III B.Sc PHYSICS – COURSE MATERIALS

SUBJECT CODE 18 UPH 7 - ELECTRICITY, MAGNETISM AND ELECRTROMAGNETISM

UNIT I - ELETROSTATICS

Gauss law:

It states that the net electric flux through any imaginary closed surface is equal to 1/ ε_0 times the net electric charge within that closed surface. It is also known as Gauss's flux theorem. This law relates the distribution of electric charge to the resulting electric field.

Integral form: In its integral form, it states that the flux of (Φ_E) the electric field out of an arbitrary closed surface is proportional to the electric charge enclosed by the surface, irrespective of how that charge is distributed. Even though the law alone is not enough to determine the electric field across a surface enclosing any charge distribution, this may be possible in cases where symmetry mandates uniformity of the field, where no such symmetry exists, Gauss's law can be used in its differential form, which states that the divergence of the electric field is proportional to the local density of charge.

Suppose ,

Φ_E is the electric flux through a closed surface,
S enclosing any volume *V*,
Q is the total charge enclosed within *V*,
and ε_0 is the electric constant.

The electric flux Φ_E is defined as a surface integral of the electric field:

where **E** is the electric field, d**A** is a vector representing an microscopic element of area of the surface, and represents the dot product of two vectors.

$$\Phi_E = \int E. dA = \int E\, dA \cos \theta.$$

The electric field is the basic concept to know about electricity. Generally, the electric field of the surface is calculated by applying Coulomb's law, but to calculate the electric field distribution in a closed surface, It explains the electric charge enclosed in a closed or the electric charge present in the enclosed closed surface.

As per the Gauss theorem, the total charge enclosed in a closed surface is proportional to the total flux enclosed by the surface. Therefore, if ϕ is total flux and ϵ_0 is electric constant, the total electric charge Q enclosed by the surface is;

$Q = \phi \epsilon_0$

The Gauss law formula is expressed by;

$\phi = Q/\epsilon_0$

Where,

Q = total charge within the given surface,

ε_0 = the electric constant.

Applications of Gauss Law:

1. It is used to find the electric field in the case of a charged ring of radius R on its axis at a distance x from the centre of the ring.

2. It is used to find the electric field in case of an infinite line of charge, at a distance ‘r’.
$E = (1/4\pi r\varepsilon_0)(2\pi/r) = \lambda/2\pi r\varepsilon_0$.

where λ is the linear charge density.

3. It is used to find the electric field the intensity of the electric field near a plane sheet of charge is $E = \sigma/2\varepsilon_0 K$

where σ is the surface charge density.

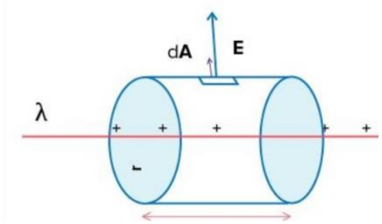
4. It is used to find the electric field the intensity of the electric field near a plane charged conductor $E = \sigma/K\varepsilon_0$ in a medium of dielectric constant K. If the dielectric medium is air, then $E_{air} = \sigma/\varepsilon_0$.

5. The field between two parallel plates of a condenser is $E = \sigma/\varepsilon_0$, where σ is the surface charge density.

Derivations of Applications of Gauss law :

(i) Electric Field due to Infinite length of wire

Consider an infinitely long line of charge with the charge per unit length being λ. We can take improvement of the cylindrical symmetry of this situation. By symmetry,the electric fields all point radially away from the line of charge, there is no component parallel to the line of charge. We can use a cylinder with an arbitrary radius r and length l centred on the line of charge as our Gaussian surface.



As we can see in the diagram, the electric field is perpendicular to the curved surface of the cylinder. Thus, the angle between the electric field and area vector is zero and $\cos\theta = 1$

The top and bottom surfaces of the cylinder lie parallel to the electric field. Thus the angle between area vector and the electric field is 90 degrees and $\cos\theta = 0$.

Thus, the electric flux is only due to the curved surface , according to Gauss Law,

$\Phi = \rightarrow E.dA$

$\Phi = \Phi_{curved} + \Phi_{top} + \Phi_{bottom}$

$\Phi = \rightarrow E . dA = \int E . dA \cos 0 + \int E . dA \cos 90° + \int E . dA \cos 90°$

$\Phi = \int E . dA \times 1$

Due to radial symmetry, the curved surface is equidistant from the line of charge and the electric field in the surface has a constant magnitude throughout.

$\Phi = \int E . dA = E \int dA = E . 2\pi rl$

The net charge enclosed by the surface is:

$q_{net} = \lambda.l$

Using Gauss theorem,

$\Phi = E \times 2\pi rl = q_{net}/\varepsilon_0 = \lambda l/\varepsilon_0$

$E \times 2\pi rl = \lambda l/\varepsilon_0$

$E = \lambda/2\pi r\varepsilon_0$

(ii) <u>Electric Field due to plane sheet of charge:</u>

Consider an plane sheet of charge with the charge per unit area being σ. We can take improvement of the cylindrical symmetry of this situation. By symmetry, the electric fields all point radically away from the line of charge; there is no component parallel to the area of charge. We can use a cylinder with an arbitrary radius r and surface area A centered on the line of charge as our Gaussian surface. The suitable Gaussian surface would be a rectangular parallelepiped of cross sectional area A , only the two faces 1 and 2 will contribute to the flux the unit vector n and and E are parallel to each other. The electric field lines are perpendicular to the other faces and therefore, do not contribute to the total flux.

Therefore electric flux over these edges E. n dS are equal and add up as the unit vector to surface 1 is in negative x direction while for surface 2, it is in positive x direction.

That is net flux through the Gaussian surface = 2 EA

But, the net charge enclosed by the closed surface, q = σ xA

Hence , $2EA = q / \varepsilon_0$

$2EA = \sigma A / \varepsilon_0$

$E = \sigma / 2\varepsilon_0$

Where n is the unit vector in the direction of the outward normal to the sheet of charge.

The nature of charge distribution decides the direction of electric field vector.

If, σ is greater than zero, the direction of E is directed outwards.

If σ is less than zero, the direction of E is directed inwards.

It is clear from the above expression that E is independent of the distance of the point from the plane charged sheet.

COULOMB THEOREM:

The law states that the magnitude of the electrostatic force of attraction or repulsion between two point charges is directly proportional to the product of the magnitudes of charges and inversely proportional to the square of the distance between them.

$F = k_e q_1 q_2 / r^2$

Here, k_e is Coulomb's constant ($k_e \approx 8.988\times10^9$ N·m^2·C^{-2}), q_1 and q_2 are the signed magnitudes of the charges, and the scalar r is the distance between the charges.

Capacitance of the conductor:

Capacitance is the ability of a body to hold an electrical charge. In numerical terms: it is the ratio of the amount of electric charge stored on a conductor to a difference in electric potential. There are two closely related notions of capacitance: The SI unit of capacitance is the farad F.

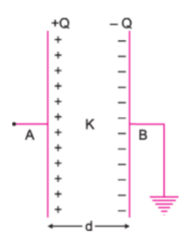
Therefore $C = q / V$

where

q is the charge held on the conductor, V is the electric potential.

Principle of the capacitor:

A capacitor works on the principle that the capacitance a conductor increases appreciably potential decreases when an earthed conductor is brought near it.



Consider a parallel plate capacitor having two plane metallic plates A and B, placed parallel to each other see figure. The plates carry equal and opposite charges +Q and -Q repectively. In general, the electric field between the plates due to charges +Q and -Q remains uniform, but at the edges, the electric field lines.

Electrified soap bubble:

Consider a soap bubble is produced at the end of the metal tube. The metal tube is insulated by fixing it in a block of paraffin wax. The soap bubble is electrified by touching with charged ebonite rod. Now, the charged soap bubble is small increase in size due to the outward pressure. When the surface tension of the bubble decreases, the radius of the bubble increases.

UNIT II – MAGNETIC PROPERTIES OF MATERIALS

Classes of Magnetic Materials

- Diamagnetism.
- Paramagnetism.
- Ferromagnetism.

