ELECTROMAGNETIC INDUCTION AND ALTERNATING CURRENT

PHYSICS - VOL 1 **UNIT - 4**

NAME :

STANDARD : 12 SECTION :

SCHOOL :

EXAM NO :

உவப்பத் தலைக்கூடி உள்ளப் பிரிதல்
அனைத்தே புலவர் தொழில்

மகிழும் படியாக கூடிப்பழகி இனி இவரை எப்போது காண்போம் என்று வருந்தி நினைக்கும் படியாகப் பிரிதல் புலவரின் தொழிலாகும்

victory **R. SARAVANAN. M.Sc, M.Phil, B.Ed.,**
PG ASST (PHYSICS)
GBHSS, PARANGIPETTAI - 608 502

PART - II 2 MARK QUESTIONS & ANSWERS

1. Define magnetic flux.

- The magnetic flux through an area 'A' in a magnetic field is defined as the number of magnetic field lines passing through that area normally.
- The S.I unit of magnetic flux is $T\ m^2$ **(or)** ***weber***

2. Define electromagnetic induction.

- Whenever the magnetic flux linked with a closed coil changes, an emf is induced and hence an electric current flows in the circuit.
- This emf is called induced emf and the current is called induced current. This phenomenon is called electromagnetic induction.

3. What is the importance of electromagnetic induction?

- There is an ever growing demand for electric power for the operation of almost all the devices used in present day life.
- All these are met with the help of electric generators and transformer which function on electromagnetic induction.

4. State Faraday's laws of electromagnetic induction.

(i) Whenever magnetic flux linked with a closed circuit changes, an emf is induced in the circuit.
(ii) The magnitude of induced emf in a closed circuit is equal to the time rate of change of magnetic flux linked with the circuit.

5. State Lenz's law.

- Lenz's law states that the direction of the induced current is such that is always opposes the cause responsible for its production.

6. State Flemming's right hand rule.

- The thumb, index finger and middle finger of right hand are stretched out in mutually perpendicular directions. If index finger points the direction of magnetic field and the thumb points the direction of motion of the conductor, then the middle finger will indicate the direction of the induced current.
- Flemming's right hand rule is also known as ***generator rule***.

7. What are called eddy currents? How are they produced?

- When magnetic flux linked with a conductor in the form of a sheet or a plate changes, an emf is induced. As a result, the induced current flow in concentric circular paths which resembles eddies of water. Hence these are known as Eddy currents or Foucault currents.

8. A spherical strone and a spherical metallic ball of same size and mass are dropped from the same height. Which one will reach earth's surface first? Justify your answer.

- The stone will reach the earth's surface earlier than the metal ball.
- Because when the metal ball falls through the magnetic field of earth, the eddy currents are produced in it which opposed its motion.
- But in the case of stone, no eddy currents are produced and it falls freely.

9. What is called inductor?

- Inductor is a device used to store energy in a mangnetic field when an electric current flows through it.
  (e.g.) solenoids and toroids

10. What is called self induction?

- The phenomenon of inducing an emf in a coil, when the magnetic flux linked with the coil itself changes is called self induction.
- The emf induced is called self-induced emf.

11. Define self inductance or coeffient of self induction.

- Self inductance of a coil is defined as the flux linkage of the coil, when 1 A current flows through it.
- Its S.I unit is $\boldsymbol{H}$ (or) $\boldsymbol{Wb\ A^{-1}}$ (or) $\boldsymbol{V\ s\ A^{-1}}$ and its dimension is $[\boldsymbol{M\ L^2 T^{-2} A^{-2}}]$

12. Define the unit of self inductance (one henry)

- The inductance of the coil is one henry, if a current changing at the rate of 1 A s^{-1} induces an opposing emf of 1 V in it.

13. What is called mutual induction?

- When an electric current passing through a coil changes with time, an emf is induced in the neighbouring coil. This phenomenon is known as mutual induction and the emf is called mutually induced emf.

14. Define mutual inductance or coefficient of mutual induction.

- Mutual inductance is also defined as the opposing emf induced in the one coil, when the rate of change of current through the other coil is 1 A s^{-1}
- Its S.I unit is $\boldsymbol{H}$ (or) $\boldsymbol{Wb\ A^{-1}}$ (or) $\boldsymbol{V\ s\ A^{-1}}$ and its dimension is $[\boldsymbol{M\ L^2 T^{-2} A^{-2}}]$

15. What the methods of producing induced emf?

- By changing the magnetic field 'B'
- By changing the area 'A' of the coil
- By changing the relative orientation 'θ' of the coil with magnetic field.

16. How an emf is induced by changing the magnetic field?

- Change in magnetic flux of the field is brought about by,
  (i) The relative motion between the circuit and the magnet
  (ii) Variation in current flowing through the nearby coil

17. What is called AC generator or alternator?

- AC generator is a device which converts mechanical energy used to rotate the coil or field magnet in to electrical energy.

18. State the principle of AC generator (alternator)

- It work on the principle of ***electromagnetic induction.*** (i.e.) The relative motion between a conductor and a magnetic field changes the magnetic flux linked with the conductor which in turn induces an emf.
- The magnitude of the induced emf is given by Faraday's law and its direction by Flemming's right hand rule.

19. State single phase AC generator.

- In a single phase AC generator, the armature conductors are connected in series so as to form a single circuit which generates a single - phase alternating emf and hence it is called single-phase alternator.

20. State three phase AC generators.

- If there are three separate coils, which would give three separate emf's then they are called three phase AC generators.

21. What are the advantages of three phase AC generators?

- For a given dimension of the generator, three - phase machine produces higher power output than a single -phase machine.
- For the same capacity, three phase alternator is smaller in size when compared to single phase genarators.
- Three phase transmission system is cheaper. A relatively thinner wire is sufficient for transmission of three phase power.

22. What is called poly phase generator?

- Some AC generators may have more than one coil in the armature core and each coil produces an alternating emf. In these generators, more than one emf is produced. Thus they are called poly-phase generators.

23. What is called transformer?

- It is a stationary device used to transform electrical power from one circuit to another without changing its frequency.
- The applied alternating voltage is either increased or decreased with corresponding decrease or increase in current in the circuit.

24. **Distinguish between step up and step down transformer.**

Step up transformer	Step down transformer
If the transformer converts an alternating current with low voltage in to an alternating current with high voltage is called step up transformer.	If the transformer converts an alternating current with high voltage in to an alternating current with low voltage is called step down transformer.

25. State the principle of transformer.

- The principle of transformer is the **<u>mutual induction</u>** between two coils. (i.e.) when an electric current passing through a coil changes with time, and emf is induced in the other coil.

26. Define the efficiency of the transformer.

- The efficiency (η) of a transformer is defined as the ratio of the useful output power to the input power.

$$\eta = \frac{output\ power}{input\ power} X\ 100\ \%$$

27. Define Sinusoidal alternating voltage.

- If the waveform of alternating voltage is a sine wave, then it is known as sinusoidal alternating voltage and it is given by,

$$v = V_m \sin \omega t$$

28. Define mean value or average value of AC.

- The mean or average value of alternating current is defined as the average of all values of current over a positive half cycle or negative half cycle.

$$I_{avg} = \frac{2\, I_m}{\pi} = 0.6371\, I_m$$

29. Define RMS value of AC.

- The root mean square value of an alternating current is defined as the square root of the mean of the square of all currents over one cycle.

$$I_{RMS} = \frac{I_m}{\sqrt{2}} = 0.707\, I_m$$

30. Define effective value of alternating current.

- RMS value of AC is also called effective value of AC
- The effective value of AC (I_{eff}) is defined as the value of steady current which when flowing through a given circuit for a given time produces the same amount of heat as produced by the alternating current when flowing through the same circuit for the same time.

31. The common house hold appliences, the voltage rating is specified as 230 V, 50 Hz. What is the meaning of it?

- The voltage rating specified in the common house hold appliences indicates the RMS value or effective value of AC. (i.e.) $V_{eff} = 230\ V$
- Its peak value will be,

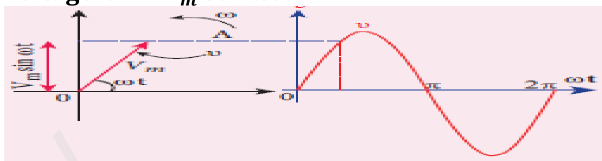
$$V_m = V_{eff}\sqrt{2} = 230\ X\ 1.414 = 325\ V$$

- Also 50 Hz indicates, the frequency of domestic AC supply.

32. Define phasor and phasor diagram.

- A sinusoidal alternating voltage or current can be represented by a vector which rotates about the orgin in anti-clockwise direction at a constant angular velocity 'ω'. Such a rotating vector is called a phasor.
- The diagram which shows various phasors and phase relations is called phasor diagram.

33. Draw the phasor diagram for an alternating voltage $v = V_m \sin \omega t$



34. Define inductive reactance.

- The resistance offered by the inductor in an ac circuit is called inductive reactance and it is given by ; $X_L = \omega L = 2\,\pi\, f\, L$
- Its unit is ***ohm*** (Ω)

35. An inductor blocks AC but it allows DC. Why?

- The DC current flows through an inductor produces uniform mangetic field and the magnetic flux linked remains constant. Hence there is no self induction and self induced emf (opposing emf). So DC flows through an inductor.
- But AC flows through an inductor produces time varying magnetic field which inturn induces self induced emf and this opposes any change in the current. Since AC varies both in magnitude and direction, it flow is opposed by the back emf induced in the inductor and hence inductor blocks AC

36. Define capacitive reactance.

- The resistance offered by the capacitor is an ac circuit is called capacitive reactance and it is given by ; $X_C = \frac{1}{\omega\, C} = \frac{1}{2\,\pi\, f\, C}$
- Its unit is ***ohm*** (Ω)

37. A capacitor blocks DC but it allows AC. Why?

- When DC flows through capacitor, electrons flows from negative terminal and accumulated at one plate making it negative and hence another plate becomes positive. This process is known as charging and once capacitor is fully charged, the current will stop and we say capacitor blocks DC.
- But AC flows through capacitor, the electron flow in one direction while charging the capacitor and its direction is reversed while discharging. Though electrons flow in the circuit, no electrons crosses the gap between the plates. In this way, AC flows through a capacitor.

38. Define resonance.

- When the frequency of the applied sourch is equal to the natural frequency of the RLC circuit, the current in the circuit reaches it maximum value. Then the circuit is said to be in electrical resonance.
- The frequency at which resonance takes place is called resonant frequency.
- Hence the condition for resonance is : $X_L = X_C$

39. What are the applications of series RLC resonant circuit?

- RLC circuits have many applications like filter circuits, oscillators, voltage multipliers etc.,
- An important use of series RLC resonant circuits is in the tuning circuits of radio and TV systems. To receive the signal of a particular station among various broadcasting stations at different frequencies, tuning is done.

40. Resonance will occur only in LC circuits. Why?

- When the circuits contains both L and C, then voltage across L and C cancel one another when V_L and V_C are 180° out of phase and the circuit becomes purely resistive.
- This implies that resonance will not occur in a RL and RC circuits.

41. Define Q - factor or quality factor.

- Q - factor is defined as the ratio of voltage across L or C to the applied voltage at resonance.

42. Define power in an AC circuits.

- Power of a circuits is defined as the rate of consumption of electric energy in that circuit.
- It is the product of the voltage and current.

