RGPVNOTES.IN

Program : **B.Tech**

Subject Name: **Basic Electrical & Electronics Engineering**

Subject Code: **BT-104**

Year: **1st**

Unit - III Magnetic Circuits - Syllabus

Basic definitions, Magnetization characteristics of Ferro magnetic materials, Magnetic field produced by current carrying conductor, Force on a current carrying conductor, AC excitation in magnetic circuits. Laws of electromagnetic Induction, induced voltage, direction of induced E.M.F, selfinductance and mutual inductance, energy in linear magnetic systems, Coils connected in series.

MAGNETIC CIRCUITS

Magnetic flux: The total number of flux lines coming out of the N-pole of a magnet is called the Magnetic flux. It is represented by Φand the unit is weber

Magnetic flux density: It is the number of flux lines passing through an unit area of cross section held perpendicular to the lines of flux. It is given by the expression $B = \Phi/A$ its unit is Wb/m²

Magnetic field strength or Magnetic intensity or Magnetizing force: The magnetic field strength at any point within a magnetic field is given by the force experienced by a unit N-pole of one weber placed at that point. It is represented by H and the unit is Newton/weber

Absolute permeability: A magnetic material when placed in a magnetic field acquires magnetization due to induction. A measure of the degree to which the lines of force of the magnetizing field can penetrate the medium is called the absolute permeability of the medium.

It is also defined as the ratio of flux density in that material to the magnetizing force producing that flux density. It is given by $\mu = B/H$ and the unit is Henry/metre

It is also given by $\mu = \mu_o \mu_r$ where $\mu_o = 4\pi \times 10^{-7}$ Henry/metre

Relative permeability: It is given by the ratio of the flux density produced in that material to the flux density produced in vacuum by the same magnetizing force. It is given by $\mu_r = B/B_o$

Magneto motive force: It drives or tends to drive flux through a magnetic circuit orIt is also equal to the work done in joules in carrying a unit magnetic pole once through the entire magnetic circuit. Its unit is Ampere turns.

Reluctance: It is defined as the property of a material that opposes the creation of magnetic flux in it. It is a measure of the opposition offered to the passage of magnetic flux through a material. It is given by $S = l/\mu_o \mu_r A$or $S = mmf/\Phi$its unit is AT/Wb.

Permeance - It is the reciprocal of reluctance. It is defined as the property of a material that initiates the development of magnetic flux. It is given by, $Permeance = \Phi/mmf$ its unit is Wb/AT or Henry.

Relations in magnetic circuits:

$$We have, H = \frac{NI}{l} \; or \; NI = Hl \; ; \; B = \mu_o \mu_r H \; or \; H = \frac{B}{\mu_o \mu_r} \; ; \; B = \frac{\Phi}{A} \; ; \; NI = \frac{B}{\mu_o \mu_r} \times l$$

$$Amp. turns\ for\ any\ material, AT_M = \frac{B}{\mu_o \mu_r} \times l_M \; ; \; Amp. turns\ for\ airgap, AT_G = \frac{B}{\mu_o} \times l_G$$

Leakage flux: Whenever a magnetic material is magnetized flux lines are produced in the material. The flux lines existing in the material and the air gap is called Useful fluxΦ_U. The flux lines not existing in the

material and existing around the coil wound on the magnetic material is called leakage fluxΦ_L. Leakage flux is the flux that follows a path not intended for it. The total flux produced by the solenoid $\Phi = \Phi_U + \Phi_L$. The ratio of total flux produced by the solenoid to the useful flux set up in the material and air gap is known as leakage co: efficient. It is given by $\lambda = \Phi/\Phi_U$ and its value is more than 1.