Diamagnetic materials

Diamagnetic materials are substances that are usually repelled by a magnetic field. Electrons in an atom revolve around the nucleus thus possess orbital angular momentum. The resultant magnetic momentum in an atom of the diamagnetic material is zero.

In diamagnetic materials, there are no atomic dipoles due to the pairing between the electrons. When an external magnetic field is applied, dipoles are induced in the diamagnetic materials in such a way that induced dipoles opposes the external magnetic field according to Lenz's law.

Thus, all the materials whose atoms contain paired electrons show diamagnetic properties. The materials which are repelled by a magnet such as zinc. mercury, lead, sulfur, copper, silver, bismuth, wood etc., are known as diamagnetic materials. Their permeability is slightly less than one. For example the relative permeability of bismuth is 0.00083, copper is 0.000005 and wood is 0.9999995. They are slightly magnetized when placed in a very strong magnetic field and act in the direction opposite to that of applied magnetic field. In diamagnetic materials , the two relatively weak magnetic fields caused due to the orbital revolution and and axial rotation of electrons around nucleus are in opposite directions and cancel each other. Permanent magnetic dipoles are absent in them.

Paramagnetic materials

Paramagnetic materials have some unpaired electrons due to these unpaired electrons the net magnetic moment of all electrons in an atom is not added up to zero. Hence atomic dipole exists in this case. On applying external magnetic field the atomic dipole aligns in the direction of the applied external magnetic field. In this way, paramagnetic materials are feebly magnetized in the direction of the magnetizing field. we can say that these materials usually experience a weak attraction to magnets. This type of magnetism is known as paramagnetism. It occurs mainly due to the presence of unpaired electrons in the material or due to the partial alignment of randomly oriented atomic dipole along the field.

The materials which are not strongly attracted to a magnet are known as paramagnetic material. For example: aluminium, tin magnesium etc. Their relative permeability is small but positive. For example: the permeability of aluminium is: 1.00000065. Such materials are magnetized only when placed on a super strong magnetic field and act in the direction of the magnetic field.

Paramagnetic materials have individual atomic dipoles oriented in a random fashion as shown below: The resultant magnetic force is therefore zero. When a strong external magnetic field is applied , the permanent magnetic dipoles orient them self parallel to the applied magnetic field and give rise to a positive magnetization. Since, the orientation of the dipoles parallel to the applied magnetic field is not complete, the magnetization is very small.

Ferromagnetic materials

Ferromagnetism which means iron which was the first metal known to show attractive properties to magnetic fields. Ferromagnetism is a unique magnetic behavior that is exhibited by certain materials such as iron, cobalt, alloys, etc. It is a phenomenon where these materials attain permanent magnetism or they acquire attractive powers. It is also described as a process where some of the electrically uncharged materials attract each other strongly. Ferromagnetism is a property that considers not only the chemical make-up of a material but it also takes into account the microstructure and the crystalline structure. Most of the ferromagnetic materials are metals. Common examples of ferromagnetic substances are Iron, Cobalt, Nickel, etc. Besides, metallic alloys and rare earth magnets are also classified as ferromagnetic materials.

Magnetite is a ferromagnetic material which is formed by the oxidation of iron into an oxide. It has a Curie temperature of 580°C. Earlier, it was recognized as a magnetic substance. Magnetite has the greatest magnetism among all the natural minerals on earth.

The materials which are strongly attracted by a magnetic field or magnet is known as ferromagnetic material for eg: iron, steel , nickel, cobalt etc. The permeability off these materials is very very high ranging up to several hundred or thousand. The opposite magnetic effects of electron orbital motion and electron spin do not eliminate each other in an atom of such a material. There is a relatively large contribution from each atom which aids in the establishment of an internal magnetic field, so that when the material is placed in a magnetic field, it's value is increased many times the value that was present in the free space before the material was placed there. For the purpose of electrical engineering it will suffice to classify the materials as simply ferromagnetic and and non-ferromagnetic materials. The latter includes material of relative permeability practically equal to unity while the former have relative permeability many times greater than unity. Paramagnetic and diamagnetic material falls in the non-ferromagnetic materials.

Soft Ferromagnetic materials:

They have high relative permeability, low coercive force, easily magnetized and demagnetized and have extremely small hysteresis. Soft ferromagnetic materials are iron and it's various alloys with materials like nickel, cobalt, tungsten and aluminium . ease of magnetization and demagnetization makes them highly suitable for applications involving changing magnetic flux as in electromagnets, electric motors, generators, transformers, inductors, telephone receivers, relays etc. They are also useful for magnetic screening. Their properties may be greatly enhanced through careful manufacturing and and by heating and slow annealing so as to achieve a high degree of crystal purity. Large magnetic moment at room temperate makes soft ferromagnetic materials extremely useful for magnetic circuits but ferromagnetics are very good conductors and suffer energy loss from eddy current produced within them. There is additional energy loss due to the fact that magnetization does not proceed smoothly but in minute jumps. This loss is called magnetic residual loss and it depends purely on the frequency of the changing flux density and not on it's magnitude.

Hard Ferromagnetic materials

They have relatively low permeability, and very high coercive force. These are difficult o magnetize and demagnetize. Typical hard ferromagnetic materials include cobalt steel and various ferromagnetic alloys of cobalt, aluminium and nickel. They retain high percentage of their magnetization and have relatively high hysteresis loss. They are highly suited for use as permanent magnet as speakers, measuring instruments etc.

Properties of Diamagnetic Materials:

1. There are no atomic dipoles in diamagnetic materials because the resultant magnetic moment of each atom is zero due to paired electrons.

2. Diamagnetic materials are repelled by a magnet.

3. The substances are weakly repelled by the field so, in a non uniform field, these substances have a tendency to move from a strong to a weak part of the external magnetic field.

4. The intensity of magnetization I is very small, negative and proportional to the magnetizing field.

5. Magnetic susceptibility is small and negative.

6. The relative permeability is slightly less than unity.

Properties of Paramagnetic Materials:

1. When the net atomic dipole moment of an atom is not zero, the atoms of paramagnetic substances have permanent dipole moment due to unpaired spin.
2. The substances are weakly attracted by the magnetic field.
3. In the non-uniform external magnetic field, paramagnetic substances move from week field region to a strong field region.
4. A paramagnetic rod sets itself parallel to the field because the field is strongest near poles.
5. The intensity of magnetization is very small, positive and directly proportional to the magnetizing field.
6. Magnetic susceptibility is small and positive.

7. The relative permeability is slightly greater than 1. The field inside the material is greater than the magnetizing field.
8. Magnetic field lines become denser inside paramagnetic substances.
9. Magnetization of paramagnetic substances is inversely proportional to absolute temperature.
10. Paramagnetic substances obey Curie's law, according to which magnetic susceptibility is inversely proportional to its Absolute Temperature.
11. The magnetic dipole moment of paramagnetic substances is small and parallel to the magnetizing field.

Properties of Ferromagnetic Materials:

1. The atoms of ferromagnetic substances have permanent dipole moment present in domains.
2. Atomic dipoles in ferromagnetic substances are oriented in the same direction as the external magnetic field.
3. The magnetic dipole moment is large and is in the direction of the magnetizing field.
4. The intensity of magnetization **(M)** is very large and positive and varies linearly with the magnetizing field **(H)**. Hence saturation depends on the nature of the material.
5. The magnetic susceptibility is very large and positive. Magnetic susceptibility $X_m = M / H$, where **M** is the intensity of magnetization and **H** is the strength of the applied magnetic field.
6. The magnetic flux density of the material will be very large and positive. Magnetic field lines become very dense inside ferromagnetic materials. The relative permeability is also very large and varies linearly with the magnetizing field the field inside the material is much stronger than the magnetizing field. They tend to pull in a large number of lines of force by the material.
7. If a ferromagnetic powder is placed in a watch glass placed on two poles pieces which are sufficient apart then powder accumulates at sides and shows depression in the middle because the field is strongest at poles.