43. Define power factor.

- Power factor ($\cos\phi$) of a circuit is defined as the cosine of the angle of lead or lag
- Power factor is also defined as the ratio of true power to the apparent power.

44. Define wattles current.

- If the power consumed by an AC circuit is zero, then the current in that circuit is said to be wattless current.
- This wattles current happens in a purely inductive or capacitive circuit.

45. What are called LC oscillations?

- Whenever energy is given to a circuit containing a pure inductor of inductance L and a capacitor of capacitance C, the energy oscillates back and forth between the magnetic field of the inductor and the electric field of the capacitor.
- Thus the electrical oscillations of definite frequency are generated. These oscillations are called LC oscillations.

46. Define Flux linkage.

- The product of magnetic flux (Φ_B) linked with each turn of the coil and the total number of turns (N) in the coil is called flux linkage ($N\Phi_B$)

47. Define impedeance of RLC circuit.

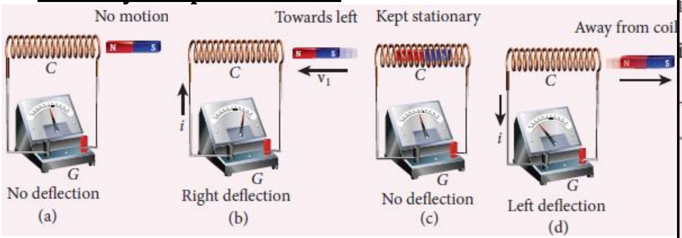
- The effective opposion by resistor, inductor and capacitor to the circuit current in the series RLC circuit is called impedance (Z)

$$Z = \sqrt{R^2 + (X_L - X_C)^2}$$

PART - III 3 MARK QUESTIONS AND ANSWERS

1. Establish the fact that the relative motin between the coil and the magnet induces an emf in the coil of a closed circuit.

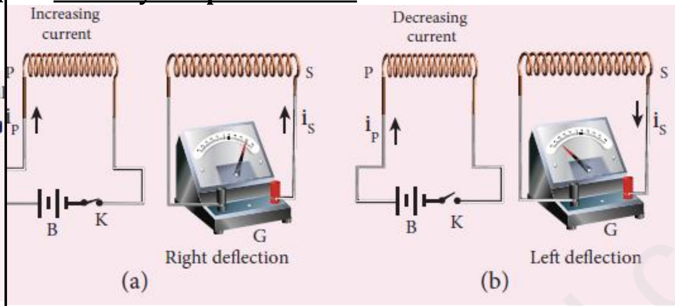
Faraday's experiment - 1 :



- Consider a closed circuit consisting of a coil 'C' and a galvanometer 'G'. Initially the galvanometer shows no deflection.
- When a bar magnet move towards the stationary coil with its north pole (N) facing the coil, there is a momentary deflection in the galvanometer. This indicates that an electric current is set up in the coil
- If the magnet is kept stationary inside the coil, the galvanometer does not indicate deflection.
- The bar magnet is now withdrawn from the coil, the galvanometer again gives a momentary deflection but is opposite direction. This indicates current flows in opposite direction.
- Now if the magnet is moved faster, it gives a larger deflection due to a greater current in the circuit.
- The bar magnet is reversed (i.e.) the south pole now faces the coil and the experiment is repeated, same results are obtained but the directions of deflection get reversed.
- Simillarly if the magnet is kept stationary and the coil moved towards or away from the coil, similar results are obtained.
- Thus the above experiments concluded that, whenever there is a relative motion between the coil and the magnet, ther is a deflection in the galvanometer, indicating the electric current set up in the coil.

2. Prove that experimentaly if the current in a one closed circuit changes, an emf is induced in another circuit.

Faraday's experiment - 2 :



- Consider a closed circuit called primary consisting of coil 'P', a battery 'B' and a key 'K'
- Consider an another closed circuit called secondary consisting of coil 'S and a galvanometer 'G'
- Here the two coils 'P' and 'S' are kept at rest in close proximity with respect to one another.
- When the primary circuit is closed, current starts flowing in this circuit. At this time, the galvanometer gives a momentary deflection. After that, when current reaches a steady value, no deflection is observed in the galvanometer.
- Similarly, if the primary circuit is broken, current starts decreasing and there is again a momentary deflection but in the opposite direction. When current becomes zero, the galvanometer shows no deflection.
- From the above observations, it is concluded that whenever the electric current in the primary changes, the galvanometer in secondary shows a deflection.

3. How we understood the conclusions obtained from Faraday's experiment.

Faraday's experiment - Explanation :

Experiment - 1 :

- In the first experiment, when a bar magnet is placed close to a coil, then there is some magnetic flux linked with the coil.
- When the barmagneti and coil approach each other, the magnetic flux linked with the coil increases and this increase in magnetic flux induces an emf and hence a transient current flows in one direction.
- At the same time, when they recede away from one another, the magnetic flux linked with the coil decreases. The decrease in magnetic flux again induces an emf in opposite direction and hence an electric current flows in opposite direction.
- So there is deflection in the galvanometer, when there is a relative motion between the coil and the magnet.

Experiment - 2 :

- In the second experiment, when the primary coil 'P' carries an electric current, a magnetic field is established around it. The magnetic lines of this field pass through itself and the neighbouring secondary coil 'S'
- When the primary circuit is open, no current flows in it and hence the magnetic flux linked with secondary coil is zero
- When the primary circuit is closed, the increasing current increases the magnetic flux linked with primary as well as secondary coil. This increasing flux induces a current in the secondary coil.
- When the current in the primary coil reaches a steady value, the magnetic flux linked with the secondary coil does not change and the current in it will disappear.
- Similarly, when the primary circuit is broken, the decreasing current induces an electric current in the secondary coil, but in opposite direction.
- So there is a deflection in the galvanometer, whenever there is a change in the primary current.

4. State and explain Faraday's laws of electromagnetic induction.

Faraday's first law :

- Whenever magnetic flux linked with a closed circuit changes, an emf is induced in the circuit.
- The induced emf lasts so long as the change in magnetic flux continues.

Faraday's second law :

- The magnitude of induced emf in a closed circuit is equal to the time rate of change of magnetic flux linked with the circuit.
- If magnetic flux linked with the coil changes by $d\Phi_B$ in time dt , then the induced emf is given by,

$$\epsilon = -\frac{d\Phi_B}{dt}$$

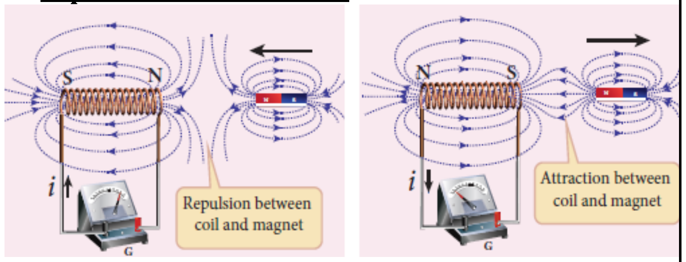
- The negative sign in the above equation gives the direction of the induced current
- If a coil consisting of 'N' turns, then

$$\epsilon = -N\frac{d\Phi_B}{dt} = -\frac{d\,(N\,\Phi_B)}{dt}$$

- Here $N\,\Phi_B$ is called flux linkage.

5. Give an illustration of determining direction of induced current by using Lenz's law.

<u>Explanation of Lenz's law</u> :



- Let a bar magnet move towards the solenoid with its north pole pointing the solenoid.
- This motion increases the magnetic flux linked with the solenoid and hence an electric current is induced. Due to the flow of induced current, the coil become a magnetic dipole whose two magnetic poles are on either end of the coil.
- Here the cause producing the induced current is the movement of the magnet.
- According to Lenz's law, the induced current should flow in such a way that it opposed the movement of the north pole towards coil.
- It is possible if the end nearer to the magnet becomes north pole. Then it repels the north pole of the bar magnet and opposed the movement of the magnet.
- Once pole end are known, the direction of the induced current could be found by using right hand thumb rule.
- Whwn the bar magnet is with drawn, the nearer end becomes south pole which attracts north pole of the bar magnet, opposing the receding of the magnet.
- Thus the direction of the induced current can be found from Lenz's law.

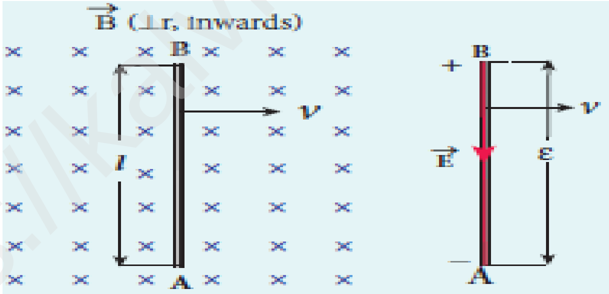
6. Show that Lenz's law is in accordance with the law of conservation of energy.

Conservation of energy - Lenz's law :

- According to Lenz's law, when a magnet is moved either towards or away from a coil, the induced current produced opposes its motion.
- As a result, there will always be a resisting force on the moving magnet. So work has to be done by some external agency to move the magnet against this resistive force.
- Here the mechanical energy of the moving magnet is converted into the electrical energy which inturn gets converted in to Joule heat in the coil. (i.e) energy is conserved from one form to another
- On the contrary to Lenz's law, let us assume that the induced current helps the cause responsible for its production.
- If we push the magnet little bit towards the coil, the induced current helps the movement of the magnet towards the coil.
- Then the magnet starts moving towards the coil without any expense of energy, which is impossible in practice.
- Therefore the assumption that the induced current helps the cause is wrong.

7. Obtain an expression for motional emf from Lorentz force.

<u>Motional emf from Lorentz force</u>:



- Consider a straight conductor rod AB of length 'l' in a uniform magnetic field $\vec{B}$ which is directed perpendicularly in to plane of the paper.
- Let the rod move with a constant velocity $\vec{v}$ towards right side.
- When the rod moves, the free electrons present in it also move with same velocity $\vec{v}$ in $\vec{B}$
- As a result, the Lorentz forec acts on free electron in the direction from B to A and it is given by,

$$\vec{F_B} = -e\,(\vec{v}\ X\ \vec{B}) \quad ---- \ (1)$$

- Due to this force, all the free electrons are accumulate at the end A which produces the potential difference across the rod which inturn establishes an electric field $\vec{E}$ directed along BA
- Due to the electric field, the Coulomb force starts acting on the free electron along AB and it is given by,

$$\vec{F_E} = -e\,\vec{E} \quad ----- \ (2)$$

- At equilibrium, $|\vec{F_B}| = |\vec{F_E}|$

$$|-e\,(\vec{v}\ X\ \vec{B})| = |-e\,\vec{E}|$$

$$B\,e\,v\sin 90° = e\,E$$

$$B\,v = E \quad ---- \ (3)$$

- The potential difference between two ends of the rod is ,

$$V = E\,l = B\,v\,l$$

- Thus the Lorentz force on the free electrons is responsible to maintain this potential difference and hence produces an emf

$$\boldsymbol{\epsilon = B\,l\,v} \quad ---- \ (4)$$

- Since this emf is produced due to the movement of the rod, it is often called as ***motional emf***.

