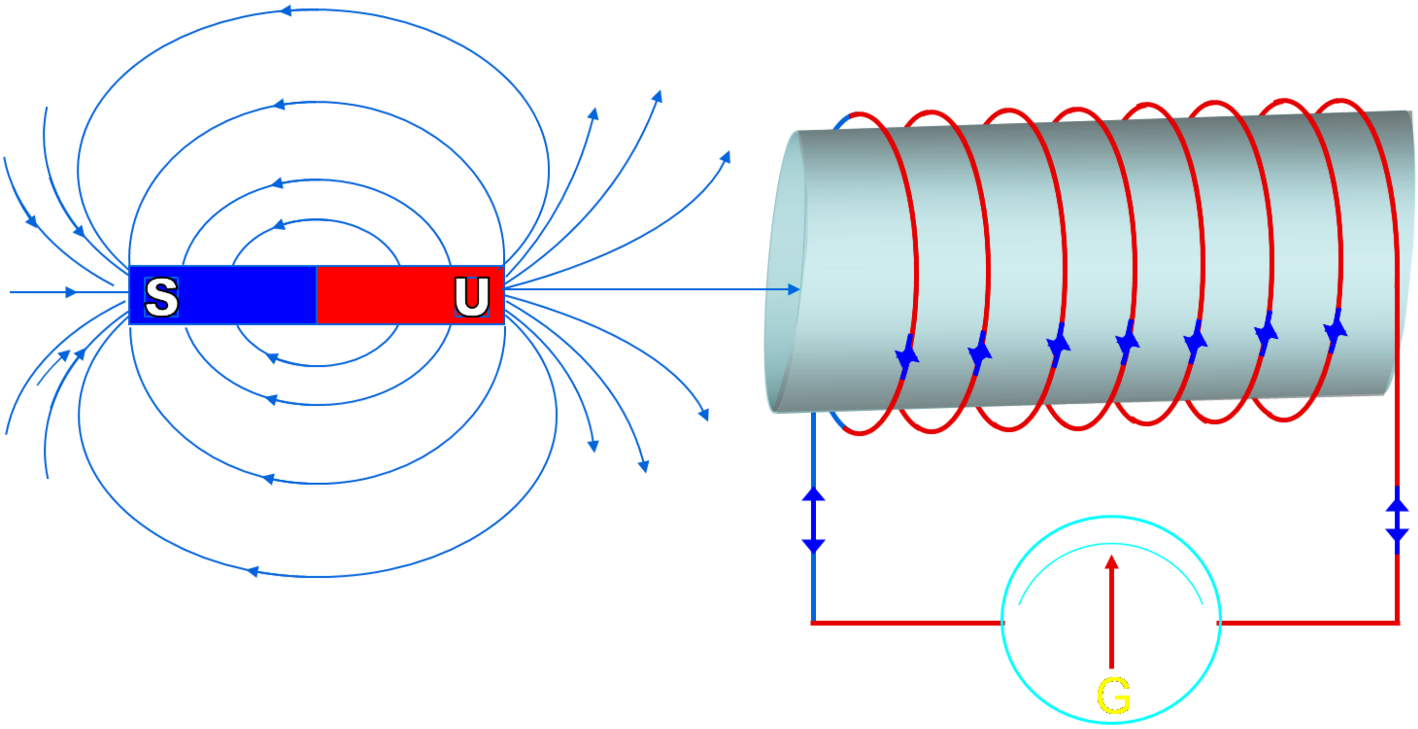
ELECTROMAGNETIC INDUCTION



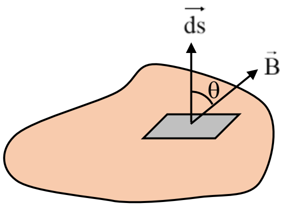
Electromagnetic Induction

Introduction

Experiments performed by scientists like Oersted, Ampere etc, during the early years of 19th century established that magnetic fields may be produced using electric currents. It was natural to enquire whether an electric current be produced using magnetic fields. Producing electric currents from magnetic fields was not so easy as to produce magnetic fields from currents. However, careful experimental observations made independently by Michael Faraday in England and Joseph Henry in USA around the year 1831, showed that under certain conditions electrical current can be produced using magnetic fields. It was found that when the magnetic flux linked with a loop of a conductor changes there will be an electric current in the loop. The phenomenon in which an emf is developed in a conductor due to the change in the magnetic flux linked with it is called the electromagnetic induction. Almost all the entire electrical energy used in the world today is produced making use of electromagnetic induction.

