. The direction in which these eddy currents whirl are given by Lenz’s law.

Examples of eddy currents

When a solid metal plate is swung between the poles of a strong magnet eddy currents are induced in the plate. These eddy currents produce the following effects:

- the motion is damped and in a little while the plate comes to a halt in the magnetic field.
- Directions of eddy currents are opposite when the plate swings into the region between the poles and when it swings out of the region.

Ways to reduce eddy current damping

Eddy currents can be reduced by cutting slots in the plate as shown below.

Reasons:- As magnetic moments ($\vec{m} = I\vec{A}$) of the induced currents (which oppose the motion) depend upon the area enclosed by the eddy cutting slots reduces the area hence the plate moves more freely thereby reducing damping.

Ways of Minimising EDDY currents

Eddy currents are undesirable in some cases since they dissipate electrical energy in the form of heat. Eddy currents are minimised by:-

- By punching holes or having slots the effect of eddy currents can be reduced
- By making the cores of electrical machinery (like the transformer) with thin sheets of laminated metal

Applications of Eddy currents

1. Electromagnetic brakes in trains
2. Speedometers

Figure 13: Eddy currents are generated in the copper plate, while entering and leaving the region of magnetic field.
3. Induction Furnace

4. Medical application like diathermy

**INDUCTANCE**

**Self Inductance:** is the property by virtue of which a change in current $I$ in a coil of $n$ turns causes a change magnetic field produced by the coil $(\text{remember } B = \mu_0 n I)$, and hence a change in flux through the coil, this induces an emf in the coil in a direction which opposes the growth or decay of the current $I$.

**Co-efficient of self inductance L**

Consider a coil (a Long solenoid) carrying a current $I$ and having $N$ turns, then the flux through the coil is given by

$$\phi_B = NBA$$

as the geometry of the coil is constant we can say that

$$\phi_B \propto B$$

We know that

$$B \propto I$$

$$\therefore B = \mu_0 n I$$

this implies that

$$\phi_B \propto I$$

or

$$\phi_B = LI \quad (11)$$

Here $L$ is called the co-efficient of self inductance. $L$ depends on the

1. The no of turns $N$
2. The geometry (shape, area etc) of the coil
3. The material of the core on which the coil is wound
4. The self inductance of a coil is similar to inertia in mechanics just as mass(inertia) of a body tends to oppose the force which tries to change the state of rest or motion, the self inductance offers opposition to the change in current(time varying) in the coil. In mechanics more the mass more the opposition to change, more the inductance more opposition to current.

**Unit of Coefficient of Self Inductance $L$**

Inductance is a scalar quantity. It has the dimensions of $[ML^2T^{-2}A^{-2}]$ (the dimensions are got from the equation $L = \frac{\phi B}{I}$-check it out). The SI unit of self inductance is Henry (H) other units are

$$L = \frac{\phi B}{I} = \frac{Tm^2}{A} \equiv \text{Webber} A^{-1}$$

**INDUCED EMF IN A COIL**

When the current is varied, the flux linked with the coil also changes and an emf is induced in the coil. From Faraday’s law we know that

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

but

$$\phi_B = LI$$

∴ $$E = -L \frac{dI}{dt}$$  \hspace{1cm} (12)

where $L$ is the self inductance of the coil.

**COEFFICIENT OF SELF INDUCTANCE($L$) OF A LONG SOLENOID(coil)**

Consider a coil of length $l$, area of cross section $A$ and having $n$ turns/unit length, if a current $I$ is passed through the solenoid, the magnetic field inside it is given by:-

$$B = \mu_o n I$$

Magnetic flux through each turn of the coil = $B \times$ Area of each turn = $\mu_o n IA$ Total magnetic flux linked with all turns $\phi = \mu_o n I A N$ Where $N$ is the total no of turns

$$N = nl$$

∴ $$\phi = \mu_o I An^2 l$$

using equan. (11) for $\phi$ we get

$$LI = \mu_o I An^2 l$$

∴ $$L = \mu_o An^2 l$$

If the core of the solenoid is having a material with permeability $\mu$ then

$$L = \mu An^2 l = \mu_0 \mu_r An^2 l \hspace{1cm} (\because \mu = \mu_0 \mu_r)$$

**SELF INDUCED EMF/BACK EMF:** When a time varying current($I$) flows in a coil it induces an emf in itself, the current due to this emf($I_L$) has direction which tends to oppose the time varying current($I$). This emf is called the **back emf or self induced emf**.