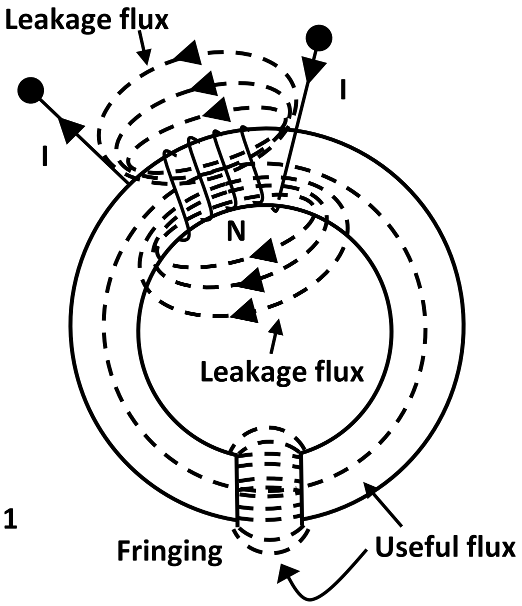


Fig. - 1

Fringing is the bulging of the magnetic flux lines in the air gap of a magnetic material. This increases the effective area in the air gap and decreases the flux density. Every magnetic material with air gaps suffer from the problem of fringing. Fringing is directly proportional to the length of the air gap. Fig.-1 shows a magnetic circuit with mmf (NI), Total flux, Useful flux and Leakage flux. The effect of Fringing is also shown in the air gap of the magnetic material.

<u>Series magnetic circuit</u>:

A magnetic circuit that is made up of a number of magnetic materials of different cross sectional areas, of different lengths, of different relative permeability along with an air gap carrying the same value of flux represents a series magnetic circuit. This magnetic circuit will have only one path for the magnetic flux.

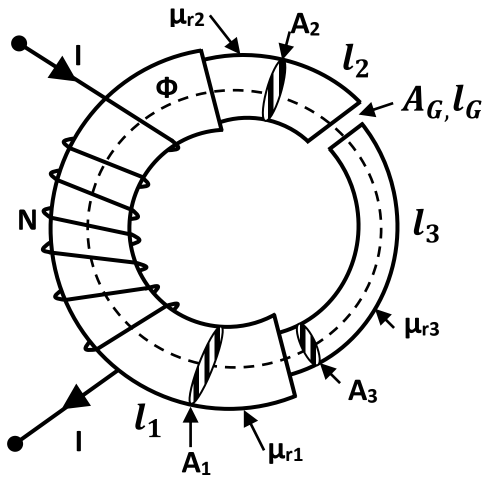


Fig. - 2

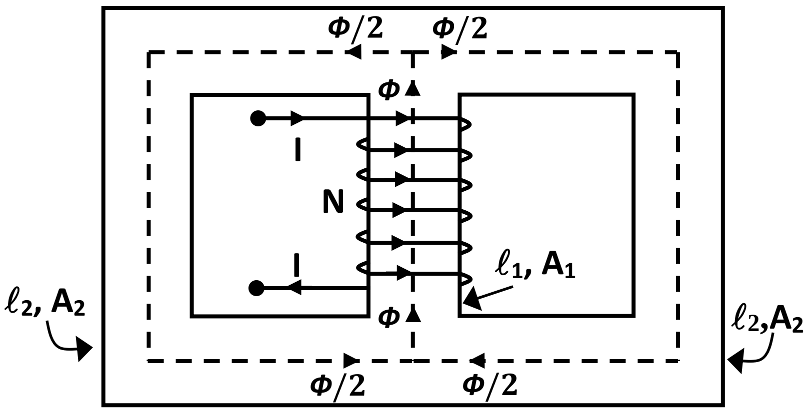


Fig. - 3

A series magnetic circuit made of three parts is as shown in fig. -2. The total ampere turns required for the magnetic circuit will be equal to the sum of all the ampere turns required for each of the magnetic material as well as the air gap. Total AT = $AT_1 + AT_2 + AT_3 + AT_G$

Parallel magnetic circuit:

A magnetic circuit that has two or more than two paths for the magnetic flux is called a parallel magnetic circuit. In these circuits the value of flux will not be the same in all the parts of the magnetic circuit. A parallel magnetic circuit can also have an air gap in the central limb or in the side limbs or in all the limbs. A simple parallel magnetic circuit is as shown in fig. - 3. The total ampere turns required for the magnetic circuit will be equal to the sum of the ampere turns required for the central limb and the ampere turns required for one of the side limbs. It indicates that the ampere turns required for one side limb is capable of driving flux in both the side limbs.

Total AT = Ampere turns required for central limb + Ampere turns required for any one side limb.