Magnetic flux

The number of field lines passing normally across a surface is called the flux across the surface. The flux associated with a magnetic field is defined in a manner similar to that used to define electric flux. Let dS be an element of area on an arbitrary shaped surface as shown. If the magnetic field at this element is $\vec{B}$, the magnetic flux through the element is,



$d\phi_B = \vec{B}\cdot\vec{dS} = BdS\cos\theta$.

$\vec{dS}$ here is a vector that is perpendicular to the surface and has a magnitude equal to the area dS and θ is the angle between $\vec{B}$ and $\vec{dS}$. In general $d\phi_B$ varies from element to element. The total magnetic flux through the surface is the sum of the contributions from the individual area elements.

$\therefore \phi_B = \int Bds\cos\theta = \int \vec{B}\cdot\vec{dS}$

☞

(i)Magnetic flux is a scalar quantity (dot product of two vector quantities is a scalar quantity)

(ii) The SI unit of magnetic flux is tesla–meter^2 (1 T-m^2). This unit is called *weber* (1 Wb)

1 Wb = 1 T-m^2 = I N-m/A

Thus unit of magnetic field is also weber/m^2 (1 Wb/m^2),

or 1 T = 1 Wb/m^2

In the special case where B is uniform over a plane surface with total area S and is normal to the surface then cos θ ≈ 1 and $\phi_B = BS$

Faraday's law of electromagnetic induction

The results of systematic experimental observations made by Faraday may be summarised in the form laws called Faradays laws of electromagnetic induction.

These laws states that

(i) whenever the flux of magnetic field through the area bounded by a closed conducting loop changes, an emf is produced in the loop, and

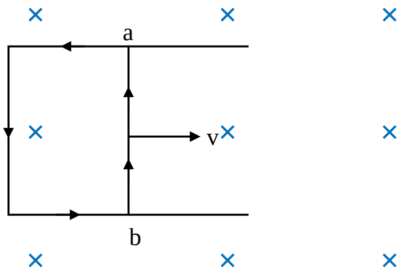
(ii) the magnitude of emf induced in a coil is equal to the rate of change of magnetic flux linked with the coil.

The induced emf is given by $E = -\dfrac{d\Phi}{dt}$ ...(1)

where $\Phi = \int \vec{B}\cdot\vec{dS}$ is the flux of the magnetic field through that area.

The law described by equation (1) is called *Faraday's law of electromagnetic induction*. The flux may be changed in a number of ways. One can change the magnitude of the magnetic field $\vec{B}$ at the site of the loop, the area of the loop or the angle between the area-vector $\vec{dS}$ and the magnetic field $\vec{B}$. In any case, as long as the flux keeps changing, the emf is present. The emf produced so drives an electric current through the loop. If R is the resistance of the loop, the current then is

$$i = \frac{E}{R} = -\frac{1}{R}\frac{d\Phi}{dt} \qquad \text{...(2)}$$



The emf developed by a changing flux is called induced emf and the current produced by this emf is called *induced current*.

Suppose the circuit (loop) consists of N loops all of same area and if ϕ_B is the flux through one loop, then the total induced emf is given by

$$e = -N\frac{d\varphi_B}{dt}$$

significance of –ve sign will be explained below.

Direction of induced current

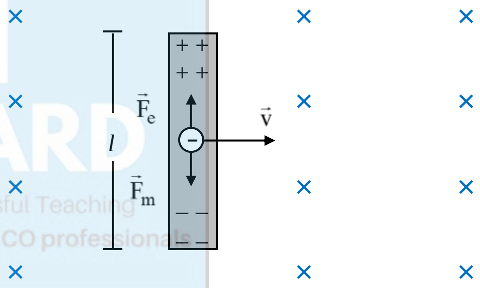
Lenz's law

Soon after Faraday gave his law of induction, Lenz devised a rule-now known as Lenz's law for finding the direction of an induced current in a loop.

An induced current has a direction such that the magnetic field due to this current opposes the change in the magnetic flux that induces the current.

Furthermore, the direction of an induced emf is same as that of the induced current.

Motional electromotive force (emf induced in a rod moving in a magnetic field)



(emf Until now, we considered the cases where an emf is induced in a stationary circuit placed in a magnetic field when the field changes with time. We now describe what is called *motional emf*, which is the emf induced in a conductor when it is moving through a constant magnetic field.