8. When a ferromagnetic substance is liquefied, it loses ferromagnetic properties due to higher temperature.

Curie Law:

Paramagnetic type of magnetization is based on Curie's law. According to the law, paramagnetic materials' magnetic susceptibility χ is inversely proportional to their temperature. It is represented as;

$M = \chi H = C/T \times H$

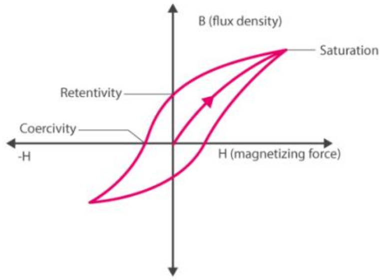
Where,

M = magnetization,
χ = magnetic susceptibility,
C = material-specific Curie constant,
T = absolute (Kelvin) temperature,
H = auxiliary magnetic field.

Hysteresis:

On removing the external magnetic field, a ferromagnetic material doesn't get demagnetized fully. To bring the material back to zero magnetization, a magnetic field in the opposite direction has to be applied. The property of ferromagnetic materials retaining magnetization after the external field is removed is called hysteresis.

The magnetization of the material measured in terms of magnetic flux density (B) when plotted against the external applied magnetic field intensity (H) will trace out a loop. This is called the hysteresis loop.



Retentivity is the magnetic flux density that remains when the magnetizing force is reduced to zero. Coercivity is the strength reverse magnetizing field that must be applied to completely demagnetize the material.

Curie Temperature:

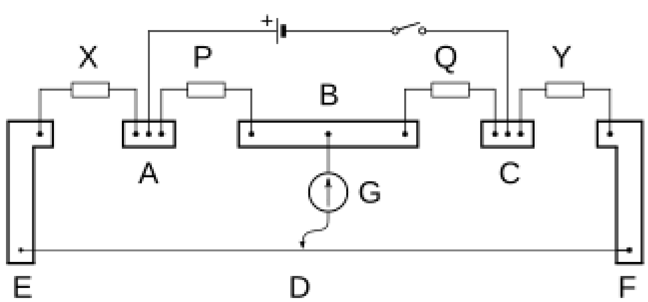
Ferromagnetic property depends on temperature. At a high enough temperature, ferromagnetic substances become paramagnetic. The temperature at which this transition occurs is called Curie's temperature. It is denoted by T_C.

Uses of Ferromagnetic Materials:

There are wide applications of ferromagnetic materials in the industry. They are widely used in devices like an electric motor, generators, transformers, telephone, loudspeakers, magnetic stripe at the back of credit cards.

UNIT III – CURRENT ELECTRICITY AND MAGNETIC EFFECYS OF CURRENT

<u>Carey foster bridge circuit diagram:</u>



Temperature Coefficient of Resistance:

The temperature coefficient of resistance is defined as the change in electrical resistance of a substance with respect to per degree change in temperature. So the electrical resistance of conductors such as gold, aluminium, silver, copper, it all depends upon the process of collision between the electrons within the material. When the temperature increases, the process of electron collision becomes rapid and faster. As a result, the resistance will increase with the rise in temperature of the conductor.

Let us consider a conductor whose resistance at 0°C is R_0 and the resistance at a temperature T°C is R_T. The relation between temperature and resistances R_0 and R_T is approximately given as

$R_T = R_0 [1+ \alpha (T-T_0)]$;

$R_T = R_0 [1+ \alpha (\Delta T)]$

Magnetic induction of a long solenoid:

A solenoid is a ling cylindrical coil having number of circular turns. Consider a solenoid having radius R consists of n number of turns per unit length. Let P be the point at a distance x_0 from the origin of the solenoid where we have to calculate the magnitude of the magnetic field. The current carrying element dx at a distance x from origin and a distance r from point P

$$r = \sqrt{R^2 + (x_0 - x)^2}$$

The magnetic field due to current carrying circular coil at any axis is

$$dB = \frac{\mu_0}{2}\frac{IR^2}{r^3} \times N$$
$$where\ N = ndx$$
$$then$$
$$dB = \frac{\mu_0}{2}\frac{nIR^2 dx}{r^3}$$

Ballistic galvanometer:

A ballistic galvanometer is a type of sensitive galvanometer; commonly a mirror galvanometer. Unlike a current-measuring galvanometer, the moving part has a large moment of inertia, thus giving it a long oscillation period. It is really an integrator measuring the quantity of charge discharged through it. It can be either of the moving coil or moving magnet type. Grassot fluxmeter calibration arrangement using a standard mutual inductor and known quantity of electrical discharge. Before first use the ballistic constant of the galvanometer must be determined. This is usually done by connecting to the galvanometer a known capacitor, charged to a known voltage, and recording the deflection. The constant K is calculated from the capacitance C, the voltage V and the deflection d:

where K is expressed in coulombs per centimeter.
In operation the unknown quantity of charge Q in coulombs is simply:

Construction of Ballistic Galvanometer:

The ballistic galvanometer consists coil of copper wire which is wound on the non-conducting frame of the galvanometer. The phosphorous bronze suspends the coil between the north and south poles of a magnet. For increasing the magnetic flux the iron core places within the coil. The lower portion of the coil connects with the spring. This spring provides the restoring torque to the coil.

When the charge passes through the galvanometer, their coil starts moving and gets an impulse. The impulse of the coil is proportional to the charges passes through it. The actual reading of the galvanometer achieves by using the coil having a high moment of inertia. The moment of inertia means the body opposes the angular movement. If the coil has a high moment of inertia, then their oscillations are large. Thus, accurate reading is obtained.

Current sensitivity :

It is defined as the deflection of coil per unit current flowing in it.

Voltage sensitivity:

It is defined on the deflection of coil per unit potential difference across its ends.

When number of turns N is doubled, then the current sensitivity ($\propto$ N) is doubled; but at the same time, the resistance of galvanometer coil (G) will also be doubled, so voltage sensitivity ($S_v \propto N/G$) will remain unchanged; hence increasing current sensitivity does not necessarily increase the voltage sensitivity.

Current sensitivity of a galvanometer is defined as the deflection produced in the galvanometer when a unit current flows through it. Is=θI=nBAcIs=θI=nBAc Where n is no of turns in the coil of galvanometer, B is Magnetic field around coil, A is Area of coil and c is restoring torque per unit twist. Voltage Sensitivity of a galvanometer is defined as the deflection produced in the galvanometer when a unit voltage is applied across two terminals.

Current sensitivity does not depend upon resistance(R), whereas voltage sensitivity does, as evident from their expressions. Current sensitivity can be increased by increasing the number of turns of the coil. However, this increases the resistance of the coil also R is proportional to length of conductor. Since voltage sensitivity decreases with increase in resistance of the coil, the effect of increase in number of turns is nullified in the case of voltage sensitivity. Hence, there is no increase in voltage sensitivity.

Ampere circuital law

Ampere's law allows us to calculate magnetic fields from the relation between the electric currents that generate these magnetic fields. It states that for a closed path the **sum** over elements of the component of the magnetic field is equal to electric current multiplied by the empty's permeability. He discovered that an electric current creates a magnetic field around it, when he noticed that the needle of a compass next to a wire carrying current turned so that the needle was perpendicular to the wire. He investigated and discovered the rules which govern the field around a straight current-carrying wire.

- The magnetic field lines encircle the current-carrying wire.
- The magnetic field lines lie in a plane perpendicular to the wire.
- If the direction of the current is reversed, the direction of the magnetic field reverses.
- The strength of the field is directly proportional to the magnitude of the current.
- The strength of the field at any point is inversely proportional to the distance of the point from the wire.

	Integral form	Differential form
Using **B**-field and total current	$\oint_C \mathbf{B} \cdot \mathrm{d}\boldsymbol{l} = \mu_0 \iint_S \mathbf{J} \cdot \mathrm{d}\mathbf{S} = \mu_0 I_{\mathrm{enc}}$	$\nabla \times \mathbf{B} = \mu_0 \mathbf{J}$
Using **H**-field and free current	$\oint_C \mathbf{H} \cdot \mathrm{d}\boldsymbol{l} = \iint_S \mathbf{J}_{\mathrm{f}} \cdot \mathrm{d}\mathbf{S} = I_{\mathrm{f,enc}}$	$\nabla \times \mathbf{H} = \mathbf{J}_{\mathrm{f}}$

Damping correction

For the purpose of making a moving coil galvanometer ballistic, i.e., to measure charge that passes for a short duration, its coil is required to get deflected under the action of an impulse imparted by a momentary current. Hence, the coil has to be light-weight. Further, motion of the coil should not be damped.