Total AT = $AT_C + AT_S$

Magnetization characteristics of Ferromagnetic materials:

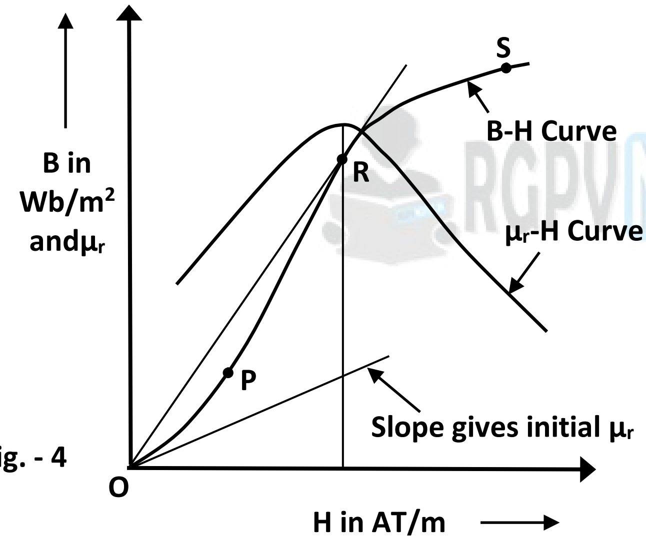


Fig. - 4

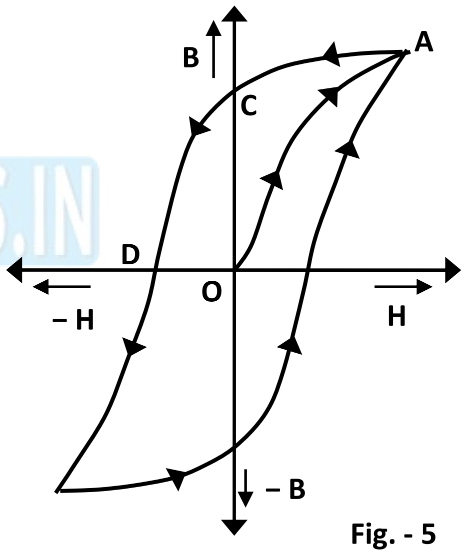


Fig. - 5

When an iron specimen is subjected to an increasing value of magnetizing force, H and the corresponding values of flux density B plotted against H helps in realizing the B-H curve shown in fig.-4. Using the relation $\mu_r = B/\mu_o H$the curve of relative permeability μ_r against H may be obtained from the plotted magnetisation characteristics. From the $\mu_r - H$ curve it is observed that the value of μ_r varies considerably with the value of H that helps in ascertaining the value of operating flux density. The B-H curve obtained can be divided into three regions - initial region OP, middle region PR and the region beyond R. The curve near the origin is nearly a straight line through the origin and the slope yields the value of initial permeability. The value of H at which the curve begins to bend varies over a wide range from material to material. In the middle region, increase in a small value of H will have a very large increase in the value of B. The slope is the greatest and the maximum value of permeability is within this region. At point R the tangent to the curve passes through the origin, where μ_r has its maximum value. In the region beyond R,

any further increase in the value of H will have a small change in the value of B. The curve indicates the extent of magnetization due to the increase in value of H. The curve beyond point S shows that any further increase in the value of H will not have any variation in the value of B indicating the magnetic saturation of the material.

<u>Hysteresis</u>: Whenever an iron bar is taken through one cycle of magnetization a Hysteresis loop shown in fig. - 5 is traced. The area of the loop represents the total energy spent in taking the iron bar through one cycle of magnetization. The Hysteresis loop is a plot of B and H, it is also defined as the lagging of flux density B behind the magnetizing force H. When H is increased initially the curve OA is traced and the iron bar gets magnetically saturated. As and when H is decreased B also decreases. But when H is zero the value of B is not zero. The distance OC on the Y-axis represents the Residual flux density B_r . The value of flux density B_r measures the retentivity of the material. To demagnetize the iron bar, we have to apply the magnetising force in the reverse direction. When H is reversed the value of B is reduced to zero at point D. The distance OD on the X-axis represents the Coercive force H_C . The value of H required to eliminate the residual magnetism is known as Coercive force and is a measure of the Coercivity of the material. Fig.-5 shows a Hysteresis loop traced for an iron bar taken through one cycle of magnetization.

