ELECTROMAGNETS AND ELECTROMAGNETIC INDUCTION

An electromagnet is a device made of soft iron that behaves as magnets only when current is flowing through them. They lose their magnetic properties (almost) immediately the current stops flowing through them.

USES OF ELECTROMAGNETS

1. They are used in the construction of earpieces
2. They are employed in the construction of electric bell
3. They are used for lifting heavy metals
4. They are used in separation techniques like removing impurities from metals.
5. They are used in the construction of the magnetic relay.

ELECTROMAGNETIC INDUCTION

Michael Faraday observed that when a magnet is moved towards a (stationary) coil, a current (induced in the coil) is observed to flow in the coil and if the magnet is moved away from the coil, the current is also produced but in the opposite direction. Also, if the coil is moved to or away from the (stationary) magnet a similar effect is seen to occur. However if both the magnet and the coil are held stationary, there is no current produced.

The phenomenon of current production resulting from the **relative motion** between the magnet and the coil is called Electromagnetic induction. The current produced in the coil is known as the induced current and it is as a voltage induced in the coil called the induced emf.

For electromagnetic induction to occur, at least one of the materials (either the magnet or the coil) must be in motion relative to each other

FACTORS AFFECTING INDUCED EMF IN A COIL

1. Strength of the magnet:

$E_i \propto B$

2. Area of the coil

$E_i \propto A$

3. Number of turns in the coil:

$E_i \propto N$

4. Velocity between the magnet and the coil

$E_i \propto v$

If the velocity is angular velocity

$E_i \propto \omega_o$

On combining,

$E_i \propto BANv$

$E_i = kBANv$

Taking k as 1

$E_i = BANv$

Or

$E_i = BAN\,\omega_o$

FACTORS AFFECTING THE MOTIONAL EMF (EMF INDUCED IN A WIRE)

When a conductor moves through a magnetic field so as to cut the lines of flux, an induced emf will exist in it. When a conductor is pulled or allowed to move in a uniform field, an emf will be induced in the conductor. This emf is called the motional emf.

1. Magnetic field intensity: Motional Emf is directly proportional to the magnetic flux density

$E_m \propto B$

2. Length of the conductor $E_m \propto l$

3. Relative velocity between the conductor and the field: $E_m \propto v$

4. Angle between the conductor and the field $E_m \propto \sin\theta$

On combining

$E_m \propto Blv \sin\theta$

$E_m = Blv \sin\theta$

The maximum electromotive force in conductors is $E_m = Blv$ where B and v must be perpendicularly

If the conductor has a resistance R, then the current flow is

$$I = \frac{E_m}{R} = \frac{Blv}{R}$$

Recall that the force on a current-carrying conductor is

$F = BIl$

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

$Power = Fv$

$P = I^2 R$

FARADAY'S LAW OF ELECTROMAGNETIC INDUCTION

This law states: The induced emf (which appears in a coil of a wire containing N loops) is directly proportional to the rate of change of the magnetic flux

$$Induced\,emf = \frac{Change \in magetic\,flux}{(Change) \in time}$$

$$E_i \propto N \frac{\Delta \Phi}{\Delta t}$$

$$E_i = -kN \frac{\Delta \Phi}{\Delta t}$$

Where k = 1

Here, N is the number of turns in the coil.

Magnetic flux is dependent on the magnetic field intensity (also known as magnetic flux density). Its relation to the flux density is expressed as

$$Magnetic\ flux = Magnetic\ flux\ density \times Area$$

$$\Phi = BA$$

Or

$$\Phi = BA\cos\theta$$

The unit of magnetic flux is Weber.

$$E_i = \frac{-N\,\Delta\Phi}{\Delta t}$$

In the equation above, the negative sign is gotten from Lenz's law

LENZ'S LAW

This states that the induced current will flow in a way so as to oppose the motion producing it. Since the motion of the current is trying to oppose the motion of its production it makes work done negative. The Lenz's law is a statement/consequence of the conservation of energy.

It can also be stated that an induced emf always gives rise to a current whose magnetic field opposes the original change in magnetic flux.

BACK EMF

An electric motor uses electrical energy to produce mechanical energy. Te reverse process which involves the use of mechanical energy to produce electrical energy is accomplished by a generator or a dynamo. When the armature of a motor rotates, an emf is induced in its coils. This emf opposes the current which is making the coils to rotate, according to the Lenz's law. The armature current is given as

$$I_a = \frac{V - \varepsilon}{R_a}$$

R_a is the resistance of the armature and V is the potential difference applied to the armature by the supply

The battery emf of a motor depends on the rotational speed of the armature and builds up from zero to some maximum value as the armature goes from rest to its normal operating speed.

$V = I_a R_a + \varepsilon$

Multiply through by I_a

$I_{aV} = I_a^2 R_a + I_a \varepsilon$

EDDY CURRENT

This is the current produced by back emf. They generate unwanted heat which can destroy electronic components. Eddy currents are named so because the current looks like eddies or whirlpools. When a conductor is placed in the changing magnetic field, the induced current in the conductor is termed eddy currents.