**ENERGY STORED IN AN INDUCTANCE**

Self induced emf or the back emf as opposes any change in the current in a circuit. (remember self-inductance $L$ plays the role of inertia.) So, work needs to be done against the back emf ($E$) in establishing the current. This work done is stored as magnetic potential energy.

Power or rate of doing work is given by

$$\frac{dW}{dt} = |E|I$$  \hspace{1cm} (13)
from equan.(12) we know that 

$$|E| = L \frac{dI}{dt}$$

substituting for E in equan. (13) we get 

$$\frac{dW}{dt} = LI \frac{dI}{dt}$$

Total amount of work done in establishing the current I is 

$$\int dW = W = \int_0^1 LI dI = \frac{1}{2} LI^2$$

MUTUAL INDUCTANCE

The phenomenon according to which an opposing emf is induced in one coil due to the change in current(and hence the magnetic flux) in the neighboring coil is called mutual Induction.

Co-efficient of MUTUAL INDUCTANCE M

If there are two coils P and Q (near each other) and if current I flows in one say P then the flux $\phi$ linked to S due to the current in P is directly proportional to I or

$$\phi \propto I$$

$$\phi = MI$$

Where M is the co-efficient of mutual inductance. note: Unit and dimensions of mutual Inductance is the same as self inductance

Figure 15: Two co axial solenoids

RELATION BETWEEN MUTUAL INDUCTANCES OF 2 COILS ($M_{12} = M_{21}$)

Consider two long co-axial solenoids(fig.15) each of length l. The radius of the inner solenoid $S_1$ is $r_1$ and the number of turns per unit length is $n_1$. The corresponding quantities for the outer solenoid $S_2$ are $r_2$ and $n_2$, respectively. Let $N_1$ and $N_2$ be the total number of turns of coils $S_1$ and $S_2$, respectively. When a current $I_2$ is set up through $S_2$, it in turn sets up a magnetic flux $\phi_1$ through $S_1$. The corresponding flux linkage with solenoid $S_1$ is

$$N_1\phi_1 = M_{12}I_2$$

(16)
$M_{12}$ is the constant of proportionality and is called the mutual inductance of coil $S_1$ w.r.t $S_2$. 

NOTE: Remember if there is 1 turn flux is $\phi$ if there are N turns then it is $N\phi$

The induced emf in $S_1$ due to a time varying current $I_2$ flow in $S_2$ is given by using the Faraday’s law ($E = -\frac{d\phi}{dt}$) 

$$E_1 = -N_1 \frac{d\phi_1}{dt} = -M_{12} \frac{dI_2}{dt} \quad (\because \phi_1 = M_{12}I_2/N_1)$$

(refer equan.(16))

Calculation of mutual Inductance

Magnetic field due to current $I_2$ in $S_2 = B_2 = \mu_o n_2 I_2$

Flux through $S_1$ due to current $I_2$ in $S_2$ is given by

$$\phi_1 = N_1 B_2 \times \text{area of } S_1$$

$$\phi_1 = N_1 B_2 A = N_1 \mu_o n_2 I_2 \pi r_1^2$$

AS $N_1 = n_1 l$

$$\phi_1 = n_1 l \mu_o n_2 I_2 \pi r_1^2$$

$$M_{12} = \frac{\phi_1}{I_2} = \mu_o n_1 n_2 \pi r_1^2 l$$

(17)

Consider the reverse case. A current $I_1$ is passed through the solenoid $S_1$ and the flux linkage with coil $S_2$ is,

$$N_2 \phi_2 = M_{21} I_1$$

(18)

$M_{21}$ is called the mutual inductance of solenoid $S_2$ with respect to solenoid $S_1$.