8. Define eddy currents. Demonstrate the production of eddy currents.

<u>Eddy currents</u>:

- When magnetic flux linked with a conductor in the form of a sheet or a plate changes, an emf is induced.
- As a result, the induced current flow in concentric circular paths which resembles eddies of water. Hence these are known as Eddy currents or Foucault currents.

<u>Demonstration</u> :

- Let a pendulum that can be freely suspended between the poles of a powerful electromagnet.
- Keeping the magnetic field switched off, If the pendulum is made to oscillate, it executes a large number of oscillations before stops. Here air friction is a only damping force.
- When the electro magnet is switched on, and the pendulum is made to oscillate, it comes to rest within a few oscillations. Because eddy currents are produced in it and it will oppose the oscillations (Lenz's law)

- However some slots are cut in the disc, the eddy currents are reduced and now the pendulum executes several oscillations before coming to rest.
- This clearly demonstrates the production of eddy current in the disc of the pendulum.

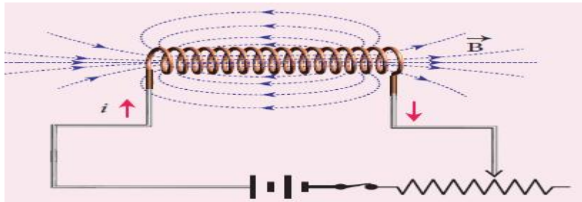
9. What are the drawbacks of Eddy currents. How it is minimized?

Drawbacks of Eddy currents :

- When eddy currents flow in the conductor, a large amout of energy is dissipated in the form of heat.
- The energy loss due to flow of eddy current is inevitable but it can be reduced.
- To reduce eddy current losses, the core of the transformer is made up of thin laminas insulated from one another. In case of electric motor the winding is made up of a group of wire insulated from one another.
- The insulation used does not allow huge eddy currents to flow and hence losses are minimized.

10. Explain self induction and define coefficient of self induction on the basis of (1) magnetic flux and (2) induced emf

Self induction :



- When an electric current flowing through a coil changes, an emf is induced in the same coil. This phemomenon is known as self induction. The emf induced is called self-induced emf.
- Let Φ_B be the magnetic flux linked with each turn of the coil of turn 'N', then total flux linkage $(N\Phi_B)$ is directly proportional to the current 'i'

$$\mathrm{N}\,\Phi_B \propto i \qquad (or) \qquad \mathrm{N}\,\Phi_B = L\,i$$

$$\therefore \quad \mathbf{L} = \frac{\mathbf{N}\,\boldsymbol{\Phi_B}}{\boldsymbol{i}}$$

- Where, L → constant called coefficient of self induction (or) self inductance
- When the current (i) changes with time, an emf is induced in the coil and it is given by,

$$\epsilon = -\frac{d(\mathrm{N}\,\Phi_B)}{dt} = -\frac{d\,(L\,i)}{dt} = -\boldsymbol{L}\,\frac{\boldsymbol{di}}{\boldsymbol{dt}}$$

$$\therefore \qquad L = -\frac{\epsilon}{\left(\frac{di}{dt}\right)} \qquad ----(2)$$

Coefficient of self induction - Definition :

- Self inductance of a coil is defined as the flux linkage of the coil, when 1 A current flows through it.
- Self inductance of a coil is also defined as the opposing emf induced in the coil, when the rate of change of current through the coil is 1 A s^{-1}

11. How will you define the unit of inductance?

Unit of inductance :

- Inductance is a scalar and its unit is $\boldsymbol{Wb\,A^{-1}}$ (or) $\boldsymbol{V\,s\,A^{-1}}$ (or) ***henry (H)***
- It dimension is $[\boldsymbol{M\,L^2T^{-2}A^{-2}}]$

Definition - 1 :

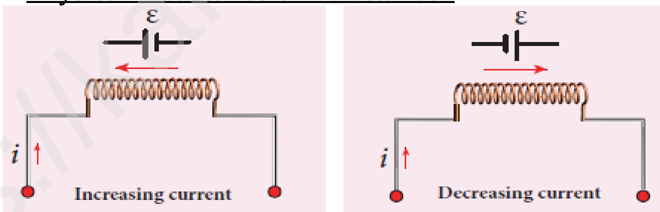
- The self inductance is given by, $\mathbf{L} = \frac{\mathbf{N}\,\Phi_B}{i}$
- The inductance of the coil is one henry if a current of 1 A produces unit fux linkage in the coil.

Definition - 2 :

- The self inductance is given by, $\boldsymbol{L} = -\frac{\epsilon}{\left(\frac{di}{dt}\right)}$
- The inductance of the coil is one henry if a current changing at the rate of $\mathbf{1\,A\,s^{-1}}$ induces an opposing emf of 1 V in it.

12. Discuss the physical significance of inductance.

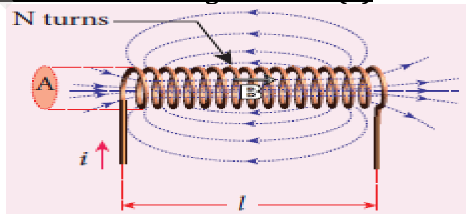
Physical inductance of inductance :



- Generally inertia means opposition to change the state of the body.
- In translational motion, mass is a measure of inertia, whereas in rotational motion, moment of inertia is a measure of rotational inertia.
- Simillarly inductance plays the same role in a circuit as the mass and moment of inertia play in mechanical motion.
- When a ciruit is switched on, the increasing current induces an emf which opposes the growth of current in a circuit.
- Simillarly, when a circuit is broken, the decreaing current induces an emf in the reverese direction which opposed the decay of the current.
- Thus inductance on the coil opposes any change in current and tries to maintain the original state.

13. Assuming that the length of the solenoid is large when compared to its diameter, find the equation for its inductance.

Self inductance of a long solenoid (L) :



- Consider a long solenoid of length 'l', area of cross section 'A' having 'N' number of turns
- Let 'n' be number of turns per unit length (i.e.) turn density
- When an electric current 'i' is passed through the coil, a magnetic field at any point inside the solenoid is,

$$B = \mu_o\,n\,i$$

- Due to this field, the magnetic flux linked with the solenoid is,

$$\Phi_B = \oint \vec{B}\,.\,d\vec{A} = \oint B\,dA\cos 90^\circ = B\,A$$

$$\Phi_B = [\mu_o\,n\,i]\,A$$

- Hence the total magnetic flux linked (i.e.) flux linkage

$$N\,\Phi_B = N\,\mu_o\,n\,i\,A = (n\,l)\,\mu_o\,n\,i\,A$$

$$\boldsymbol{N\,\Phi_B = \mu_o\,n^2\,i\,A\,l}$$

- Let 'L' be the self inductance of the solenoid, then

$$L = \frac{N\,\Phi_B}{i} = \frac{\mu_o\,n^2\,i\,A\,l}{i}$$

$$\boldsymbol{L = \mu_o\,n^2\;A\,l}$$

- If the solenoid is filled with a dielectric medium of relative permeability 'μ_r', then

$$\boldsymbol{L = \mu_o\,\mu_r\,n^2\,A\,l = \mu\,n^2\,A\,l}$$

- Thus, the inductance depens on
  - (i) geomentry of the solenoid
  - (ii) medium present inside the solenoid

14. An inductor of inductance 'L' carries an electric current 'i'. How much energy is stored while establishing the current in it?

Energy stored in an solenoid :

- Whenever a current is established in the circuit, the inductance opposes the growth of the current.
- To establish the current, work has to done against this opposition. This work done is stored as magnetic potential energy.
- Consider an inductor of negligible resistance, the induced emf '$\in$' at any instant 't' is

$$\in = -L\frac{di}{dt}$$

- Let 'dW' be the workdone in moving a charge 'dq' in a time 'dt' against the opposition, then

$$dW = -\in dq = -\in i\, dt$$

$$dW = -\left[-L\frac{di}{dt}\right] i\, dt = L\, i\, di$$

- Total wor done in establishing the current 'i' is

$$W = \int dW = \int L\, i\, di = L\left[\frac{i^2}{2}\right]_0^i = \frac{1}{2}L\, i^2$$

- This work done is stored as magnetic potential energy. (i.e)

$$\boldsymbol{U_B = \frac{1}{2}L\, i^2}$$

- The energy stored per unit volume of the space is called ***energy density*** (u_B) and it is given by,

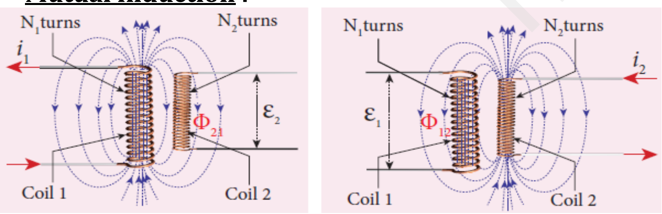
$$u_B = \frac{energy\ (U_B)}{volume\ (A\, l)} = \frac{\frac{1}{2}L\, i^2}{A\, l} = \frac{1}{2}\frac{(\mu_o n^2\ A\, l)\, i^2}{A\, l}$$

$$\boldsymbol{u_B = \frac{\mu_o n^2 i^2}{2}}$$

$$\boldsymbol{u_B = \frac{B^2}{2\,\mu_o}} \qquad [\because B = \mu_o n\, i]$$

15. Explain mutual induction. Define coefficient of mutual induction on the basis of (1) magnetic flux and (2) induced emf

Mutual induction :



- When an electric current passing through a coil changes with time, an emf is induced in the neighbouring coil. This phenomenon is known as mutual induction and the emf is called mutually induced emf.
- Consider two coils 1 and 2 which are placed close to each other. If an electric current 'i_1' is sent through coil -1, the magnetic field produced by it also linked with the coil -2
- Let 'Φ_{21}' be the magnetic flux linked with each turn of the coil-2 of N_2 turns due to coil -1, then the total flux linked with coil -2 is proportional to the current 'i_1' in the coil -`1 (i.e.)

$$N_2\Phi_{21} \propto i_1 \qquad (or) \qquad N_2\Phi_{21} = M_{21}i_1$$

$$\therefore \quad \boldsymbol{M_{21} = \frac{N_2\Phi_{21}}{i_1}} \qquad ----\ \textbf{(1)}$$

- Here M_{21} → constant called coefficient of mutual induction or mutual inductance coil -2 with respect to coil -1
- When the current 'i_1' changes with time, an emf '$\in_2$' is induced in coil -2 and it is given by,

$$\in_2 = -\frac{d\,(N_2\Phi_{21})}{dt} = -\frac{d\,(M_{21}i_1)}{dt} = -M_{21}\frac{di_1}{dt}$$

$$\therefore \quad \boldsymbol{M_{21} = -\frac{\in_2}{\left(\frac{di_1}{dt}\right)}} \qquad ----\ (2)$$

- Similarly,

$$\boldsymbol{M_{12} = \frac{N_1\Phi_{12}}{i_{12}}} \qquad ----\ \textbf{(3)}$$

$$\& \qquad \boldsymbol{M_{12} = -\frac{\in_1}{\left(\frac{di_2}{dt}\right)}} \qquad ----\ (4)$$