EDDY CURRENT PRINCIPLE

The eddy current method is based on the principle of generating circular electrical currents (eddy currents) in a conductive material. The eddy currents are flowing beneath the surface of the material with the highest density close to the surface.

APPLICATIONS OF EDDY CURRENT

1. They can be employed in speedometers.
2. They can be used in electric furnace
3. They are also applicable in induction coils. Induction motor, the eddy currents may be used to rotate the rotor.
4. Strong eddy currents are set up in the metal melts. This process is used in extracting a metal from its ore. The arrangement of heating the metal by means of strong induced current is called the induction furnace.

DISADVANTAGES OF EDDY CURRENT

1. Eddy current can result in the loss of electrical energy in the form of heat.
2. There will be magnetic flux leakage in induction coils due to eddy current.

WAYS OF REDUCING EDDY CURRENT

1. Using laminated soft iron cylinder
2. Using thin sheet of metals
3. Using insulated soft iron

MACHINES AND TOOLS BASED ON THE PRINCIPLE OF ELECTROMAGNETIC INDUCTION

1. Transformers
2. Generators
3. Induction Coil

TRANSFORMERS

These are devices used for changing (increasing or decreasing) Alternating current (A.C)[or alternating voltages]. Its operation is based on Faraday's law of electromagnetic induction.
The transformer consists of two coils (a primary and a secondary) each wound around the arm of a continuous laminated soft iron core.

In transformers there are primary and secondary areas and these primary and secondary areas have coils around them. The primary area is where the voltage comes into the transformer and the secondary area is where the voltage goes out of the transformer (output)
The voltage in the secondary coil depends on the voltage in the primary coil.

The magnitude of the alternating voltage induced in the secondary is

$$V_s = -N_s \frac{d\phi}{dt}$$

where N_s is the number of turns in the secondary coil.

The changing magnetic flux in the primary coil produces a back emf equal to

$$V_p = -N_p \frac{d\phi}{ddt}$$

If we assume that there is no power loss in the primary coil, that is, the resistance of the primary coil is neglected, then

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

TYPES OF TRANSFORMERS

1. Step up Transformer: This transformer increases AC voltages. It has a higher number of turns in the secondary coil than in the primary coil. A step-up transformer steps up voltage but steps down current For step up transformers,

$N_s > N_p$

$V_s > V_p$

$I_s < I_p$

2. Step-down Transformer: This transformer reduces AC voltages. It has a higher number of turns in the primary coil than in the secondary coil.

For all transformers, the ratio of the voltage (or emf) in the primary coil to the voltage (or emf) of the secondary coil is equal to the ratio of the number of turns in the primary coil to the number of turns in the secondary

$$\frac{E_p}{E_s} = \frac{N_p}{N_s}$$

$\frac{N_p}{N_s}$ Is also called the Turns ratio

$$Turns\,ratio = \frac{N_p}{N_s}$$

EFFICIENCY OF A TRANSFORMER

This is defined as the percentage ratio of the power output to the power input

$$Eff = \frac{Power\ output}{Power\ input} \times 100$$

$$Eff = \frac{Power \in secondary\ coil}{Power \in primary\ coil} \times 100$$

$$Eff = \frac{P_s}{P_p} \times 100$$

$$Eff = \frac{I_s E_s}{I_p E_p} \times 100$$

The efficiency of most transformers is less than 100 as a result of power loss

IDEAL TRANFORMER

Practically, there is no ideal transformer. An ideal transformer is a perfect transformer which has an efficiency of 100. For such transformers, the power output (secondary power) equals the power input (primary power).

$$Power\ output = Power\ input\, P_s = P_p$$

$$I_s E_s = I_p E_p$$

$$\frac{E_s}{E_p} = \frac{I_p}{I_s}$$

WAYS POWER CAN BE LOST IN TRANSFORMERS

1. Power loss due to eddy current
2. Power loss due to resistance of the coil: This is also called joule heating effect and the formula for the heat lost is $H = I^2 Rt$
3. Power loss due to reversal of the magnetic core: This is called Hysteresis
4. Power loss due to magnetic flux leakage

WAYS OF MINIMIZING POWER LOSS IN TRANSFORMERS

1. The use of laminated soft iron cores to reduce eddy current
2. The use of coils of low resistances
3. The use of soft iron to reduce magnetic flux leakage

GENERATORS

These are devices used for converting mechanical energy into electrical energy. They are also called dynamos. Their operation is based on faraday's law of electromagnetic induction.

TYPES OF GENERATORS

AC Generators

DC Generators

The major structural difference between AC generator and the DC generator is that AC generator has Slip Ring while DC has a Split Ring (Commutator)

AC GENERATORS

This is a device for converting mechanical (or rotational) motion into electric energy. Its actions are based on the principles of electromagnetic induction.