The damping effect of Eddy Currents is used in some moving coil galvanometers to make them dead-beat. When the coil and the frame rotate in the field of the permanent magnet, the eddy currents set up in the frame oppose the motion so that the coil returns to zero quickly.

A ballistic galvanometer will oscillate if it has not been properly damped. The proper amount of resistance at which the motion just ceases to be oscillatory is called the critical external damping resistance. When shunted by it's, the galvanometer is said to be critically damped.

Applications of Ampere law:

Ampere's law has many practical applications. The main usage is of course calculating the magnetic field generated by an electric current. This is useful in electromagnets, motors, generators, transforms etc. In calculations that could be done using Biot-Savart's law, Ampere's law simplifies the calculation process by using certain symmetry.

(i) Straight wire

The magnetic field "circles" around the wire, which means that we choose a circular Amperian loop of radius r centered at the wire consider that the wire has no thickness. The magnetic field is constant and equal at all the points, which means that B.ds is also constant. By enclosing it in the total circumference from 0 to 2πr the integral gives us 2πr and so we finally have:

$$\oint Bds = \mu_0 I_{encl} \leftrightarrow$$

$$B(2\pi r) = \mu_0 I \leftrightarrow$$

$$B = \frac{\mu_0 I}{2\pi r}$$

which is exactly the same that we calculated using Biot-Savart's law.

(ii) Cylindrical conductor / Thick wire

Let us consider the same wire as before, but now with thickness. The outer radius of the wire is R and the current is distributed uniformly along the wire. What is the magnetic field now if the total current is I again.

We again choose a circular Amperian loop of radius r, centered this time at the axis of the wire. If r > R we are outside of the wire, which means that we get the same results as before for a standard thin wire. So, let's say that r <= R, which takes is in the "inside" of the wire. Because the current is uniformly distributed the total enclosed current now is:

$$I_{encl} = I_{total}\frac{r^2}{R^2}$$

And so Ampere's law gives us:

$$\oint Bds = \mu_0 I_{encl} \leftrightarrow$$

$$B(2\pi r) = \mu_0 I \frac{r^2}{R^2} \leftrightarrow$$

$$B = \frac{\mu_0 I r}{2\pi R^2}$$

The current increases quadratically with r (r^2), whilst the magnetic field increases linearly with r.

(iii) Solenoid

Let's now consider a Solenoid, which is a helical winding of wire on a cylinder. To make the calculations simpler we will suppose that the length is much greater then the cross-section diameter and so that coils are very tighly wound! The internal magnetic field near the axis is uniform and parallel to the axis. The solenoid has a current I and n turns of wire per unit length.

$$\oint Bds = \mu_0 I_{encl} \leftrightarrow$$

$$\int_a^b Bds + \int_b^c Bds + \int_c^d Bds + \int_d^a Bds = \mu_0 I_{encl} \leftrightarrow$$

$$BL + 0 + 0 + 0 = \mu_0 nLI \leftrightarrow$$

$$B = \mu_0 nI$$

where only the "parallel" to the axis "section" inside of the solenoid gives us a non-zero value! By integrating in a length L (a -> b) the integral gives us L, similar to the previous calculations where we had the circumference of a circle.

(iv) Torodial Solenoid

Let's now consider a donut-shaped torodial soleniod with N turns of wire and carrying a current I. The radius is R. Let's find the magnetic field at all points. We can define 3 circular paths:

1. radius smaller then the donut's (r < R)
2. inside of the donut (r = R)
3. radius larger the the donut's (r > R)

In the paths where r is not equal to R there is no enclosed current, which means that the magnetic field along those paths is zero.

Inside of the donut we have:

$$\oint B ds = \mu_0 I_{encl} \leftrightarrow$$

$$B(2\pi r) = \mu_0 N I \leftrightarrow$$

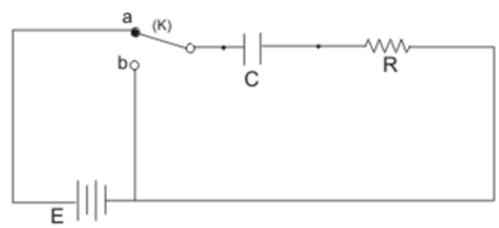
$$B = \frac{\mu_0 N I}{2\pi r}$$

which is an equation that looks similar to the straigh-line equation multiplied by N, which is the number of turns.

UNIT IV- DC AND AC CIRCUITS

The R-C circuit

- Consider a circuit containing a capacitor of capacitance C and a resistor R connected to a constant source of emf (battery) through a key (K) as shown below in the figure.



Source of EMF E can be included or excluded from circuit using this two way key

Growth of charge

- when the battery is included in the circuit by throwing the switch to a, the capacitor gradually begins to charge and because of this capacitor current in the circuit will vary with time
- There are two factors which contributes to voltage drop V across the circuit i.e. if current I flows through resistor R, voltage drop across the resistor is IR and if there is a charge Q on the capacitor then voltage drop across it would be Q/C
- At any instant, instantaneous potential difference across capacitor and resistor are

  V_R=IR and V_C=q/C

  Therefore total potential difference drop across circuit is

  $V=V_R+V_C=IR+q/C$

  Where V is a constant
- Now current is circuit

  $$I = \frac{V}{R} - \frac{q}{RC}$$

  Initially at time t=0 ,when the connection was made, charge on the capacitor q=0 and initial current in the circuit would be I_{max}=V/R ,which would be the steady current in the circuit in the absence of the capacitor

- As the charge q on the capacitor increase ,the term q/RC becomes larger and current decreases until it becomes zero .Hence for I=0

  V/R=q/RC

  or q=CV=Q_f

  where Q_f is the final charge on the capacitor

- Again consider above equation

  $$I = \frac{V}{R} - \frac{q}{RC}$$

  we know that I=dq/dt

  So,

  $$R\frac{dq}{dt} + \frac{q}{C} = V$$

  rearranging this equation we get

  $$\frac{dq}{VC - q} = \frac{dt}{RC}$$

  Integrating this we get

  $$t = -CR\ln(VC - q) + A$$

  Where A is the constant of integration

  Now at t=0,q=0 So

  A=CR lnCV

  From this we have

  $$t = -CR\ln(CV - q) + CR\ln CV$$

  $$\frac{-t}{CR} = \ln\left(\frac{CV - q}{CV}\right)$$

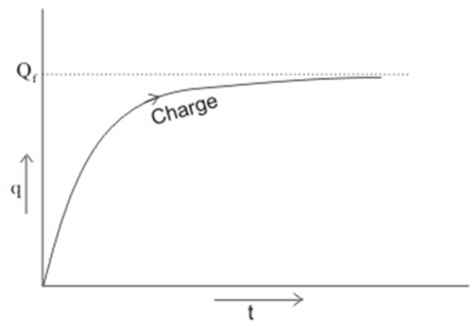
  Or,

  $$\frac{-t}{CR} = \ln\left(\frac{Q_f - q}{Q_f}\right)$$

  As CV=Q_f so, $$q = Q_f(1 - e^{-t/CR})$$

  Where Q_f=CV as defined earlier is the final charge on the capacitor when potential difference across it becomes equal to applied to EMF

- Equation represents the growth of charge on the capacitor and shows that it grows exponentially as shown below in the figure,



Now since

$$I = \frac{dq}{dt}$$

$$= \frac{d}{dt}\left[Q_f(1 - e^{-t/Rc})\right]$$

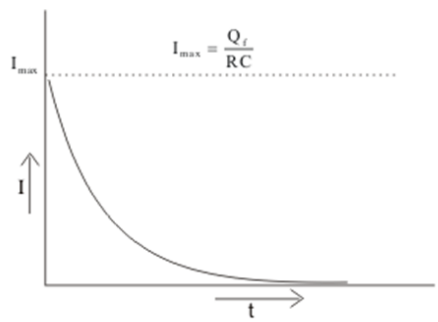
$$= Q_f \frac{1}{RC} e^{-t/RC}$$

$$= \frac{V}{R} e^{-t/RC}$$

Again I_{max}=V/R,so we have,

$$I = I_{max} e^{-t/RC}$$

Thus from equation , we see that current decreases exponentially from its maximum value I_{max}=V/R to zero