<u>Magnetic field produced by a current carrying conductor</u>:

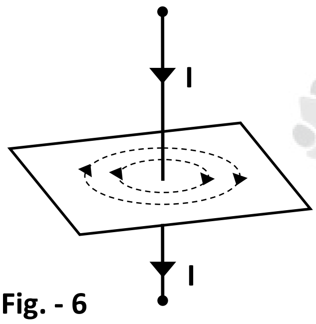


Fig. - 6

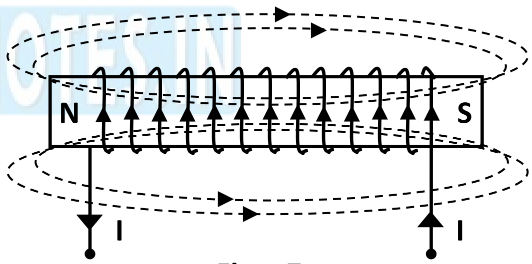


Fig. - 7

Let us consider a conductor passing through a card board as shown in fig.- 6, let a current I flow through it from top to the bottom. A magnetic compass when placed close to the wire has its needle pointing in a specific direction. The points of the needle are marked by moving the magnetic compass around the current carrying conductor. All the points when joined together appear in the form of a circle showing the existence of flux lines around the current carrying conductor. This simple experiment shows that a current carrying conductor will always have a magnetic field created around it. The Right hand thumb rule helps us to find out the direction of flux lines created around the current carrying conductor. If the current carrying conductor is grasped by the right hand such that the thumb held perpendicular to all the fingers points to the direction of current flow, then the fingers curled around the conductor points to the direction of magnetic flux around it.

Right hand thumb rule can also be applied to a coil wound around a magnetic material and carrying current as shown in fig.-7. If the coil is grasped by the right hand such that the four fingers curl around the coil

pointing to the direction of current flow, the thumb held perpendicular to the four fingers points to the N-pole of the magnetic material.

Force on a current carrying conductor placed in a magnetic field:

Let us consider a current carrying conductor placed in a magnetic field of a permanent magnet. The flux lines produced by the magnet come out of the N pole and end up at the S pole. The flux lines of the magnetic field created by the current carrying conductor are in a circular form, aiding certain flux lines and opposing certain flux lines of the magnetic field of the magnet as shown in fig. - 8. The side on which the flux is aided becomes stronger and the side on which the flux gets opposed becomes weaker. The current carrying conductor is pushed from the side which has a stronger flux towards the side which has a weaker flux. Hence, due to the interaction between the two fluxes, a mechanical force is experienced by the current carrying conductor as shown in fig. - 9. The direction of the mechanical force experienced by the current carrying conductor placed in a magnetic field can be determined by Fleming's left hand rule.

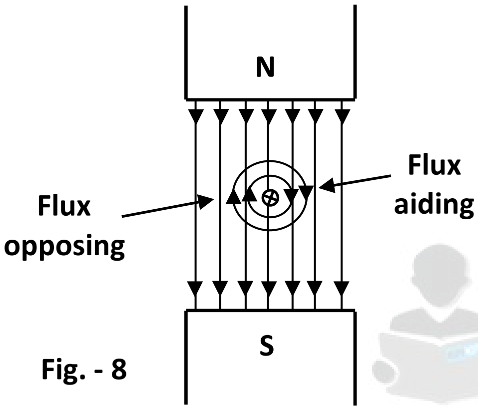


Fig. - 8

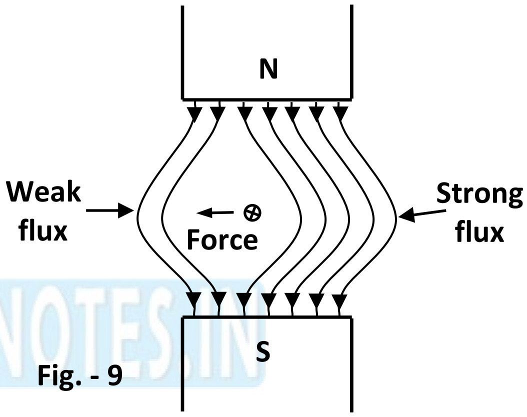


Fig. - 9

AC excitation of Magnetic circuit: A magnetic circuit with input given from an AC supply is called an AC magnetic circuit. Fig. - 10 shows a circular iron core wound with a coil of N turns. An alternating current, $i = I_m Sin\omega t$ flowing through the coil, creates an alternating flux Φ. As the current through the coil is sinusoidal in nature the flux created is also sinusoidal in nature varying with time.