The straight conductor of length l shown in figure is moving through a uniform magnetic field directed into the page (denoted by the sign ×). For simplicity let us assume that the conductor is moving in a direction perpendicular to the field with constant velocity under the influence of some external agent. The electrons in the conductor experience a force, $\vec{F}_m = -e(\vec{v}\times\vec{B})$

Under the influence of this force, the electrons move to the lower end of the conductor and accumulate there, leaving a net positive charge at the upper end. As a result of this charge separation, an electric field is produced inside the conductor. The charges accumulate at both ends until magnetic force evB which is along downward direction is balanced by the upward electric force eE. At equilibrium electrons stop moving. The condition for equilibrium requires that, $eE = evB$ or $E = vB$

The electric field produced in the conductor (once the electrons stop moving and E is constant) is related to the potential difference across the ends of the conductor by,

$\Delta V = El = Blv$

$\therefore\ \Delta V = Blv$

where the upper end is at a higher electric potential than the lower end.

Thus, "*a potential difference is maintained between the ends of the conductor as long as the conductor continues to move through the uniform magnetic field.*"

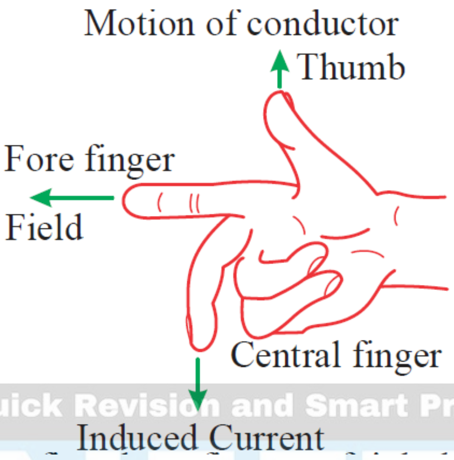
Now let us suppose the moving rod slides along a stationary U-shaped conductor, forming a complete circuit. No magnetic force acts on the charges in the stationary U-shaped conductor, but there is an electric field resulting from the charge accumulations at a and b. Under the action of this field a counter clockwise current is established around this complete circuit. The moving rod acts as a source of electromotive force. Within it, positive charge moves from lower to higher potential and in the remainder of the circuit, charge moves from higher to lower potential. We call this a *motional electromagnetic force* denoted by e, we can write,

$$\mathbf{e = Bv}\boldsymbol{l} \qquad \ldots(1)$$

If R is the resistance of the circuit, then current in the circuit is,

$$\mathbf{i} = \frac{e}{R} = \frac{Bv\boldsymbol{l}}{R} \qquad \ldots(2)$$

Fleming’s right hand rule



The direction of induced emf in a conductor in a magnetic field is given by **Fleming’s right hand rule.**

If the fingers of the right hand are held such that the fore finger, middle finger and the thumb are mutually perpendicular and the fore finger shows the direction of field and the thumb shows the direction of motion of the conductor then the middle finger shows the direction of induced current. This principle is used in ac generator.

Induced electric field

Consider a conducting loop which is located in a magnetic field $\vec{B}$. The free electrons cannot flow in the loop until an electric field is applied. As long as $\vec{B}$ is constant no electric field is induced. Suppose the flux of magnetic induction through the loop starts changing say at t = 0, then an electric field $\vec{E}$ is produced. Obviously this electric field is produced by the changing magnetic field and not by charged particles.

Using Faraday’s law of induction, induced emf ‘e’ is given by $e = -\frac{d\Phi}{dt}$ or, $\oint \vec{E}\cdot\vec{dl} = -\frac{d\Phi}{dt}$.

A conducting closed loop need not be there to have an induced electric field $\vec{E}$. As long as B keeps changing, the induced electric field is present. If a closed loop is there, the free electrons start drifting and consequently an induced current results. Changing of $\vec{B}$ is not the only method of producing an induced electric field and consequently an induced emf. There are other methods also.

Various methods of producing induced emf

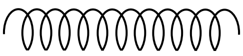
The three major methods generally employed are

(i) change of $\vec{B}$, the magnetic field acting on the object

(ii) change of area of material

(iii) change of relative orientation of surface area and the applied magnetic field

Inductors and inductance



An inductor is a coil of wire (conductor) with a number of turns as shown in the figure. Such an inductor can be used to produce a desired magnetic field. It is essentially a short