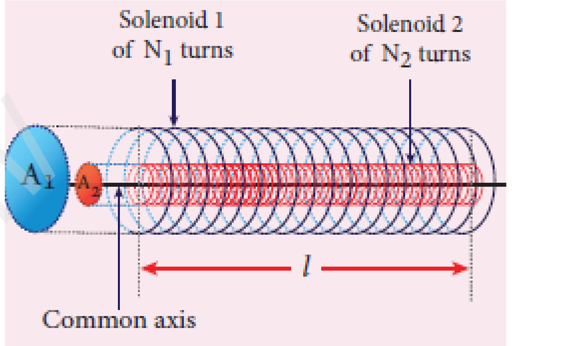
- Here M_{21} → constant called coefficient of mutual induction or mutual inductance coil -2 with respect to coil -1

Coefficient of mutual induction - Definition :

- The mutual inductance is defined as the flux linkage of the one coil, when 1 A current flow through other coil.
- Mutual inductance is also the opposing emf induced in one coil, when the rate of change of current through other coil is 1 $A\, s^{-1}$

16. Show that the mutual inductance between a pair of coils is same $(M_{12} = M_{21})$

Mutual inductance between a pair of coils :



- Consider two long co-axial solenoids of same length 'l'
- Let A_1 and A_2 be the area of cross section of the solenoids. Here $A_1 > A_2$
- Let the turn density of these solenoids are n_1 and n_2 resectively.
- Let 'i_1' be the current flowing through solenoid -1, then the magnetic field produced inside it is,

$$B_1 = \mu_o\, n_1\, i_1$$

- Hence the magnetic flux linked with each turn of solenoid -2 due to solenoid -1 is

$$\Phi_{21} = \oint \vec{B_1}\,.\,\vec{dA_2} = \oint B_1\, dA_2 \cos 0° = B_1\, A_2$$

$$\Phi_{21} = (\mu_o\, n_1\, i_1)\, A_2$$

- Then total flux linkage of solenoid -2 of N_2 turns is

$$N_2\Phi_{21} = (n_2\, l)\,(\mu_o\, n_1\, i_1)\, A_2$$

$$N_2\Phi_{21} = \mu_o\, n_1\, n_2\ A_2\, l\, i_1 \qquad ----\ (1)$$

- So the mutual inductance of solenoid -2 with respect to solenoid -1 is given by,

$$M_{21} = \frac{N_2\Phi_{21}}{i_1} = \frac{\mu_o\, n_1\, n_2\ A_2\, l\, i_1}{i_1}$$

$$\boldsymbol{M_{21} = \mu_o\, n_1\, n_2\ A_2\, l} \qquad ----\ (2)$$

- Similarly, Let 'i_2' be the current flowing through solenoid -2, then the magnetic field produced inside it is,

$$B_2 = \mu_o\, n_2\, i_2$$

- Hence the magnetic flux linked with each turn of solenoid -1 due to solenoid -2 is

$$\Phi_{12} = \oint \vec{B_2}\,.\,\vec{dA_2} = \oint B_2\, dA_2 \cos 0° = B_2\, A_2$$

$$\Phi_{12} = (\mu_o\, n_2\, i_2)\, A_2$$

- Then total flux linkage of solenoid -1 of N_1 turns is

$$N_1\Phi_{12} = (n_1\, l\,)\,(\mu_o\, n_2\, i_2\,)\, A_2$$
$$N_1\Phi_{12} = \mu_o\, n_1\, n_2\;\, A_2\, l\, i_2 \qquad ---- \; (3)$$

- So the mutual inductance of solenoid -1 with respect to solenoid -2 is given by,

$$M_{12} = \frac{N_1\Phi_{12}}{i_2} = \frac{\mu_o\, n_1\, n_2\;\, A_2\, l\, i_2}{i_2}$$
$$\boldsymbol{M_{12} = \;\mu_o\, n_1\, n_2\;\, A_2\, l} \qquad ---- \; (4)$$

- From equation (2) and (4), $\boldsymbol{M_{12} = \;M_{21}}$
- In general, the mutual inductance between two long co-axial solenoids is given by

$$\boldsymbol{M \;=\; \mu_o\, n_1\, n_2\;\, A_2\, l}$$

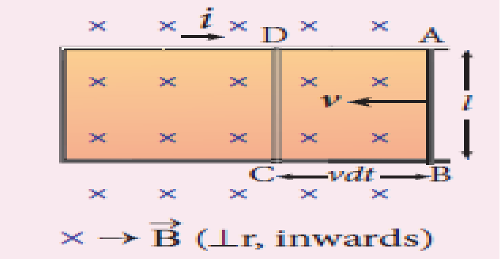
- If the solenoid is filled with a dielectric medium of relative permeability 'μ_r', then

$$\boldsymbol{M = \;\mu_o\, \mu_r\, n_1\, n_2\;\, A_2\, l = \;\mu\;\, n_1\, n_2\;\, A_2\, l}$$

- Thus, the inductance depens on
  - (i) geomentry of the solenoids
  - (ii) medium present inside the solenoids
  - (iii) proximity of the two soienoids

17. How will you induce an emf by changing the area enclosed by the coil.

<u>EMF induced by changing area enclosed by the coil</u>



- Consider a conducting rod of length 'l' moving with a velocity 'v' towards left on a rectangular metallic frame work.
- The whole arangemetn is placed in a uniform magnetic field '$\vec{B}$' acting perpendicular to the plane of the coil inwards.
- As the rod moves from AB to DC in a time 'dt', the area enclosed by the loop and hence the magnetic flux through the loop decreases.
- The change in magnetic flux in time 'dt' is

$$d\Phi_B = B\; dA = B\;(l\;\; X\; v\; dt)$$
$$\frac{d\Phi_B}{dt} = B\; l\; v$$

- This change in magnetic flux results and induced emf and it is given by,

$$\epsilon = \frac{d\Phi_B}{dt}$$
$$\epsilon = \boldsymbol{B\; l\; v}$$

- This emf is called motional emf. The direction of induced current is found to be clock wise from Fleming's right hand rule.

18. What are the advantages of stationary armature - rotating field alternator?

<u>Advantages of stationary armature - rotating field alternator</u> :

- The current is drawn directly from fixed terminals on the stator without the use of brush contacts.
- The insulation of stationary armature winding is easier.
- The number of slip rings is reduced. Moreover the sliding contacts are used for low-voltage DC source.
- Armature windings can be constructed more rigidly to prevent deformation due to any mechanical stress.

19. Explain various energy losses in a transformer.

<u>Energy losses in a transformer</u> :

(i) **<u>Core loss or Iron loss</u>** :

- Hysterisis loss and eddy current loss are known as core loss or Iron loss.
- When transformer core is magnetized or demangnetized repeatedly by the alternating voltage applied across primary coil, hyterisis takes place and some energy lost in the form of heat. It is minimized by using ***silicone steel*** in making transformer core.
- Alternating magnetic flux in the core induces eddy currents in it. Therefore there is energy loss due to the flow of eddy current called eddy current loss. It is minimized by using ***very thin laminations*** of transformer core.

(ii) **<u>Copper loss</u>** :

- The primary and secondary coils in transformer have electrical resistance.
- When an electric current flows through them, some amount of energy is dissipated due to Joule's heating and it is known as copper loss.

It is minimized by using ***wires of larger diameter (thicki wire)***

(iii) **<u>Flux leakage</u>** :

- The magnetic flux linked with primary coil is not completely linked with secondary. Energy loss due to this flux leakage is minimize by ***winding coils one over the other***.

20. Discuss the advantages of AC in long distance power transmission.

<u>Long distance power transmission</u> :

- The electric power is generated in power stations using AC generators are transmitted over long distances through transmission lines to reach towns or cities. This process is called ***power transmission***.
- But during power transmission, due to Joules's heating $((I^2R)$ in the transmission lines, sizable fraction of electric power is lost.
- This power loss can be reduced either by reducing current (I) or by reducing resistance (R)
- Here the resistance 'R' can be reduced with thick wires of copper or aluminium. But this increases the cost of production of transmission lines and hence this method is not economically viable.
  - Thus by using transformer, the current is reduced by stepped up the alternating voltage and thereby reducing power losses to a greater extent.

<u>Illustration</u> :

- Let an electric power of 2 MW is transmitted through the transmission lines of resistance $40\;\Omega$ at $10\;kV$ and $100\;kV$

(i) $P = 2\;MW,\quad R = 40\;\Omega,\quad V = 10\;kV$, then

$$I = \frac{P}{V} = \frac{2\;X\;10^6}{10\;X\;10^3} = 200\;A$$
$$\text{Power loss} \;=\; I^2\;R = (200)^2\;X\;40 = 1.6\;X\;10^6\;\;W$$
$$\%\text{ of Power loss} \;=\; \frac{1.6\;X\;10^6}{2\;X\;10^6} = 0.8 = \mathbf{80}\;\%$$

(ii) $P = 2\;MW,\quad R = 40\;\Omega,\quad V = 100\;kV$, then

$$I = \frac{P}{V} = \frac{2\;X\;10^6}{100\;X\;10^3} = 20\;A$$
$$\text{Power loss} \;=\; I^2\;R = (20)^2\;X\;40 = 0.016\;X\;10^6\;\;W$$
$$\%\;of\;power\;loss = \frac{0.016\;X\;10^6}{2\;X\;10^6} = 0.008 = \mathbf{0.8}\;\%$$

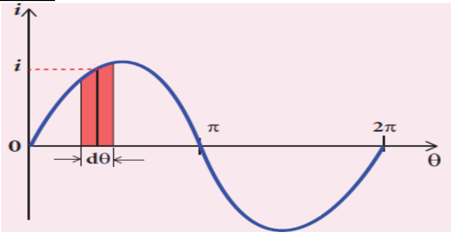
- Thus it is clear that, when an electric power is transmitted at high voltage, the power loss is reduced to a large extent.
- So at transmitting point the voltage is increased and the corresponding current is decreased by using step-up transformer. At receiving point, the voltage is decreased and the current is increased by using step-down transformer

21. Obtain the expression for average value of alternating current.

<u>Average or Mean value of AC</u> :

- The average value of AC is defined as the average of all values of current over a positive half-cycle or negative half-cycle.

<u>Expression</u> :



- The average or mean value of AC over one complete cycle is zero. Thus the average or mean value is measured over one half of a cycle.
- The alternating current at any instant is

$$i = I_m \sin \omega t = I_m \sin \theta$$

- The sum of all currents over a half-cycle is given by area of positive half-cycle (or) negative half-cycle.
- Consider an elementary strip of thickness '$d\theta$' in positive half-cycle,

  Area of the elementary strip $= i\ d\theta$

- Then area of positive half-cycle,

$$= \int_0^{\pi} i\ d\theta = \int_0^{\pi} I_m \sin\theta\ d\theta = I_m[-\cos\theta]_0^{\pi}$$

$$= -I_m\,[\cos\pi - \cos 0] = -I_m\,[-1-1] = 2\,I_m$$

- Then Average value of AC,

$$I_{av} = \frac{area\ of\ positve\ or\ negative\ half-cycle}{base\ length\ of\ half-cycle}$$

$$\mathbf{I_{avg}} = \frac{\mathbf{2\,I_m}}{\boldsymbol{\pi}} = \mathbf{0.637\,I_m}$$

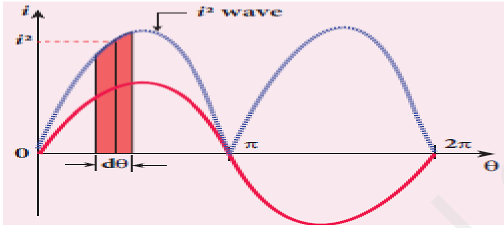
- For negative half-cycle ; $\mathbf{I_{avg}} = -\mathbf{0.637\,I_m}$

22. Obtain an expression for RMS value of alternating current.

<u>RMS value of AC</u> (I_{RMS}) :

- The root mean squae value of an alternating current is defined as the square root of the mean of the squares of all currents over one cycle.