The flux produced is given by $\Phi = \Phi_m Sin\omega t$

When the changing flux Φ links with N number of turns of the coil, emf is induced in the coil given by,

$$e = -N\frac{d\Phi}{dt} \quad = -N\frac{d}{dt}(\Phi_m Sin\omega t)$$

$$= -N\omega\Phi_m Cos\omega t \quad = N\omega\Phi_m(Sin\omega t - 90°)$$

Maximum value of induced emf, $E_m = N\omega\Phi_m$

$$\therefore e = E_m(Sin\omega t - 90°)$$

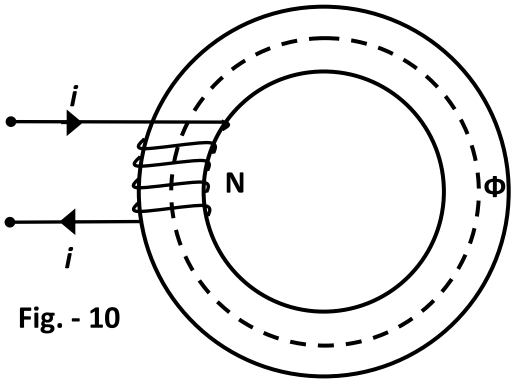


Fig. - 10

Electromagnetism: The phenomenon whereby an emf and hence current is induced in any conductor which is cut across or is cut by a magnetic flux is known as Electromagnetic induction.

Faraday's laws of electromagnetic induction - First law: Whenever the flux linked with a circuit changes, an emf is always induced in it or whenever a conductor cuts across magnetic field lines, an emf is induced in that conductor.

Second law: The magnitude of the induced emf is equal to the rate of change of flux linkages.

$$e = -N\frac{d\Phi}{dt} volts$$

The first law explains the phenomenon of Electromagnetic induction and the second law helps us to ascertain its magnitude.

Lenz's law: The direction of induced emf is always such that it tends to set up a current opposing the motion or the change of flux responsible for inducing that emf or The direction of induced emf is such as to oppose the very cause producing it.

Lenz's law helps us to ascertain the direction of the induced emf (statically)

Fleming's right hand rule: If the first finger of the right hand be pointed in the direction of the magnetic flux and if the thumb be pointed in the direction of motion of the conductor relative to the magnetic field, then the second finger held at right angles to both the thumb and the first finger, represents the direction of induced emf.

Fleming's right hand rule helps us to ascertain the direction of the dynamically induced emf

Fleming's left hand rule: If the first finger of the left hand be pointed in the direction of the magnetic flux and the second finger points in the direction of the current, then the thumb held at right angles to the first finger and second finger, would point in the direction of the mechanical force produced on the current carrying conductor.

Fleming's left hand rule helps us to find out the direction of the force experienced by a current carrying conductor when placed in a magnetic field.

Induced emf's: Electro magnetically induced emf's are of two types - Statically induced emf and Dynamically induced emf

Dynamically induced emf: Whenever a moving conductor cuts across magnetic flux lines, an emf is induced in the conductor called as dynamically induced emf or when a stationary conductor is cut by a rotating magnetic field, an emf is induced in the conductor.

This is observed in D.C and A.C. Generators.

If the conductor cuts the flux at right angles then the dynamically induced emf, $e = Blv$ volts and If the conductor moves at an angle θ with the direction of the lines of flux, then the dynamically induced emf, $e = BlvSin\theta$ volts

Statically induced emf: Whenever a changing flux links with a stationary coil, an emf is induced in the coil called as statically induced emf. This is observed in Transformers.

$$Statically\ induced\ emf, \qquad e = -N\frac{d\Phi}{dt} volts$$

Statically induced emf's are of two types - Self induced emf and Mutually induced emf

Self induced emf: This is the emf induced in a coil due to the change of its own flux linked with it.

$$We\ have\ self\ induced\ emf, \quad e_L = L\frac{dI}{dt}\text{volts}$$

Mutually induced emf: This is the emf induced in one coil by the influence of another coil.

$$We\ have\ mutually\ induced\ emf, \quad e_M = M\frac{dI_1}{dt}volts$$

Self inductance: The property of a coil by virtue of which an emf is induced in it, whenever a changing current flows through it is called as self Inductance or The property of a coil due to which it opposes any change of current through it is known as self inductance. Its unit is Henry

$$We\ have\ self\ inductance, \quad L = \frac{N\Phi}{I} \ \ or \ \ L = \frac{\mu_o \mu_r A N^2}{l} \ \ or \ \ e_L = L\frac{dI}{dt}$$