It consists of wire which is wound on a shaft and placed between the poles of a permanent magnet. A (circular) ring of copper known as Slip Ring and carbon brushes are attached to each end of the coil. The coil is made to rotate between the poles of the magnet and a current is induced in the coil. The carbon brushes tap the current from the coil via the slip rings.

The direction of the current changes as the plane of the coil passes through the vertical plane i.e. twice during a complete rotation thus producing an alternating current.

The armature (loop of coil) is rotated mechanically in a magnetic field by an external means. The ends of the loop are connected to an external circuit by means of slip rings

let A be the area of the loop

%theta = angle between the magnetic field and the normal of the plane of the loop

$$\phi_B = BA\cos\theta$$

$$= -N\frac{d\,\phi_B}{dt}$$

$$= -N\frac{d\,BA\cos\theta}{dt}$$

$$= -N\frac{d\,BA\cos\omega t}{dt}$$

on differentiating, since the above is a derivative

$$E = \omega NBA\sin\omega t$$

The maximum emf or the peak emf is

$$E = \omega NBA$$

When the plane of the coil is parallel to the magnetic field, $\theta = 90$ and $E = E_o(max)$

When the plane of the coil is perpendicular to the magnetic field,

If the output of the coil is connected to an external circuit of resistance, R

$$I = \frac{E}{R} = \frac{E_o \sin \omega t}{R}$$

DC GENERATORS

This is similar to the AC generator except that the slip rings are replaced by a split ring commutator. As the direction in the coil changes, the commutator reverses the electrical connection between the coil and the external circuit. The external circuit thus reverses current in the same direction and direct current is produced.

For a DC generator, the same principles of the AC applies except that the ends of the loop are connected to an external circuit through split rings (commutator).

COMMUTATORS

This is a device used for changing the direction of flow of current. It allows current to flow in only one direction.

ELECTRIC MOTOR

This converts electrical energy into mechanical (rotational) energy.

INDUCTION COILS

This is a device used for increasing DC voltages or direct current. Its operation is based on (Faraday's law of electromagnetic induction). From the definition above, it can be seen that the induction coil is a type of (step up) transformer which has a higher number of turns (up to a thousand probably) in the secondary coils than in the primary. In fact, the induction coil was the first transformer made.

The induction coil was invented by Nicholas Challan in 1836 with additional research by Charles Grafton Page and others.

An induction coil is a transformer used for producing high-voltage alternating current from a low-voltage direct current, consisting essentially of two concentric coils with a common soft-iron core, a primary coil with relatively few windings (turns) of heavy wire and a secondary coil with many turns of fine wire. The excitation of the primary coil by 5rapidly interrupted or variable current induces high voltage in the secondary coil.

The induction coil is used in car ignition systems where the induced voltage in the secondary, which is passed on to the spark plug, is sufficiently large (up to 25kV) to ionize air and cause a spark across the gap in the spark plug.

THE INDUCTOR

This is also called a coil, choke or reactor. It is a passive (or inactive) two-terminal electrical component (or device) that **stores (electromagnetic) energy** in a magnetic field when electric current flows through it. This shows that the inductor is an electromagnet.
An inductor typically consists of an insulated wire wound into a coil. It works on the principle of electromagnetic induction

When the current flowing through the coil changes, the time-varying magnetic field induces an e.m.f. (or voltage) in the conductor, described by Faraday’s law of induction. According to Lenz’s law, the induced voltage has a polarity (or direction) which opposes the change in current that created it. As a result, inductors oppose any changes in current through them.

An inductor is characterized by its inductance. The voltage across the inductor is directly proportional to the rate of change of the current flow

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

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

L is called the inductance of the inductor.

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

The SI unit of inductance is the **Henry (H)**

ARRANGEMENT OF INDUCTORS

1. Arrangement in series: The combined inductance is given as

$$L = L_1 + L_2 + L_3 + \ldots + L_n$$

2. Arrangement in parallel

$$\frac{1}{L} = \frac{1}{L_1} + \frac{1}{L_2} + \frac{1}{L_3} + \ldots + \frac{1}{L_n}$$

ENERGY STORED IN AN INDUCTOR

When an inductor of Inductance L is carrying a current I that is changing with time at the rate dI/dt, the energy supplied to the inductor is at the rate

$$P = I\,\varepsilon = LI\,\frac{di}{dt}$$

P = power

$$\varepsilon = induced\,emf$$

The work done

$$dW = P\,dt = LI\,dI$$

$$E = \int_0^1 L\,I\,dI = L\int_0^1 I\,dI$$

$$E = \frac{1}{2}L\,I^2$$

Consider a coil (or solenoid) with inductance

$$L = \mu_o n^2 Al$$

The magnetic field of the solenoid is given by

$$B = \mu_o nl$$

USES OF INDUCTORS

1. They are used for storing electromagnetic energy
2. They can also be used for limiting the value of current flowing in a circuit
3. They are essential components of electronic such as Televisions, computer panels.