<u>Expression</u> :



- The alternating current at any instant is

$$i = I_m \sin\omega t = I_m \sin\theta$$

- The sum of the squares of all currents over one cycle is given by the area of one cycle of squared wave.
- Consider an elementary area of thickness '$d\theta$' in the first half-cycle of the squared current wave.

  Area of the element $= i^2\,d\theta$

- Area of one cycle of squared wave,

$$= \int_0^{2\pi} i^2\,d\theta = \int_0^{2\pi} {I_m}^2 \sin^2\theta\ d\theta$$

$$= {I_m}^2 \int_0^{2\pi} \left[\frac{1-\cos 2\theta}{2}\right] d\theta$$

$$[\because\ \cos 2\theta = 1 - 2\sin^2\theta\ ]$$

$$= \frac{{I_m}^2}{2}\left[\int_0^{2\pi} d\theta - \int_0^{2\pi} \cos 2\theta\ d\theta\right]$$

$$= \frac{{I_m}^2}{2}\left[\theta - \frac{\sin 2\theta}{2}\right]_0^{2\pi}$$

$$= \frac{{I_m}^2}{2}\left[2\pi - \frac{\sin 4\pi}{2} - 0 + \frac{\sin 0}{2}\right]$$

$$[\because\ \sin 0 = \sin 4\pi = 0]$$

$$= \frac{{I_m}^2}{2}\,[2\,\pi] = {I_m}^2\,\pi$$

- Hence,

$$I_{RMS} = \sqrt{\frac{area\ of\ one\ cycle\ of\ squared\ wave}{base\ length\ of\ one\ cycle}}$$

$$\mathrm{I_{RMS}} = \sqrt{\frac{{I_m}^2\,\pi}{2\,\pi}} = \sqrt{\frac{{I_m}^2}{2}}$$

$$\mathbf{I_{RMS}} = \frac{\mathbf{I_m}}{\sqrt{\mathbf{2}}} = \mathbf{0.707\,I_m}$$

- Similarly for alternating voltage, it can be shown that,

$$\mathbf{V_{RMS}} = \frac{\mathbf{V_m}}{\sqrt{\mathbf{2}}} = \mathbf{0.707\,V_m}$$

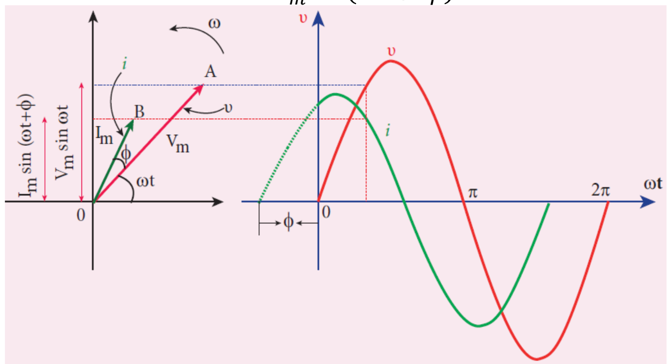
- RMS value of AC is also called effective value (I_{eff})

23. Draw the phasor diagram and wave diagram for that current 'i' leads the voltage 'V' by phase angle of 'ϕ'

<u>Phasor and wave diagram of 'i' leads 'V' by 'ϕ'</u>

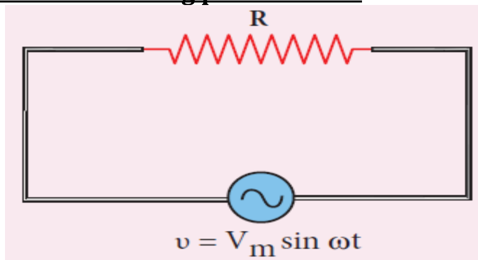
- Let the alternating current and voltage at any instant is,

$$v = V_m \sin\omega t$$
$$i = I_m \sin(\omega t + \phi)$$



24. Find out the phase relation ship between voltage and current in a pure resistive circuit.

<u>AC circuit containing pure resistor</u> :



- Let a pure resistor of resistance 'R' connected across an alternating voltage source 'v'
- The instantaneous value of the alternating voltage is given by,

$$v = V_m \sin \omega t \qquad ---- (1)$$

- Let 'i' be the alternating current flowing in the circuit due to this voltage, then the potential drop across 'R' is

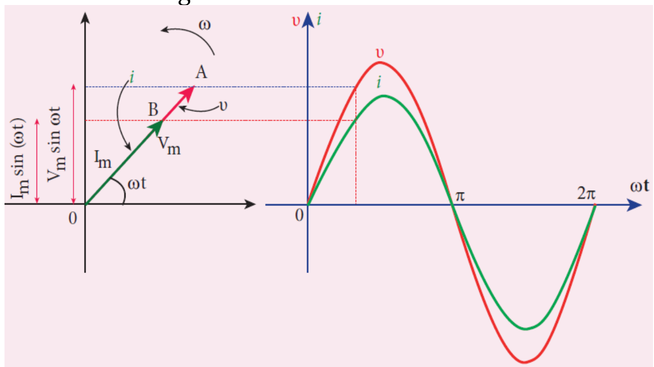
$$V_R = i\,R \qquad ---- (2)$$

- From Kirchoff's loop rule, $v - V_R = 0$

$$(or) \quad v = V_R$$
$$V_m \sin \omega t = i\,R$$
$$i = \frac{V_m}{R} \sin \omega t$$
$$\boldsymbol{i = I_m \sin \omega t} \qquad ---- (3)$$

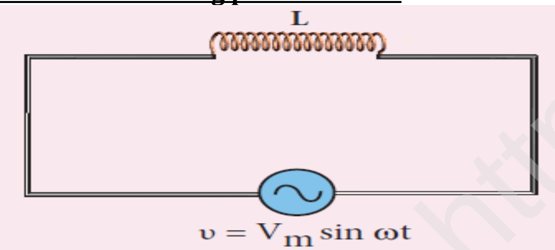
Here, $\frac{V_m}{R} = I_m \rightarrow$ Peak value of AC

- From equation (1) and (3), it is clear that, the applied voltage and the current are in phase with each other. This is indicated in the phasor and wave diagram.



25. Find out the phase relation ship between voltage and current in a pure inductive circuit.

<u>AC circuit containing pure inductor</u>:



- Let a pure inductor of inductance 'L' connected across an alternating voltage source 'v'
- The instantaneous value of the alternating voltage is given by,

$$v = V_m \sin \omega t \qquad ---- (1)$$

- Let 'i' be the alternating current flowing in the circuit due to this voltage, which induces a self induced emf (back emf) across 'L' and it is given by

$$\epsilon = -L\frac{di}{dt} \qquad ---- (2)$$

- From Kirchoff's loop rule, $v - (-\epsilon) = 0$

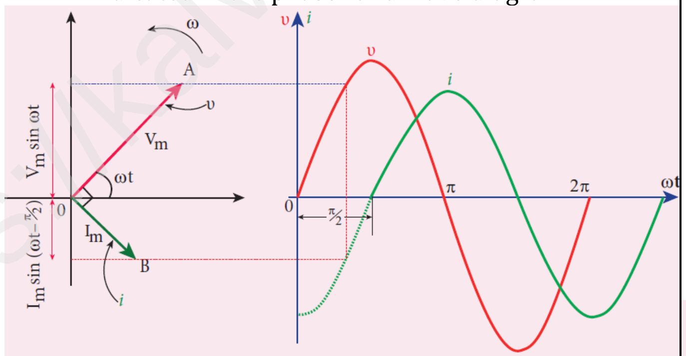
$$(or) \quad v = -\epsilon$$
$$V_m \sin \omega t = -\left(-L\frac{di}{dt}\right)$$
$$V_m \sin \omega t = L\frac{di}{dt}$$
$$\therefore \quad di = \frac{V_m}{L} \sin \omega t \; dt$$

- Integrate on both sides,

$$i = \frac{V_m}{L} \int \sin \omega t \; dt$$
$$i = \frac{V_m}{L}\left(\frac{-\cos \omega t}{\omega}\right) = \frac{V_m}{\omega L}\left[-\sin\left(\frac{\pi}{2} - \omega t\right)\right]$$
$$i = \frac{V_m}{\omega L} \sin\left(\omega t - \frac{\pi}{2}\right)$$
$$\boldsymbol{i = I_m \sin\left(\omega t - \frac{\pi}{2}\right)} \qquad ---- (3)$$

Where, $\frac{V_m}{\omega L} = I_m \rightarrow$ peak value of AC

- From equation (1) and (3), it is clear that current lags behind the applied voltage by $\frac{\pi}{2}$. This is indicated in the phasor and wave diagram.



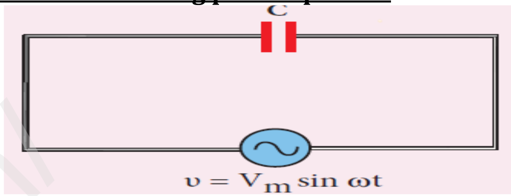
<u>Inductive reactance (X_L)</u>:

- In pure inductive circuit, 'ωL' is the resistance offered by the inductor and it is called inductive reactance (X_L). Its unit is ***ohm*** ($\boldsymbol{\Omega}$)

$$\boldsymbol{X_L = \omega L = 2\pi f L}$$

26. Find out the phase relation ship between voltage and current in a pure capacitive circuit.

<u>AC circuit containing pure capacitor</u>:



- Let a pure capacitor of capacitance 'C' connected across an alternating voltage source 'v'
- The instantaneous value of the alternating voltage is given by,

$$v = V_m \sin \omega t \qquad ---- (1)$$

- Let 'q' be the instantaneous charge on the capacitor. The emf across the capacitor at that instant is,

$$\epsilon = \frac{q}{C} \qquad ---- (2)$$

- From Kirchoff's loop rule, $v - \epsilon = 0$

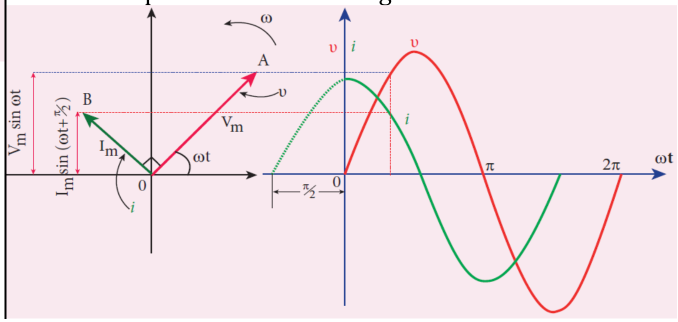
$$(or) \quad v = \epsilon$$
$$V_m \sin \omega t = \frac{q}{C}$$
$$\therefore \quad q = C\,V_m \sin \omega t$$

- By the definition of current,

$$i = \frac{dq}{dt} = C\,V_m \frac{d(\sin \omega t)}{dt} = C\,V_m (\cos \omega t)\,\omega$$
$$i = \omega\,C\,V_m \sin\left(\frac{\pi}{2} + \omega t\right) = \frac{V_m}{\left(1/_{\omega C}\right)} \sin\left(\frac{\pi}{2} + \omega t\right)$$
$$\boldsymbol{i = I_m \sin\left(\omega t + \frac{\pi}{2}\right)} \qquad ---- (3)$$

where, $\frac{V_m}{\left(1/_{\omega C}\right)} = I_m \rightarrow$ Peak value of AC

- From equation (1) and (3), it is clear that current leads the applied voltage by $\frac{\pi}{2}$. This is indicated in the phasor and wave diagram.