Mutual inductance: It is the ability of one coil to produce an emf in a nearby coil by induction when the current in the first coil changes. This action is reciprocal. Its unit is Henry.

$$We\ have\ mutual\ inductance, \quad M = \frac{N_2 \Phi_1}{I_1} \ \ or \ \ M = \frac{\mu_o \mu_r A N_1 N_2}{l} \ \ or \ \ e_M = M\frac{dI_1}{dt}$$

Energy stored in a Magnetic field: The energy stored in a magnetic field is given by the expression,

$$E = \frac{1}{2}LI^2\ Joules\ ; \ \ wehave,\ L = \frac{N\Phi}{I} \ \ \therefore E = \frac{1}{2}N\Phi I \ \ Also,\ NI = H \times l \ \ and \ \ \Phi = B \times A$$

$$\therefore E = \frac{1}{2}(H \times l)(B \times A) \ = \ \frac{1}{2}BHV\ Joules \ \ where\ V\ is\ the\ volume\ of\ magnetic\ material$$

Coils connected in Series:

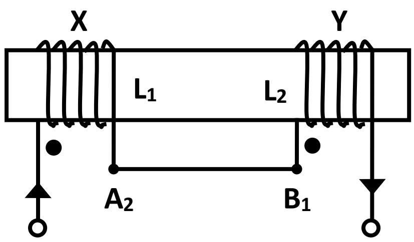


Fig. - 11

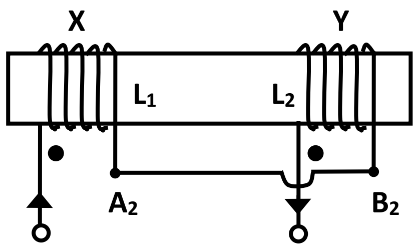


Fig. - 12

Let us consider two coils X and Y wound coaxially on an insulating cylinder with self inductances L_1 and L_2 Henry respectively and mutual inductance M Henry. Let the terminals A_2 and B_1 be joined together as shown in fig.-11. As per the dot convention as the currents are entering the dot, the fluxes produced in the coils are in the same direction and the coils are said to be cumulatively coupled. Hence, the equivalent self inductance L_A is given by $L_A = L_1 + L_2 + 2M$

Next, let the terminals A_2 and B_2 be joined together as shown in fig.-12. As per the dot convention, the fluxes produced in the coils are in opposition and the coils are said to be differentially coupled. Hence, the equivalent self inductance L_B is given by $L_B = L_1 + L_2 - 2M$

From the equations obtained for L_A and L_B, the value of Mutual inductance, $M = L_A - L_B/4$

Single phase transformer - Syllabus

General construction, working principle, emf equation, phasor diagram, equivalent circuits, voltage regulation, losses and efficiency, open circuit and short circuit test.

Transformer

A transformer is a stationary electrical apparatus that transfers power from one circuit to another by induction. It is the only A.C. machine that possesses the highest possible efficiency.

Construction: A transformer mainly consists of two windings and a laminated core with insulation. The winding connected to the supply is called primary winding and the winding connected to the load is called secondary winding. The winding made on the laminated core has a specific number of turns of copper conductors insulated from each other and from the core. The copper conductor can be of different cross sections. The core is made up of silicon steel laminations that are normally 0.3 to 0.6 mm thick. The laminations are insulated from each other by a thick coat of varnish. A bunch of laminations put together forms the core that are held together by bolts and nuts or riveted. High silicon content steel has a high relative permeability and low coefficient of Hysteresis. The use of high silicon content steel reduces hysteresis loss and by laminating the core the eddy current loss is minimized. The cores may be of different shapes. Depending on the shape of the core, we have core type transformers and shell type transformers. The figures show the magnetic cores used for shell type and core type transformers.

Core type: This type of core has a single window as shown in fig.-1 and the windingssurround a considerable part of the core. The coils are of cylindrical type and are wound in helical layers. Each layer is insulated from theother by insulating paper. The windings are always interleaved toreduce leakage flux i.e.half the primary and half the secondary on one limb and the other halves on the other limb. The LV winding is always placed close to the core and the HV winding is made above LV winding. The individual laminations of the core may be a single piece or it may be made up of two pieces.