The flux due to the current $I_1$ in $S_1$ can be assumed to be confined solely inside $S_1$ there are no magnetic fields outside $S_1$ since the solenoids are very long. The flux linked with $S_2$ due to current in $S_1$ is given by:-

$$\phi_2 = N_2 B_1 \times \text{Area of } S_1$$

NOTE: the key thing to note is why the area os $S_1$ is used instead of $S_2$-check it out!

$$B_1 = \mu_o n_1 I_1$$

$$\therefore \phi_2 = N_2 \mu_o n_1 I_1 \pi r_1^2$$

but $N_2 = n_2 l$

$$\therefore \phi_2 = n_2 l \mu_o n_1 I_1 \pi r_1^2$$

$$M_{21} = \frac{\phi_2}{I_1} = \mu_o n_1 n_2 \pi r_1^2 l$$

(19)

Comparing equan.(17) and equan. (19) we find that

$$M_{12} = M_{21}$$

The following points are key

- Mutual inductance is between two (or more) coils
- Mutual inductance depends on the geometry of the coils
- Mutual Inductance depends on the magnetic properties of the material used as the core of the coil.
AC GENERATOR

PRINCIPLE: An AC generator converts mechanical energy into electrical energy. The AC generator works on the principle **Faraday's law**. The change in flux is produced by changing the effective area \((A \cos \theta)\) of a coil exposed to the magnetic field by rotating the coil in a magnetic field, thus changing \(\theta\), hence the flux \((\phi_B = AB \cos \theta)\).

CONSTRUCTION: An AC generator as shown in Fig.16. It consists of a coil mounted on a rotor shaft. The axis of rotation of the coil is perpendicular to the direction of the magnetic field. The coil (called armature) is mechanically rotated in the uniform magnetic field by some external means (say a Diesel engine). The rotation of the coil causes the magnetic flux through it to change, so an emf is induced in the coil. The ends of the coil are connected to an external circuit by means of **slip rings** and brushes to the load.

WORKING: When the coil is rotated with a constant angular speed \(\omega\), the angle \(\theta\) between the magnetic field vector \(B\) and the area vector \(A\) of the coil at any instant \(t\) is \(\theta = \omega t\) (from defn. of angular velocity \(\omega = \frac{d\theta}{dt}\)). As a result, the effective area of the coil exposed to the magnetic field lines changes with time, and from Eq.(1), the flux at any time \(t\) is

\[
\phi_B = B A \cos \theta
\]

if there are \(N\) turns in the coil then the flux is

\[
\phi_B = N B A \cos \theta
\]

From Faraday's law, the induced emf for the rotating coil of \(N\) turns is

\[
E = -N \frac{d\phi_B}{dt} = -NBA \frac{d(\cos \theta)}{dt}
\]

differentiating and putting \(\theta = \omega t\) we get the instantaneous emf \(E\)

\[
E = -NBA \frac{d(\cos \omega t)}{dt} = NBA \omega \sin \omega t
\]

This \((E = NBA\omega \sin \omega t)\), the **instantaneous emf** at the instant \(t\) (i.e. the emf changes with time hence the \(E\) is the emf at the instant \(t\)). The **maximum value of the emf** \(E_o\), also called the **peak emf** which occurs when \(\sin \omega t = \pm 1\), is given by

\[
E_o = NBA\omega
\]
Note: $\omega = 2\pi f$, where $f$ is the frequency of rotation of the coil. Hence eqns. (21) and (20) become $E_o = NBA2\pi f$ and $E = NBA2\pi f \sin 2\pi ft$

Definition of Alternating current and its production

Since the value of the sine function varies between +1 and -1, the sign, or polarity of the emf changes with time (and the instantaneous emf changes from $+E$ to $-E$). Note from Fig. 17 that the emf has its maximum value when $\theta = 90^\circ$ (positive maximum) or $\theta = 270^\circ$, as the change of flux is greatest at these points. The direction of the current changes periodically and its magnitude varies sinusoidally therefore the current is called alternating current.