Capacitive reactance (X_C) :

- In pure capacitive circuit, '$^1/_{\omega C}$' is the resistance offered by the capacitor and it is called capacitive reactance (X_C). Its unit is ***ohm*** (***Ω***)

$$X_C = \frac{1}{\omega C} = \frac{1}{2 \pi f C}$$

27. Explain resonance in series RLC circiuit.

Resonance on series in RLC circuit :

- When the frequency of applied alternating source is increases, the inductive reactance (X_L) increases, where as capacitive reactance (X_C) decreases.
- At particular frequency (ω_R), $X_L = X_C$
- At this stage, the frequency of applied source (ω_R) is equal to the natural frequency of the RLC circuit, the current in the circuit reaches its maximum value.
- Then the circuit is said to be in ***electrical resonance***. The frequency at which resonance takes place is called ***resonant frequency***.
- Thus at resonance,

$$X_L = X_C$$
$$\omega_R L = \frac{1}{\omega_R C}$$
$$\omega_R^2 = \frac{1}{L C}$$

- Hence the resonant angular frequency,

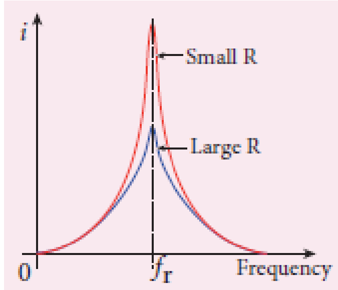
$$\omega_R = \frac{1}{\sqrt{L C}}$$

- And resonant frequency,

$$f_R = \frac{1}{2 \pi \sqrt{L C}}$$

Effects of series resonance :

- When series resonance occurs, the ***impedance of the circuit is minimum*** and is equal to the resistance of the circuit. So the current in the circuit becomes maximum.
- (i.e.) At resonance, Z = R & $I_m = \frac{V_m}{R}$
- The maximum current at resonance depends on the value of resistance (R)
- For smaller resistance, larger the current with sharper curve is obtained. But for larger resistance, smaller the current with flat curve is obtained.



28. Define quality factor. Obtain an expression for it.

Definition :

- Q - factor is defined as the ratio of voltage across L (or) C to the applied voltage at resonance.

Expression :

- The current in the series RLc circuit becomes maximum at resonance.
- Due to the increase in current, the voltage across L and C are also increased,
- This magnification of voltages at series resonance is termed as Q - factor.
- By definition,

$$Q - factor = \frac{voltage\ across\ L\ (or)\ C}{applied\ voltage}$$
$$Q - factor = \frac{I_m X_L}{I_m R} = \frac{X_L}{R} = \frac{\omega_R L}{R}$$
$$Q - factor = \frac{1}{\sqrt{L C}} \frac{L}{R}$$
$$\boldsymbol{Q - factor = \frac{1}{R}\sqrt{\frac{L}{C}}}$$

- The physical meaning is that ***Q - factor indicates the number of times the voltage across L (or) C is greaterthan the applied voltage at resonance***.

29. Obtain an expression for average power of AC over a cycle. Discuss its special cases.

Average power of AC :

- Power of a circuit is defined as the rate of consumption. It is given by the product of the voltage and current.
- The alternating voltage and alternating current in the series RLC circuit at an instance are given by,

$$v = V_m \sin \omega t$$
$$i = I_m \sin(\omega t + \phi)$$

- Then the instantaneous power is given by,

$$P = v\, i = V_m \sin \omega t \;\; I_m \sin(\omega t + \phi)$$
$$P = V_m I_m \;\sin \omega t \;(\sin \omega t \cos \phi - \cos \omega t \sin \phi)$$
$$P = V_m I_m \;(sin^2 \omega t \cos \phi - \sin \omega t \cos \omega t \sin \phi\,)$$

- Here the average of $sin^2 \omega t$ over a cycle is $\frac{1}{2}$ and that of $\sin \omega t \cos \omega t$ is zero.
- Thus average power over a cycle is,

$$P_{avg} = V_m I_m \left(\frac{1}{2} \cos \phi\right) = \frac{V_m}{\sqrt{2}} \frac{I_m}{\sqrt{2}} \cos \phi$$
$$\boldsymbol{P_{avg} = V_{RMS} I_{RMS} \cos \phi}$$

Where, $V_{RMS} I_{RMS} \rightarrow$ apparent power

$\cos \phi \rightarrow$ power factor

Special cases :

(i) For purely resistive circuit, $\phi = 0$ and $\cos \phi = 1$

$\therefore$ $\boldsymbol{P_{avg} = V_{RMS} I_{RMS}}$

(ii) For purely inductive or capacitive circuit,

$\phi = \pm \frac{\pi}{2}$ and $\cos \phi = 0$. $\therefore$ $\boldsymbol{P_{avg} = 0}$

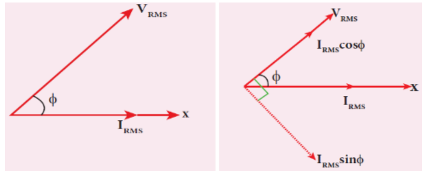
(iii) For series RLC circuit, $\phi = \tan^{-1}\left[\frac{X_L - X_C}{R}\right]$

$\therefore$ $\boldsymbol{P_{avg} = V_{RMS} I_{RMS} \cos \phi}$

(iv) For series RLC circuit at resonance, $\phi = 0$ and $\cos \phi = 1$. $\therefore$ $\boldsymbol{P_{avg} = V_{RMS} I_{RMS}}$

30. Write a note on wattful current and wattles current.

Wattful current and Wattless current :



- Consider an AC circuit in which the voltage ($\boldsymbol{V_{RMS}}$) leads the current ($\boldsymbol{I_{RMS}}$) by phase angle 'ϕ'
- Resolve the current in to two perpendicular components,
  - (i) $\boldsymbol{I_{RMS} \cos \phi}$ - Component along $\boldsymbol{V_{RMS}}$
  - (ii) $\boldsymbol{I_{RMS} \sin}$ - Component perpendicular to $\boldsymbol{V_{RMS}}$
- Here the component of current ($\boldsymbol{I_{RMS} \cos \phi}$) which is ***inphase*** with the voltage is called ative component. The power consumed by this component = $\boldsymbol{V_{RMS} I_{RMS} \cos \phi}$. It is known as wattfull current
- The other component of current which has a phase angle of with the voltage is called reactive component. The power consumed by this current is zero. It is known as wattles current.

31. Define power factor in various ways. Give some examples for power factor.

Power factor - Definitions :

(i) The cosine of the angle lead or lag is called power factor (power factor = = $\cos\phi$)

(ii) Power factor = $\frac{R}{Z} = \frac{Resistance}{Impedance}$

(iii) Power factor = $\frac{V\, I \cos\phi}{V\, I} = \frac{True\ power}{Apparent\ power}$

Examples :

- For purely resistive circuit, $\phi = 0$ and $\cos\phi = 1$
- For purely inductive or capacitive circuit, $\phi = \pm\frac{\pi}{2}$ and $\cos\phi = 0$
- For RLC circuit, power factor lies between 0 and 1

32. What are the advantages and disadvantages of AC over DC?

Advantages of AC over DC :

- The generation of AC is cheaper than that of DC
- When AC is supplied at higher voltages, the transmission losses are small compared to DC transmission.
- AC can easily be converted into DC with the help of rectifier.

Disadvantages of AC over DC :

- Alternating voltages cannot be used for certain application. (e.g) charging of batteries, electroplating, electric traction etc.,
- At high voltages, it is more dangerous to work with AC than DC.

33. Show that the total energy is conserved during LC oscillations.

Conservation of energy LC oscillations :

- During LC oscillations, the energy of the system oscillates between the electric field of the capacitor and the magnetic field of the inductor.
- Although these two energies vary with time, the total energy remains constant. (i.e)

$$U = U_E + U_B = \frac{q^2}{2C} + \frac{1}{2}L\,i^2 = constant$$

Case (i) :

- When the charge of in the ccapacitor ; $q = Q_m$ and the current through the inducor ; $i = 0$

$$U = \frac{Q_m^2}{2C} + 0 = \frac{Q_m^2}{2C} \quad ---- (1)$$

- The total energy is wholly electrical.

Case (ii) :

- When charge $q = 0$; Current ⅰ $i = I_m$, the total energy,

$$U = 0 + \frac{1}{2}L\,I_m^2 = \frac{1}{2}L\,I_m^2$$

$$\left[\because i = -\frac{dq}{dt} = -\frac{d}{dt}(Q_m\cos\omega t) = Q_m\omega\sin\omega t = I_m\sin\omega t\right]$$

- Hence, $I_m = Q_m\omega = \frac{Q_m}{\sqrt{LC}}$

$$\therefore \quad U = \frac{1}{2}L\left[\frac{Q_m^2}{LC}\right] = \frac{Q_m^2}{2C} \quad ---- (2)$$

- Here the total energy is wholly magnetic

Case (iii) :

- When charge $= q$, Current $= i$, then the total energy,

$$U = \frac{q^2}{2C} + \frac{1}{2}L\,i^2$$

- Here, $q = Q_m\cos\omega t$ & $i = Q_m\omega\sin\omega t$. So

$$U = \frac{Q_m^2\cos^2\omega t}{2\,C} + \frac{1}{2}L\,Q_m^2\omega^2\sin^2\omega t$$

- Since, $\omega^2 = \frac{1}{L\,C}$

$$U = \frac{Q_m^2\cos^2\omega t}{2C} + \frac{L\,Q_m^2\sin^2\omega t}{2\,LC}$$

$$U = \frac{Q_m^2}{2C}(\cos^2\omega t + \sin^2\omega t) = \frac{Q_m^2}{2C} \quad --- (3)$$

- From equation (1), (2) and (3) it is clear that the total energy of the system remains constant

PART - IV 5 MARK QUESTIONS AND ANSWERS

1. Explain the applications of eddy currents (or) Focault currents.

Induction stove :

- It is used to cook food quickly and safely with less consumption. Below the cooking zone, there is a tightly woind coil of insulated wire.
- A suitable cooking pan is placing over the cooking zone.
- When the stove is switched on, an AC flowing in the coil produces high frequency alternating magnetic field which induces very strong eddy currents in the cooking pan.
- The eddy currents in the pan produce so much of heat due to Joule heating which is used to cook the food.

Eddy current brake :

- This types of brakes are generally used in high speed trains and roller coasters.
- Strong electromagnets are fixed just above the rails.To stop the train, electromagnets are swiched on. The magnetic field of these magnets induces eddy currents in the rails which oppose the movement of the train. This is ***eddy current linear brake.***
- In some cases, the circular disc connected in train is made to rotate in between the pole of a electromagnet. When there is a relative motion between the disc and the magnet, eddy currents are induced in the disc which stop the train. Ths is ***eddy current circular brake***.