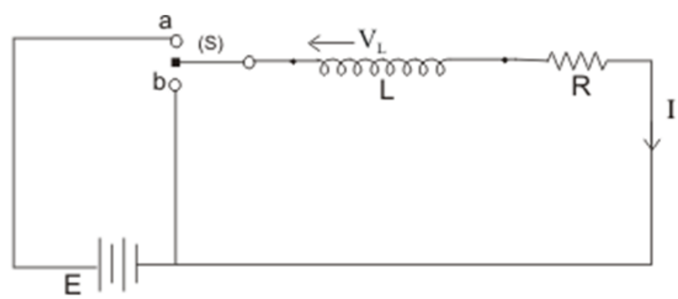
Quantity RC in equation is called capacitive time constant of the circuit

τ_C=CR

- Smaller is the value of τ_C,charge will grow on the capacitor more rapidly.
- Putting t= τ_C=CR in equation
  $q=Q_f(1-e^{-1})$
  $=6.32Q_f$
  Thus τ_C of CR circuit is the time which the charge on capacitor grows from 0 to .632 of its maximum value

Growth and decay of current in L-R circuit:

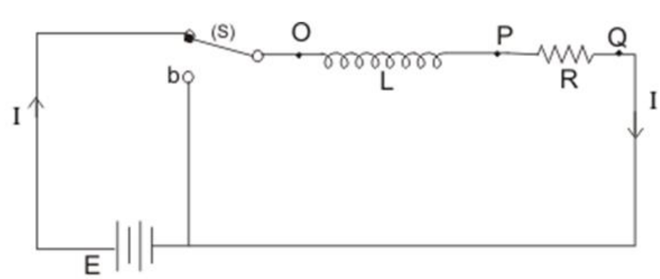
- Figure below shows a circuit containing resistance R and inductance L connected in series combination through a battery of constant emf E through a two way switch S



- To distinguish the effects of R and L,we consider the inductor in the circuit as resistance less and resistance R as non-inductive
- Current in the circuit increases when the key is pressed and decreases when it is thrown to b

(A) Growth of current

- Suppose in the beginning we close the switch in the up position as shown in below in the figure



- Switch is now closed and battery E, inductance L and resistance R are now connected in series
- Because of self induced emf current will not immediately reach its steady value but grows at a rate depending on inductance and resistance of the c circuit
- Let at any instant I be the c current in the circuit increasing from 0 to a maximum value at a rate of increase dI/dt
- Now the potential difference across the inductor is V_{op}=LdI/dt and across resistor is V_{pq}=IR , Since V=V_{op}+V_{pq} so we have, Thus rate of increase of current would be,

  $$\frac{dI}{dt}=\frac{V-IR}{L}$$

  In the beginning at t=0 when circuit is first closed current begins to grow at a rate, $\left(\frac{dI}{dt}\right)_{t=0}=\frac{V}{L}$

  from the above relation we conclude that greater would be the inductance of the inductor, more slowly the current starts to increase.
- When the current reaches its steady state value I ,the rate of increase of current becomes zero then from equation ,we have,0=(V-IR)/L or, I=V/R From this we conclude that final steady state current in the circuit does not depend on self inductance rather it is same as it would be if only resistance is connected to the source
- Now we will obtain the relation of current as a function of time Again consider equation

  $$\frac{dI}{\left(\frac{V}{R}\right)-I}=\frac{R}{L}dt$$

  let V/R=I_{max} ,the maximum current in the circuit .so we have

  $$\frac{dI}{I_{max}-I}=\frac{R}{L}dt$$

- Integrating equation on both sides we have the following equation

  $$-\ln(I_{max}-I)=\frac{R}{L}t+C$$

  where C is a constant and is evaluated by the value for current at t=0 which is i=0 so, C=-ln(V/R)=-ln I_{max} putting this value of C in equation we get,

$$\ln\left(\frac{I_{max}-I}{I_{max}}\right)=-\frac{R}{L}t$$

Or,

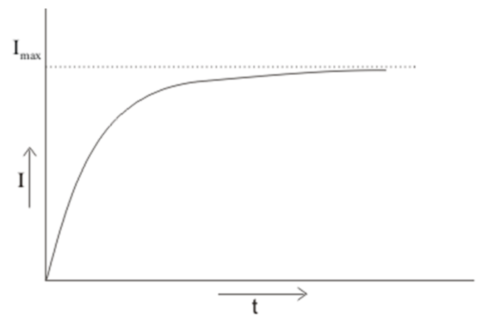
$$\frac{I_{max}-I}{I_{max}}=e^{-\frac{R}{L}t}$$

Or,

$$I=I_{max}(1-e^{-\frac{R}{L}t})$$

This equation shows the exponential increase of current in the circuit with the passage of time

- Figure below shows the plot of current versus time



If we put t=τ_L=L/R is equation then,

$$I=I_{max}(1-\frac{1}{e})=.63I_{max}$$

Hence, the time in which the current in the circuit increases from zero to 63% of the maximum value of I_{max} is called the constant or the decay constant of the circuit.

- For LR circuit, decay constant is, τ_L=L/R Again from equation

$$\frac{dI}{dt}=\frac{R}{L}(I_{max}-I_0)=\frac{I_{max}-I_0}{\tau_L}$$

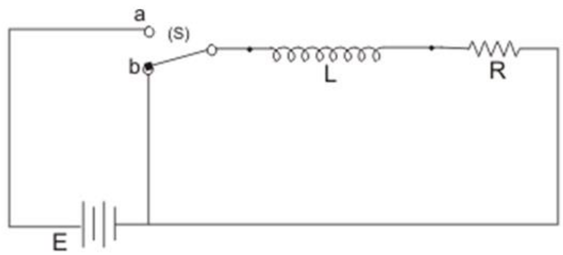
Or,

$$\frac{dI}{dt}\alpha\frac{1}{\tau_L}$$

This suggests that rate of change current per sec depends on time constant.

- Higher is the value of decay constant, lower will be the rate of change of current and vice versa.

(B) Decay of current

- When the switch S is thrown down to b as shown below in the figure ,the L-R circuit is again closed and battery is cut off
- 

  In this condition the current in the circuit begins to decay
- Again from equation since V=0 this time, so the equation for decay is

$$L\frac{dI}{dt}+RI=0$$

Or,

$$\frac{dI}{I}=\frac{-R}{L}dt$$

Integrating on both sides

$$\int\frac{dI}{I}=\frac{-R}{L}\int dt$$

Or,

$$\ln I=\frac{-R}{L}t+C_1$$

In this case initially at time t=0 current $I=I_{max}$ so $C_1=\ln I_0$
Putting this value of C_1 in equation

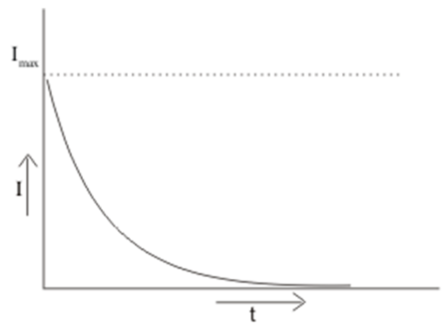
$$\ln I = \frac{-R}{L}t + \ln I_{max}$$

Or,

$$I = I_{max}e^{-\frac{R}{L}t}$$

Hence current decreases exponentially with time in the circuit in accordance with the above equation after the battery are cutoff from the circuit.