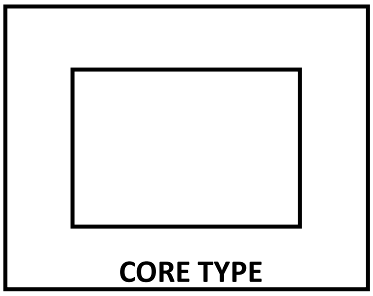


Fig. - 1

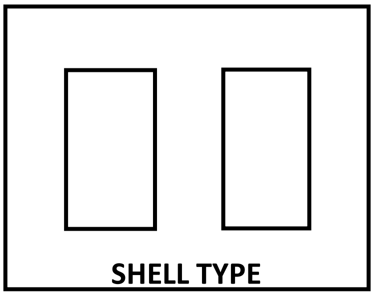


Fig. - 2

Shell type: This type of core has two windows as shown in fig. -2 and the core surrounds a considerable part of the winding. The individual laminations are usually made up of two pieces. The windings are always placed only on the central limb. Usually the HV winding is placed at the center and the LV winding is distributed equally on either sides of the HV winding. This type of winding is called Sandwich winding.

Principle of operation: The basic principle of operation of transformers is based on Faraday's laws of electromagnetic induction. The transformer has two windings wound on a laminated steel core. When AC supply is given to the primary winding, current flows through the primary winding producing a magnetic

flux that is alternating in nature. As the magnetic field lines always form a closed loop the flux produced exists in the steel core. The flux that exists in the core links the primary as well as secondary winding. Therefore according to Faraday's law both the windings get emf induced in them.

Emf equation: Let an AC voltage V_1 of supply frequency f be applied to the primary winding.

The sinusoidal flux produced by the primary will be $\Phi = \Phi_m Sin\omega t$

$$The\ instantaneous\ value\ of\ emf\ induced\ in\ primary, e_1 = -N_1 \frac{d\Phi}{dt} = -N_1 \frac{d}{dt}(\Phi_m Sin\omega t)$$

$$e_1 = -\omega N_1 \Phi_m Cos\omega t \quad = -2\pi f N_1 \Phi_m Cos\omega t \quad \therefore e_1 = 2\pi f N_1 \Phi_m Sin(\omega t - 90°)$$

From the above equation, the maximum value of induced emf in primary is $E_{m1} = 2\pi f N_1 \Phi_m$

The rms value of the primary emf $= E_1 = 0.707 E_{m1} \quad \therefore E_1 = 0.707 \times 2\pi f N_1 \Phi_m \quad = 4.44 f N_1 \Phi_m$

$E_1 = 4.44 f N_1 \Phi_m$ and $E_2 = 4.44 f N_2 \Phi_m$

Transformation ratios: Considering an ideal transformer, we have $V_1 = V_2$ and $E_1 = E_2$

The ratio of secondary voltage to primary voltage is called voltage transformation ratio.

It is represented by K and is also called as the turns ratio $V_2 = KV_1$

$$The\ voltage\ transformation\ ratio, \quad K = \frac{V_2}{V_1} = \frac{E_2}{E_1} = \frac{N_2}{N_1}$$

In an ideal transformer, we also have, Output = Input or $V_2 I_2 = V_1 I_1$

$$\therefore \frac{I_2}{I_1} = \frac{V_1}{V_2} = \frac{E_1}{E_2} = \frac{N_1}{N_2} = \frac{1}{K} \quad or \quad I_2 = \frac{I_1}{K}$$

Hence,the currents are in the inverse ratio of the voltage transformation ratio.

Transformer on no-load: If the primary winding is applied with an AC supply voltage V_1 and the secondary winding is kept open, then the transformer is considered to be on no-load. Due to the applied voltage V_1, an alternating current I_O flows in the primary that creates an alternating flux ϕ.