Eddy current testing :

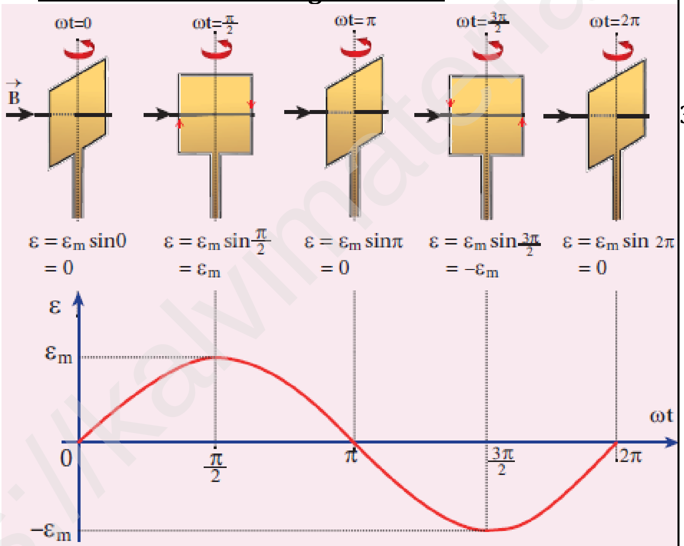
- It is one of the non - destructive testing methods to find defects like surface craks, air bubbles present in a specimen.
- A coil of insulated wire is given an alternating electric current, so that it produces an alternating magnetic field.
- When this coil is brought near the test surface, eddy current is induced in it, and the presence of defects caused the change in phase and amplitude of the eddy current.
- Thus the defects present in the specimen are identified.

Electro magnetic damping :

- The armature of the galvanometer coil is wound on a soft irom cylinder.
- Once the armature is deflected, the relative motion between the soft irom cylinder and the radial magnetic field induces eddy current in the cylinder.
- The damping force due to the flow of eddy current brings the armature to rest immediately and the galvanometer shows a steady deflection.
- This is called electromagnetic damping.

2. Show mathematically that the rotation of a coil in a magnetic field over one rotation induces an alternating emf of one cycle.

Induction of emf by changing relative orientation of the coil with the magnetic field :



- Consider a rectangular coil of 'N' turns kept in a uniform magnetic field 'B'
- The coil rotates in anti-clockwise direction with an angular velocity 'ω' about an axis.
- Initially let the plane of the coil be perpendicular to the field ($\theta = 0$) and the flux linked with the coil has its maximum value. (i.e.) $\Phi_m = B\,A$
- In time 't', let the coil be rotated through an angle $\theta\ (= \omega t)$, then the total flux linked is
$$N\,\Phi_B = N\,B\,A\cos\omega t = N\,\Phi_m\cos\omega t$$
- According to Faraday's law, the emf induced at that instant is,
$$\epsilon = -\frac{d}{dt}(N\Phi_B) = -\frac{d}{dt}(N\,\Phi_m\cos\omega t)$$
$$= -N\,\Phi_m\,(-\sin\omega t)\,\omega$$
$$\epsilon = \boldsymbol{N\,\Phi_m\,\omega\,\sin\omega t} \quad ------ \quad (1)$$
- When $\theta = 90°$, then the induced emf becomes maximum and it is given by,
$$\epsilon_m = \boldsymbol{N\,\Phi_m\,\omega = N\,B\,A\,\omega} \quad ------ \quad (2)$$
- Therefore the value of induced emf at that instant is then given by,
$$\epsilon = \epsilon_m\ \boldsymbol{\sin\omega t} \quad ------ \quad (3)$$
- Thus the induced emf varies as sine function of the time angle and this is called ***sinusoidal emf*** or ***alternating emf***.
- If this alternating voltage is given to a closed circuit, a sinusoidally varying current flows in it. This current is called ***alternating current*** an is given by,
$$\boldsymbol{i = I_m\,\sin\omega t} \quad ------ \quad (4)$$
- where, $I_m \rightarrow$ peak value of induced current

3. Elaborate the standard construction details of AC generator.

AC generator - construction :

- AC generator (alternator) is an energy conversion device. It converts mechanical energy used to rotate the coil or field magnet in to electrical energy.
- It works on the principle of electromagnetic induction.
- It consists of two major parts ***stator*** and ***rotor***.
- In commercial alternators, the armature winding is mounted on stator and the field magnet on rotor

Stator : It has three components

(i) **Stator core (Armature)** :

- It is made up of iron or steel alloy.
- It is a hollo cylinder and is laminated to minimize eddy current loss.
- The slots are cut on inner surface of the core to accommodate armature windings.

(ii) **Armature windings** :

- It the coil wound on slots provided in the armature core. One or more than one coil may be employed, depending on the type of alternator.

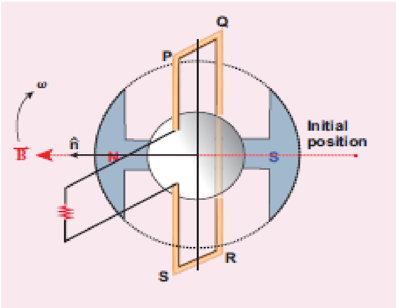
Rotor :

- It consists magnetic field windings
- The magnetic poles are magnetized bhy DC source
- The ends of field windings are connected to a pair of slip rings, attached to a common shaft about which rotor rotates. Slip rings rotate along with rotor.
- To maintain connection between the DC source and field windings, two brushed are used which continuously slide over the slip rings

4. Explain the working of a single - phase AC generator with necessary diagram.

Single phase AC generator :

- In a single phase AC generator, the armature conductors are connected in series so as to form a single circuit which generates a single-phase alternating emf and hence it is called single-phase alternator.



Principle :

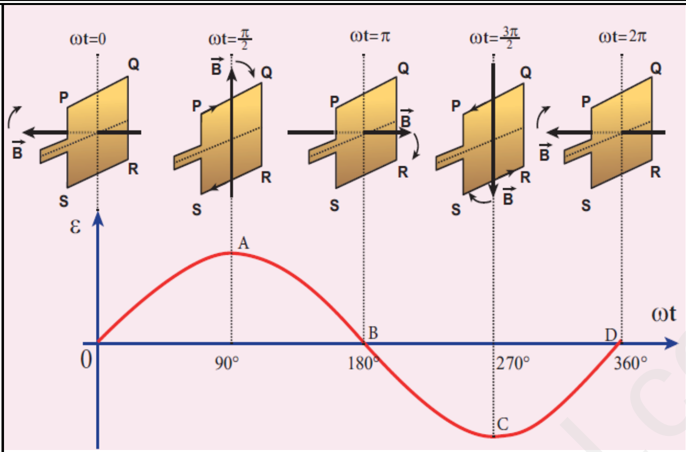
- Electro magnetic induction

Construction :

- Consider a stator core consisting of 2 slots in which 2 armature conductor PQ and RS are mounted to form single - turn rectangular loop PQRS
- Rotor has 2 salient poles with field windings which can be magnetized by means of DC source.

Working :

- The loop PQRS is stationary and is perpendicular to the plane of the paper.
- Assume the initial position of the field magnet is horizontal. At that instant, the direction of magnetic field is perpendicular to the plane of the loop PQRS. The induced emf is zero. It is represented by origin 'O' in the graph

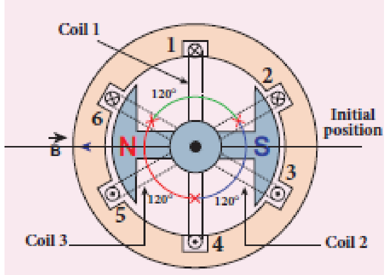


- Let the magnetic field rotate in clock-wise direction.
- When the field magnet rotates through 90°, the magnetic field becomes parallel to PQRS. The induced emf's across PQ and RS would become maximum. According to Flemming's right hand rule, the direction of induced emf for PQ is downwards and for RS is upwards. Therefore the current flows along PQRS. The point A in the graph represents this maximum emf.
- When field magnet rotates 180°, the field is again perpendicular to PQRS and the induced emf becomes zero. This is represented by point B
- When field magnet rotates 270°, the field is again parallel to PQRS, the induced emf is maximum but the direction is reversed. Thus the current flows along SRQP. This is represented by point C.
- On completion of 360, the induced emf becomes zero and it is represented by the point D.
- From the graph, it is clear that, when field magnet completes one rotation, the emf induced in PQRS is alternating in nature.

5. How are the three different emfs generated in a three-phase AC generator? Show the graphical representation of these three emfs.

Three phase AC generator :

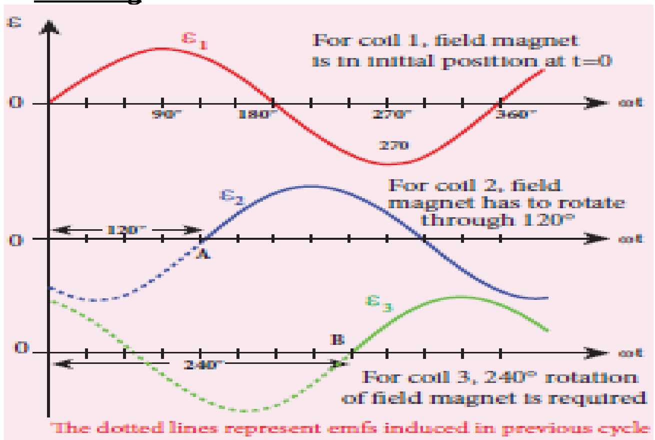
- If the AC generator consists three separate coils, which would give three separate emfs, then it is called three-phase generators.



Construction :

- It has 6 slots, cut in its inner rim. Each slot is 60° away from one another. six armature conductors are mounted in these slots.
- The conductors 1 - 4, 2 - 5 and 3 - 6 are joined in series to form coils 1, 2 and 3
- So these coils are rectangular in shape and are 120° apart from one another.

Working :



- The initial position of the field magnet is horizontal and field direction is perpendicular to the plane of the coil - 1.
- When it rotated from that position in clock-wise direction, alternating emf 'ε_1' in coil - 1 begins a cycle from origin 'O'
- When it rotated through 120°, alternating emf 'ε_2' in coil - 2 statrs at point 'A'
- When it rotated through 240°, alternating emf 'ε_3' in coil - 3 statrs at point 'B'
- Thus these emfs produced in the three phase AC generator have 120° phase difference between one another.

6. Explain the principle , construction and working of transformer.

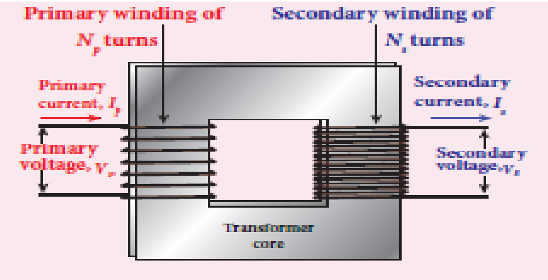
Transformer :

- It is a stationary device used to transform electrical power from one circuit to another without changing its frequency.
- It is done with either increasing or decreasing the applied alternationg voltage with corresponding decrease or increase of current in the circuit.
- If the transformer converts an alternating current with low voltage in to an alternating current with high voltage, it is called ***step-up transformer***.
- If the transformer converts an alternating current with high voltage in to an alternating current with low voltage, it is called ***step-down transformer***.