- Figure below shows the graph between current and time



- If in equation
- $t=\tau_L=L/R$

  then

  $I=I_{max}e^{-1}=.37I_{max}$

  hence the time in which the current decrease from the maximum value to 37% of the maximum value I_{max} is called the time constant of the circuit
- From equation it is clear that when R is large ,current in the L-R circuit will decrease rapidly and there is a chance of production of spark
- To avoid this situation L is kept large enough to make L/R large so that current can decrease slowly
- For large time constant the decay is slow and for small time constant the decay is fast

Series RLC Circuit:

The series RLC circuit above has a single loop with the instantaneous current flowing through the loop being the same for each circuit element. Since the inductive and capacitive reactance's X_L and X_C are a function of the supply frequency, the sinusoidal response of a series RLC circuit will therefore vary with frequency, f. Then the individual voltage drops across each circuit element of R, L and C element will be "out-of-phase" with each other as defined by:

$i_{(t)} = I_{max} \sin(\omega t)$

- The instantaneous voltage across a pure resistor, V_R is "in-phase" with current
- The instantaneous voltage across a pure inductor, V_L "leads" the current by 90^o
- The instantaneous voltage across a pure capacitor, V_C "lags" the current by 90^o
- Therefore, V_L and V_C are 180^o "out-of-phase" and in opposition to each other.

For the series RLC circuit above, this can be shown as:

The amplitude of the source voltage across all three components in a series RLC circuit is made up of the three individual component voltages, V_R, V_L and V_C with the current common to all three components. The vector diagrams will therefore have the current vector as their reference with the three voltage vectors being plotted with respect to this reference as shown below.

Individual Voltage Vectors

This means then that we cannot simply add together V_R, V_L and V_C to find the supply voltage, V_S across all three components as all three voltage vectors point in different directions with regards to the current vector. Therefore we will have to find the supply voltage, V_S as the Phasor Sum of the three component voltages combined together vectorially.

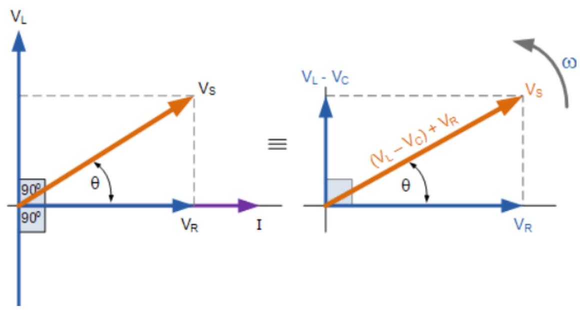
Kirchhoff's voltage law (KVL) for both loop and nodal circuits states that around any closed loop the sum of voltage drops around the loop equals the sum of the EMF's. Then applying this law to these three voltages will give us the amplitude of the source voltage, V_S as.

Instantaneous Voltages for a Series RLC Circuit

The phasor diagram for a series RLC circuit is produced by combining together the three individual phasor above and adding these voltages vectorially. Since the current flowing through the circuit is common to all three circuit elements we can use this as the reference vector with the three voltage vectors drawn relative to this at their corresponding angles.

The resulting vector V_S is obtained by adding together two of the vectors, V_L and V_C and then adding this sum to the remaining vector V_R. The resulting angle obtained between V_S and i will be the circuits phase angle as shown below.

Phasor Diagram for a Series RLC Circuit



We can see from the phasor diagram on the right hand side above that the voltage vectors produce a rectangular triangle, comprising of hypotenuse V_S, horizontal axis V_R and vertical axis $V_L – V_C$ Hopefully you will notice then, that this forms our old favourite the **Voltage Triangle** and we can therefore use Pythagoras's theorem on this voltage triangle to mathematically obtain the value of V_S as shown.

Voltage Triangle for a Series RLC Circuit

When using the above equation, the final reactive voltage must always be positive in value, that is the smallest voltage must always be taken away from the largest voltage we cannot have a negative voltage added to V_R so it is correct to have $V_L – V_C$ or $V_C – V_L$. The smallest value from the largest otherwise the calculation of V_S will be incorrect.

We know from above that the current has the same amplitude and phase in all the components of a series RLC circuit. Then the voltage across each component can also be described mathematically according to the current flowing through, and the voltage across each element as.

By substituting these values into the Pythagoras equation above for the voltage triangle will give us:

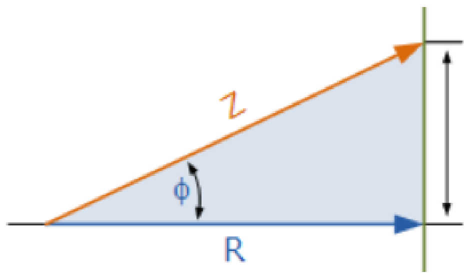
So we can see that the amplitude of the source voltage is proportional to the amplitude of the current flowing through the circuit. This proportionality constant is called the Impedance of the circuit which ultimately depends upon the resistance and the inductive and capacitive reactances.

Then in the series RLC circuit above, it can be seen that the opposition to current flow is made up of three components, X_L, X_C and R with the reactance, X_T of any series RLC circuit being defined as: $X_T = X_L - X_C$ or $X_T = X_C - X_L$ whichever is greater. Thus the total impedance of the circuit being thought of as the voltage source required to drive a current through it.

The Impedance of a Series RLC Circuit

As the three vector voltages are out-of-phase with each other, X_L, X_C and R must also be "out-of-phase" with each other with the relationship between R, X_L and X_C being the vector sum of these three components. This will give us the RLC circuits overall impedance, Z. These circuit impedance's can be drawn and represented by an **Impedance Triangle** as shown below.

The Impedance Triangle for a Series RLC Circuit



The impedance Z of a series RLC circuit depends upon the angular frequency, ω as do X_L and X_C If the capacitive reactance is greater than the inductive reactance, $X_C > X_L$ then the overall circuit reactance is capacitive giving a leading phase angle.

Likewise, if the inductive reactance is greater than the capacitive reactance, $X_L > X_C$ then the overall circuit reactance is inductive giving the series circuit a lagging phase angle. If the two reactance's are the same and $X_L = X_C$ then the angular frequency at which this occurs is called the resonant frequency and produces the effect of resonance which we will look at in more detail in another tutorial.

Then the magnitude of the current depends upon the frequency applied to the series RLC circuit. When impedance, Z is at its maximum, the current is a minimum and likewise, when Z is at its minimum, the current is at maximum.

The phase angle, θ between the source voltage, V_S and the current, i is the same as for the angle between Z and R in the impedance triangle. This phase angle may be positive or negative in value depending on whether the source voltage leads or lags the circuit current and can be calculated mathematically from the ohmic values of the impedance.

***Q* factor**:

It is defined as the ratio of the peak energy stored in the resonator in a cycle of oscillation to the energy lost per radian of the cycle. Q factor is alternatively defined as the ratio of a resonator's centre frequency to its bandwidth when subject to an oscillating driving force.

These two definitions give numerically similar, but not identical, results. Higher *Q* indicates a lower rate of energy loss and the oscillations die out more slowly. A pendulum suspended from a high-quality bearing, oscillating in air, has a high *Q*, while a pendulum immersed in oil has a low one. Resonators with high quality factors have low damping, so that they ring or vibrate longer.

Power factor:

It is defined as the ratio of the real power absorbed by the load to the apparent power flowing in the circuit, and is a dimensionless number in the closed interval of −1 to 1. A power factor of less than one indicates the voltage and current are not in phase, reducing the average product of the two.

Real power is the instantaneous product of voltage and current and represents the capacity of the electricity for performing work. Apparent power is the product of RMS current and voltage. Due to energy stored in the load and returned to the source, or due to a non-linear load that distorts the wave shape of the current drawn from the source, the apparent power may be greater than the real power. A negative power factor occurs when the device which is normally the load generates power, which then flows back towards the source.

In an electric power system, a load with a low power factor draws more current than a load with a high power factor for the same amount of useful power transferred. The higher currents increase the energy lost in the distribution system, and require larger wires and other equipment. Because of the costs of larger equipment and wasted energy, electrical utilities will usually charge a higher cost to industrial or commercial customers where there is a low power factor.

Power-factor correction

It increases the power factor of a load, improving efficiency for the distribution system to which it is attached. Linear loads with low power factor such as induction motors can be corrected with a passive network of capacitors or inductors. Non-linear loads, such as rectifiers, distort the current drawn from the system. In such cases, active or passive power factor correction may be used to counteract the distortion and raise the power factor. The devices for correction of the power factor may be at a central substation, spread out over a distribution system, or built into power-consuming equipment.