Principle :

- Mutual induction between two coils.

Construction :



- It consists of two coils of high mutual inductance wound over the same transformer core made up of silicone steel.
- To avoid eddy current loss, the core is generally laminated
- The alternating voltage is applied across primary coil (P), and the output is taken across secondary coil (S)
- The assemnbled core and coils are kept in a container which is filled with suitable medium for better insulation and cooling purpose.

Working :

- The alternating voltage given to the primary coil, set up an alternating magnetic flux in the laminated core.
- As the result of flux change, emf is induced in both primary and secondary coils.
- The emf induced in the primary coil 'ϵ_P' is almost equal and opposite to the applied voltage 'V_P' and is given by,

$$V_P = \epsilon_P = -N_P \frac{d\Phi_B}{dt} \qquad ----(1)$$

- The frequency of alternating magnetic flux is same as the frequency of applied voltage. Therefore induced in secondary will also have same frequency as that of applied voltage,
- The emf induced in the secondary coil 'ϵ_S' is,

$$V_S = \epsilon_S = -N_S \frac{d\Phi_B}{dt} \qquad ----(2)$$

- Dividing equation (1) by (2),

$$\frac{\boldsymbol{V_S}}{\boldsymbol{V_P}} = \frac{\boldsymbol{N_S}}{\boldsymbol{N_P}} \qquad ----(3)$$

Where, K → transformation ratio

- For an ideal transformer,

input power = output power

$$V_P\, i_P = V_S\, i_S$$

$$\frac{\boldsymbol{V_S}}{\boldsymbol{V_P}} = \frac{\boldsymbol{i_P}}{\boldsymbol{i_S}} \qquad ----(4)$$

- From equation (3) and (4), we have

$$\frac{\boldsymbol{V_S}}{\boldsymbol{V_P}} = \frac{\boldsymbol{N_S}}{\boldsymbol{N_P}} = \frac{\boldsymbol{i_P}}{\boldsymbol{i_S}} = \boldsymbol{K} \qquad ----(5)$$

(i) If K > 1 (or) $\boldsymbol{N_S > N_P}$, then $\boldsymbol{V_S > V_P}$ and $\boldsymbol{i_S < i_P}$
This is step up transformer in which voltage increased and the corresponding current is decreased.

(ii) If K < 1 (or) $\boldsymbol{N_S < N_P}$, then $\boldsymbol{V_S < V_P}$ and $\boldsymbol{i_S > i_P}$
This is step down transformer in which voltage decreased and the corresponding current is increased.

Efficiency of a transformer :

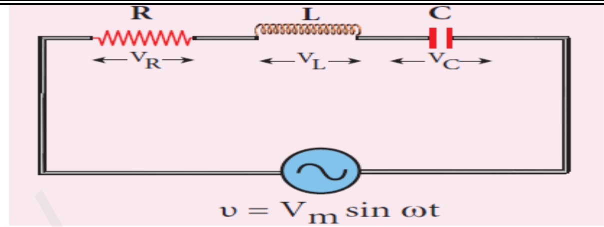
- The efficiency (η) of a transformer is defined as the ratio of the useful output power to the input power.

$$\eta = \frac{output\ power}{input\ power}\ X\ 100\ \%$$

7. Derive an expression for phase angle between the applied voltage and current in a series RLC circuit.

Series RLC circuit :

- Consider a circuit containing a resistor of resistance 'R', a inductor of inductance 'L' and a capacitor of capacitance 'C' connected across an alternating voltage source.



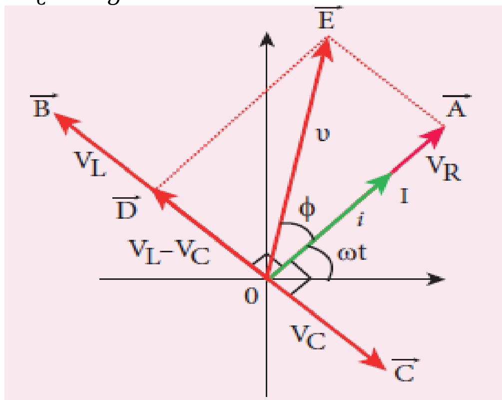
- The applied alternating voltage is given by,

$$v = V_m \sin \omega t \qquad -----(1)$$

- Let 'i' be the current in the circuit at that instant.
- Hence the voltage developed across R, L and C

$$V_R = i\,R \qquad (\ V_R\ is\ in\ phase\ with\ i)$$
$$V_L = i\,X_L \qquad (V_L\ leads\ i\ by\ \tfrac{\pi}{2})$$
$$V_C = i\,X_C \qquad (V_C\ lags\ i\ by\ \tfrac{\pi}{2})$$

- The phasor diagram is drawn by representing current along $\overrightarrow{OI}$, V_R along $\overrightarrow{OA}$, V_L along $\overrightarrow{OB}$ and V_C along $\overrightarrow{OC}$



- If $V_L > V_C$, then the net voltage drop across LC combination is $(V_L - V_C)$ which is represented by $\overrightarrow{AD}$
- By parallogram law, the diagonal $\overrightarrow{OE}$ gives the resultant voltage 'v'

$$\therefore \qquad v = \sqrt{V_R^{\,2} + (V_L - V_C)^{\,2}}$$

$$v = \sqrt{i^2\,R^2 + (i\,X_L - i\,X_C)^{\,2}}$$

$$v = i\sqrt{R^2 + (X_L - X_C)^{\,2}}$$

$$(or) \qquad i = \frac{v}{\sqrt{R^2 + (X_L - X_C)^{\,2}}} \qquad ---(4)$$

$$(or) \qquad \boldsymbol{i} = \frac{\boldsymbol{v}}{\boldsymbol{Z}} \qquad ---(5)$$

- Where, $Z = \sqrt{R^2 + (X_L - X_C)^2}$ is called impedance of the circuit, which refers to the effective opposition to the circuit current by the series RLC circuit.
- From the phasor diagram, the phase angle between 'v' and 'i' is found out by

$$\tan\phi = \frac{V_L - V_C}{V_R} = \frac{X_L - X_C}{R} \quad ---(6)$$

Special cases :

(i) When $X_L > X_C$, the phase angle ϕ *is positive*. It means that v leads i by ϕ.
$(i.e.)\ v = V_m \sin\omega t \quad \& \quad i = I_m \sin(\omega t - \phi)$
This circuit is inductive.

(ii) When $X_L < X_C$, the phase angle ϕ *is negative*. It means that v lags behind i by ϕ.
$(i.e.)\ v = V_m \sin\omega t \quad \& \quad i = I_m \sin(\omega t + \phi)$
This circuit is capacitive

(iii) When $X_L = X_C$, the phase angle ϕ *is zero*. It means that v inphase with i
$(i.e.)\ v = V_m \sin\omega t \quad \& \quad i = I_m \sin\omega t$
This circuit is resistive

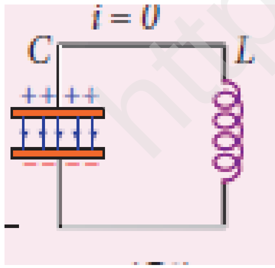
8. What are called LC oscillations? Explain the generation of LC oscillations.

LC oscillations :

- Whenever energy is given to a circuit containing a pure inductor of inductance L and a capacitor of capacitance C, the energy oscillates back and forth between the magnetic field of the inductor and the electric field of the capacitor.
- Thus the electrical oscillations of definite frequency are generated. These oscillations are called LC oscillations.

Generation of LC oscillations :

- Whenever energy is given to a circuit containing a pure inductor of inductance L and a capacitor of capacitance C, the energy oscillates back and forth between the magnetic field of the inductor and the electric field of the capacitor.



- Thus the electrical oscillations of definite frequency are generated. These oscillations are called LC oscillations.

Stage -1 :

- Consider the capacitor is fully charged with maximum charge Q_m. So that the energy stored in the capacitor is maximum (i.e.) $U_E = \frac{Q_m^2}{2C}$
- As there is no current in the inductor, $U_B = 0$
- Therefore the total energy is wholly electrical.

Stage - 2 :

- The capacitor now begins to discharge through the inductor that establishes current 'i' clockwise direction.
- This current produces a magnetic field around the inductor and energy stored in the inductor which is given by $U_B = \frac{L i^2}{2}$
- As the charge in the capacitor decreases, the energy stored in it also decreases and is given by $U_E = \frac{q^2}{2C}$
- Thus the total energy is the sum of electrical and magnetic energies.

Stage - 3 :

- When the charge in the capacitor becomes zero, its energy becomes zero (i.e.) $U_E = 0$
- In this stage maximum current (I_m) flows through inductor and its energy becomes maximum. (i.e.) $U_B = \frac{L I_m^2}{2}$
- Thus the total energy is wholly magnetic.

Stage - 4 :

- Eventhough the charge in the capacitor is zero, the current will continue to flow in the same direction.
- Since the current flow is in decreasing magnitude, the capacitor begins to charge in the opposite direction.
- Thus a part of the energy is transferred from the inductor back to the capacitor. The total energy is the sum of the electrical and magnetic energies.

Stage - 5 :

- When the current in the circuit reduces to zero, the capacitor becomes fully charged in the opposite direction.
- Thus the energy stored in the capacitor becomes maximum and the energy stored in the inductor is zero.
- So the total energy is wholly electrical.

Stage - 6 :

- This state of the circuit is similar to the initial state but the difference is that the capacitor is charged in opposite direction. So it will starts discharge through inductor in anti-clockwise direction.
- The total energy is the sum of the the electrical and magnetic energies.

Stage - 7 :

- The processes are repeated in opposite direction and finally the circuit returns to the initial state.
- Thus when the circuit goes through these stages, an alternating current flows in the circuit.
- As this process is repeated again and again, the electrical oscillations of definte frequency are generated. These are known as LC oscillations.

9. Compare the electromagnetic oscillations of LC circuit with the mechanical oscillations of block-spring system to find the expression for angular frequency of LC oscillators mathematically.

Analogies between LC oscillations and simple harmonic oscillations :

Electromagnetic oscilations	Mechanical oscilations
This circuit consists inductor and capacitor	This circuit consists spring and block
Charge 'q'	Displacement 'x'
Current $i = \frac{dq}{dt}$	Velocity $v = \frac{dx}{dt}$
Inductance 'L'	Mass 'm'
Reciprocal if capacitance $\frac{1}{C}$	Force constant 'k'
Electrical energy $= \frac{1}{2}\left[\frac{1}{C}\right] q^2$	Potential energy $= \frac{1}{2} kx^2$
Magnetic energy $= \frac{1}{2} Li^2$	Kinetic energy $= \frac{1}{2} mv^2$
Electro magnetic energy $= \frac{1}{2}\left[\frac{1}{C}\right] q^2 + \frac{1}{2} Li^2$	Mechanical energy $= \frac{1}{2} kx^2 + \frac{1}{2} mv^2$

Angular frequency of LC oscillations :

- We know that the angular frequency of mechanical oscillations, $\omega = \sqrt{\frac{k}{m}}$
- From the above table, $k \to \frac{1}{C}$ & $m \to L$
- Thus the angular frequency of LC oscillations is,

$$\omega = \frac{1}{\sqrt{LC}}$$