<u>Wattless current:</u>

An AC circuit containing only Capacitor or Inductor will have zero power dissipation even though the current is flowing through it. Such current is called wattless current. The current in a.c. circuit is said to be wattles if the average power consumed in the circuit is zero.

The average power of an a.c. circuit is given by the current *I rms* can be resolved into two components: *sine* component (y-direction) and cosine component (x-direction)

Skin effect

It is the tendency of an alternating electric current to become distributed within a conductor such that the current density is largest near the surface of the conductor and decreases exponentially with greater depths in the conductor. The electric current flows mainly at the "skin" of the conductor, between the outer surface and a level called the **skin depth**. Skin depth depends on the frequency of the alternating current; as frequency increases, current flow moves to the surface, resulting in less skin depth. Skin effect reduces the effective cross-section of the conductor and thus increases its effective resistance. Skin effect is caused by opposing eddy currents induced by the changing magnetic field resulting from the alternating current.

Tesla coil

It is an electrical resonant transformer circuit designed by inventor Nikola Tesla. It is used to produce high-voltage, low-current, high frequency alternating-current electricity. Tesla experimented with a number of different configurations consisting of two, or sometimes three, coupled resonant electric circuits. Tesla used these circuits to conduct experiments in electrical lighting, phosphorescence, X-ray generation, high frequency alternating current phenomena, electrotherapy, and the transmission of electrical energy without wires. Tesla coil circuits were used commercially in spark gap radio transmitters for wireless telegraphy until the medical equipment such as electrotherapy and violet ray devices. Today, their main usage is for entertainment and educational displays, although small coils are still used as leak detectors for high vacuum systems.

UNIT V – ELECTROMAGNETIC INDUCTION

Consider the bar magnet stationary and moved the coil back and forth within the magnetic field an electric current would be induced in the coil. Then by either moving the wire or changing the magnetic field we can induce a voltage and current within the coil and this process is known as **Electromagnetic Induction** and is the basic principle of operation of transformers, motors and generators.

Electromagnetic Induction was first discovered way back in the 1830's by **Michael Faraday**. Faraday noticed that when he moved a permanent magnet in and out of a coil or a single loop of wire it induced an Electro Motive Force or emf, in other words a Voltage, and therefore a current was produced.

Faraday discovered was a way of producing an electrical current in a circuit by using only the force of a magnetic field. This then lead to a very important law linking electricity with magnetism, **Faraday's Law of Electromagnetic Induction**.

When the magnet shown below is moved "towards" the coil, the pointer or needle of the Galvanometer, which is basically a very sensitive centre zero'ed moving-coil ammeter, will deflect away from its centre position in one direction only. When the magnet stops moving and is held stationary with regards to the coil the needle of the galvanometer returns back to zero as there is no physical movement of the magnetic field.

Likewise, when the magnet is moved "away" from the coil in the other direction, the needle of the galvanometer deflects in the opposite direction with regards to the first indicating a change in polarity. Then by moving the magnet back and forth towards the coil the needle of the galvanometer will deflect left or right, positive or negative, relative to the directional motion of the magnet.

If the magnet is now held stationary and the coil is moved towards or away from the magnet the needle of the galvanometer will also deflect in either direction. Then the action of moving a coil or loop of wire through a magnetic field induces a voltage in the coil with the magnitude of this induced voltage being proportional to the speed or velocity of the movement.

Then we can see that the faster the movement of the magnetic field the greater will be the induced emf or voltage in the coil, so for Faraday's law to hold true there must be "relative motion" or movement between the coil and the magnetic field and either the magnetic field, the coil or both can move.

Faraday's Law of Induction

From the above description we can say that a relationship exists between an electrical voltage and a changing magnetic field to which Michael Faraday's famous law of electromagnetic induction states: "that a voltage is induced in a circuit whenever relative motion exists between a conductor and a magnetic field and that the magnitude of this voltage is proportional to the rate of change of the flux".

Electromagnetic Induction is the process of using magnetic fields to produce voltage, and in a closed circuit, a current. So, voltage can be inducted into the coil using just magnetism. Well this is determined by the following 3 different factors.

- Increasing the number of turns of wire in the coil By increasing the amount of individual conductors cutting through the magnetic field, the amount of induced emf produced will be the sum of all the individual loops of the coil, so if there are 20 turns in the coil there will be 20 times more induced emf than in one piece of wire.
- Increasing the speed of the relative motion between the coil and the magnet – If the same coil of wire passed through the same magnetic field but its speed or velocity is increased, the wire will cut the lines of flux at a faster rate so more induced emf would be produced.
- Increasing the strength of the magnetic field – If the same coil of wire is moved at the same speed through a stronger magnetic field, there will be more emf produced because there are more lines of force to cut.

If we were able to move the magnet in the diagram above in and out of the coil at a constant speed and distance without stopping we would generate a continuously induced voltage that would alternate between one positive polarity and a negative polarity producing an alternating or AC output voltage and this is the basic principle of how an electrical generator works similar to those used in dynamos and car alternators.

In small generators such as a bicycle dynamo, a small permanent magnet is rotated by the action of the bicycle wheel inside a fixed coil. Alternatively, an electromagnet powered by a fixed DC voltage can be made to rotate inside a fixed coil, such as in large power generators producing in both cases an alternating current.

Lenz's Law of Electromagnetic Induction

Faraday's Law that inducing a voltage into a conductor can be done by either passing it through a magnetic field, or by moving the magnetic field past the conductor and that if this conductor is part of a closed circuit, an electric current will flow. This voltage is called an **induced emf** as it has been inducted into the conductor by a changing magnetic field due to electromagnetic induction with the negative sign in Faraday's law telling us the direction of the induced current or polarity of the induced emf.

But a changing magnetic flux produces a varying current through the coil which itself will produce its own magnetic field as we saw in the Electromagnets tutorial. This self-induced emf opposes the change that is causing it and the faster the rate of change of current the greater is the opposing emf. This self-induced emf will, by Lenz's law oppose the change in current in the coil and because of its direction this self-induced emf is generally called **a** back-emf.

Lenz's Law

It states that the direction of an induced emf is such that it will always opposes the change that is causing it". In other words, an induced current will always oppose the motion or change which started the induced current in the first place and this idea is found in the analysis of Inductance.

Likewise, if the magnetic flux is decreased then the induced emf will oppose this decrease by generating and induced magnetic flux that adds to the original flux.

Lenz's law is one of the basic laws in electromagnetic induction for determining the direction of flow of induced currents and is related to the law of conservation of energy.

According to the law of conservation of energy which states that the total amount of energy in the universe will always remain constant as energy cannot be created nor destroyed. Lenz's law is derived from Michael Faraday's law of induction. When a relative motion exists between a conductor and a magnetic field, an emf is induced within the conductor.

Eddy Current

Eddy currents generated by electromagnetic induction circulate around the coils core or any connecting metallic components inside the magnetic field because for the magnetic flux they are acting like a single loop of wire. Eddy currents do not contribute anything towards the usefulness of the system but instead they oppose the flow of the induced current by acting like a negative force generating resistive heating and power loss within the core. However, there are electromagnetic induction furnace applications in which only eddy currents are used to heat and melt ferromagnetic metals.

The changing magnetic flux in the iron core of a transformer above will induce an emf, not only in the primary and secondary windings, but also in the iron core. The iron core is a good conductor, so the currents induced in a solid iron core will be large. Furthermore, the eddy currents flow in a direction which, by Lenz's law, acts to weaken the flux created by the primary coil. Consequently, the current in the primary coil required to produce a given B field is increased, so the hysteresis curves are fatter along the H axis.

Eddy current and hysteresis losses cannot be eliminated completely, but they can be greatly reduced. Instead of having a solid iron core as the magnetic core material of the transformer or coil, the magnetic path is "laminated".

These laminations are very thin strips of insulated usually with varnish metal joined together to produce a solid core. The laminations increase the resistance of the iron-core thereby increasing the overall resistance to the flow of the eddy currents, so the induced eddy current power-loss in the core is reduced, and it is for this reason why the magnetic iron circuit of transformers and electrical machines are all laminated.

Induction

Induction is the magnetic field which is proportional to the rate of change of the magnetic field. This definition of induction holds for a conductor. Induction is also known as inductance. L is used to represent the inductance and Henry is the SI unit of inductance.

1 Henry is defined as the amount of inductance required to produce an emf of 1 volt in a conductor when the current change in the conductor is at the rate of 1 Ampere per second.

Factors Affecting Inductance

The following are the factors that affect the inductance:

1. The number of turns of the wire used in the inductor.
2. The material used in the core.
3. The shape of the core.

Electromagnetic Induction law was given by Faraday which states that by varying the magnetic flux electromotive force is induced in the circuit. From Faraday's law of electromagnetic induction, the concept of induction is derived. Inductance can be defined as the electromotive force generated to oppose the change in current at particular time duration.

According to Faraday's Law:

Electromotive force = – L ΔI Δt
Unit of Inductance = Volt Second Ampere=Henry

Types of Inductance

Two types of inductance are there:

- Self Induction
- Mutual Induction.

Self Induction

When there is a change in the current or magnetic flux of the coil, an opposed induced electromotive force is produced. This phenomenon is termed as Self Induction. When the current starts flowing through the coil at any instant, it is found that, that the magnetic flux becomes directly proportional to the current passing through the circuit. The relation is given as:

ϕ= I
ϕ = L I

where L is self-inductance of the coil or the coefficient of self-inductance. The self-inductance depends on the cross-sectional area, the permeability of the material, or the number of turns in the coil.

The rate of change of magnetic flux in the coil is given as,

$e = – d\phi/dt = – d(LI)/dt$

or $e = – L (dI/dt)$

Self Inductance Formula $L = NI\boldsymbol{\phi}$

Where,

- L is the self inductance in Henry
- N is the number of turns
- Φ is the magnetic flux
- I is the current in amperes

Mutual Induction

We take two coils, and they are placed close to each other. The two coils are P- coil (Primary coil) and S- coil (Secondary coil). To the P-coil, a battery, and a key is connected wherein the S-coil a galvanometer is connected across it. When there is a change in the current or magnetic flux linked with two coils an opposing electromotive force is produced across each coil, and this phenomenon is termed as Mutual Induction. The relation is given as:

$\phi = I$

$\phi = M I$

where M is termed as the mutual inductance of the two coils or the coefficient of the mutual inductance of the two coils.

The rate of change of magnetic flux in the coil is given as,

$e = – d\phi/dt = – d(MI)/dt$

$e = – M dI/dt$

- μ_0 is the permeability of free space
- μ_r is the relative permeability of the soft iron core

- N is the number of turns in coil
- A is the cross-sectional area in m^2
- l is the length of the coil in m

Derivation of Inductance

Consider a DC source with its switch on, when the switch is turned on, the current flows from zero to a certain value such that there is a change in the rate of current flowing. Let φ be the change in flux due to current flow. The change in flux is with respect to time which is given as

$d\varphi/dt$

Apply Faraday's law of electromagnetic induction,

$E = N\, d\phi/dt$

where,

- N is the number of turns in the coil
- E is the induced EMF across the coil

From Lenz's law, we can write the above equation as

$E = -N\, d\phi/dt$

The above equation is modified for calculating the value of inductance

$E = -N\, d\phi/dt$

$E = -L\, di / dt$

$N = d\Phi = L\, di$

$N\Phi = Li$

Therefore,

$L = N\Phi = NBA$

Where,

- B is the flux density
- A is the area of the coil

$B = \mu H$

Applications of Eddy currents

During braking, the brakes expose the metal wheels to a magnetic field which generates eddy currents in the wheels. The magnetic interaction between the applied field and the eddy currents acts to slow the wheels down. The faster the wheels spin, the stronger is the effect, meaning that as the train slows the braking force is reduces, producing a smooth stopping motion.

Electromagnetic damping

Used to design dead beat galvanometers. Usually, the needle oscillates a little about its equilibrium position before it comes to rest. This causes a delay in taking the reading so to avoid this delay; the coil is wound over a non-magnetic metallic frame. As the coil is deflected, eddy currents set up in the metallic frame and thus, the needle comes to rest almost instantly.

Thus, the motion of the coil is damped. Certain galvanometers have a fixed core made up of nonmagnetic metallic material. When the coil oscillates, the eddy currents that generate in the core oppose the motion and bring the coil to rest.

Electric Power Meters

The shiny metal disc in the electric power meter rotates due to eddy currents. The magnetic field induces the electric currents in the disc. You can also observe the shiny disc at your house.

Induction Furnace

In a rapidly changing magnetic fields, due to a large emf produced, large eddy currents are set up. Eddy currents produce temperature. Thus a large temperature is created. So a coil is wound over a constituent metal which is placed in a field of the highly oscillating magnetic field produced by high frequency. The temperature produced is enough to melt the metal. This is used to extract metals from ores. Induction furnace can be used to prepare alloys, by melting the metals at a very high temperature.

Speedometers

To know the speed of any vehicle, these currents are used. A speedometer consists of a magnet which keeps rotating according to the speed of our vehicle. Eddy currents are been produced in the drum. As the drum turns in the direction of the rotating magnet, the pointer attached to the drum indicates the speed of the vehicle

Rotating magnetic field

It is a magnetic field that has moving polarities in which its opposite poles rotate about a central point or axis. Ideally, the rotation changes direction at a constant angular rate. This is a key principle in the operation of the alternating-current motor. Rotating magnetic fields are often utilized for electromechanical applications such as induction motors and electric generators. However, they are also used in purely electrical applications such as induction regulators.

Rotating magnetic fields are also used in induction motors. Because magnets degrade with time, induction motors use short-circuited rotors instead of a magnet which follow the rotating magnetic field of a multi coiled stator. In these motors, the short circuited turns of the rotor develop eddy currents in the rotating field of the stator which in turn move the rotor by Lorentz force. These types of motors are not usually synchronous, but instead necessarily involve a degree of 'slip' in order that the current may be produced due to the relative movement of the field and the rotor.

Principle of induction motor

It is an electric motor in which the electric current in the rotor needed to produce torque is obtained by electromagnetic induction from the magnetic field of the stator winding. An induction motor can therefore be made without electrical connections to the rotor. An induction motor's rotor can be either wound type or squirrel-cage type.

The induced currents in the rotor windings in turn create magnetic fields in the rotor that react against the stator field. The direction of the magnetic field created will be such as to oppose the change in current through the rotor windings, in agreement with Lenz's Law. The cause of induced current in the rotor windings is the rotating stator magnetic field, so to oppose the change in rotor-winding currents the rotor will start to rotate in the direction of the rotating stator magnetic field. The rotor accelerates until the magnitude of induced rotor current and torque balances the applied mechanical load on the rotation of the rotor. Since rotation at synchronous speed would result in no induced rotor current, an induction motor always operates slightly slower than synchronous speed. The difference, or "slip," between actual and synchronous speed varies from about 0.5% to 5.0% for standard torque curve induction motors. The induction motor's essential character is that it is created solely by induction instead of being separately excited as in synchronous or DC machines or being self-magnetized as in permanent magnet motors.

The magnetic field would not be moving relative to the rotor conductors and no currents would be induced. As the speed of the rotor drops below synchronous speed, the rotation rate of the magnetic field in the rotor increases, inducing more current in the windings and creating more torque. The ratio between the rotation rate of the magnetic field induced in the rotor and the rotation rate of the stator's rotating field is called "slip". Under load, the speed drops and the slip increases enough to create sufficient torque to turn the load. For this reason, induction motors are sometimes referred to as "asynchronous motors".

An induction motor can be used as an induction generator, or it can be unrolled to form a linear induction motor which can directly generate linear motion. The generating mode for induction motors is complicated by the need to excite the rotor, which begins with only residual magnetization. In some cases, that residual magnetization is enough to self-excite the motor under load. Therefore, it is necessary to both snap the motor and connect it momentarily to a live grid or to add capacitors charged initially by residual magnetism and providing the required reactive power during operation. Similar is the operation of the induction motor in parallel with a synchronous motor serving as a power factor compensator. A feature in the generator mode in parallel to the grid is that the rotor speed is higher than in the driving mode. Then active energy is being given to the grid.