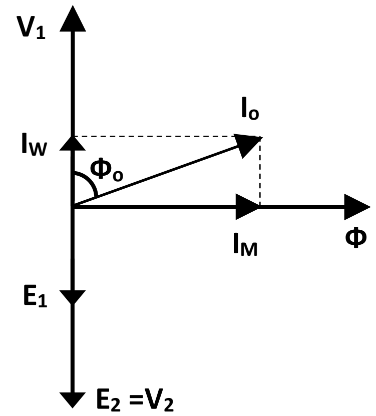


Fig. - 3

The applied voltage to the primary leads the flux by 90°. This flux that exists in the magnetic core links with the primary and secondary windings to induce emf's E_1 and E_2 that lag the flux by 90°.As there is no voltage drop in the secondary winding, $E_2 = V_2$. The no-load current I_O,also called as exciting current of the transformer lags the applied voltage V_1 by an angle ϕ_0. It is observed in fig. - 3, that the no-load current I_O has two components - I_M is the magnetising component that produces the desired flux in the core and is in phase with the flux ϕ. The other component I_W is called the working component or iron loss component that overcomes the hysteresis and eddy current losses occurring in the core. This component of the current is in phase with the applied voltage.

We have the magnetising component of the no-load current, $I_M = I_O \sin\phi_o$

and the working component of the no-load current, $I_W = I_O \cos\phi_o$

The no-load current, $I_O = \sqrt{I_M^2 + I_W^2}$; The input power on no-load, $W_O = V_1 I_O \cos\phi_o$

The no-load power factor, $\cos\phi_o = \dfrac{W_O}{V_1 I_O}$

Transformer on load : Whenever some variety of load is connected across the secondary winding of the transformer, the transformer is said to be on load. The load may be resistive, R-L or R-C. As the primary and secondary windings are made on the magnetic core using copper wires, let us assume that they possess a resistance of R_1 and R_2 respectively. The leakage flux in the primary winding varies linearly with the primary current and that in the secondary winding varies linearly with the secondary current. These leakage fluxes may be simulated by assigning primary and secondary leakage inductances along with the respective winding resistances. Let the reactance corresponding to the leakage inductance of primary and secondary be represented by X_1 and X_2. Fig. - 4, represents the circuit of a transformer with its winding resistance and leakage reactance.

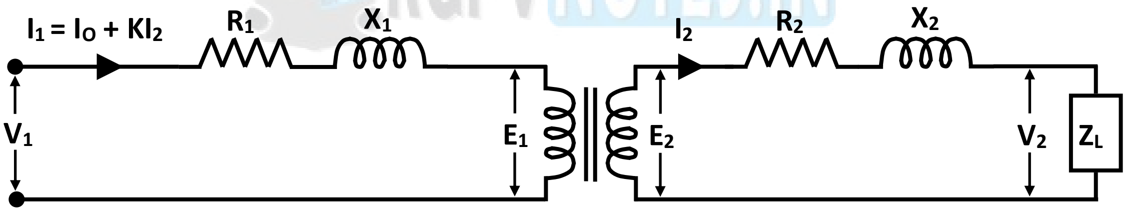


Fig. - 4

The value of R_1 and X_1 cause a voltage drop so that E_1 will be less than V_1. Similarly, V_2 is less than E_2 due to R_2 and X_2. Considering an R-L load, the current I_2 lags V_2 by an angle ϕ_2. The primary current I_1 has two components, the no-load current I_O and the current I_1^1 that neutralizes the demagnetizing effect of the secondary current I_2. The additional mmf's due to the load currents in the secondary and primary windings create fluxes which cancel each other, leaving the original flux ϕ.

The magnitude of I_1^1 will be such that $N_1 I_1^1 = N_2 I_2$

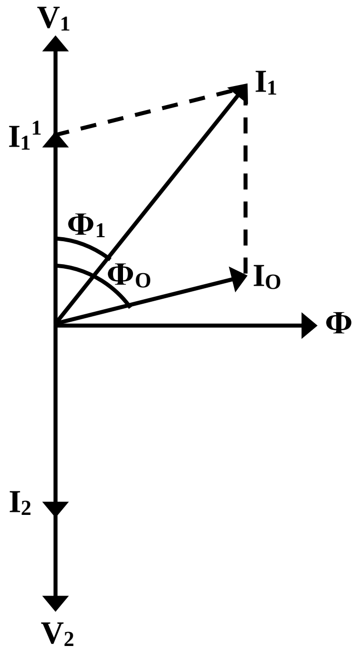
or $I_1^1 = \dfrac{N_2}{N_1} I_2 = KI_2$

The primary current on load, $I_1 = I_O + I_1^1$

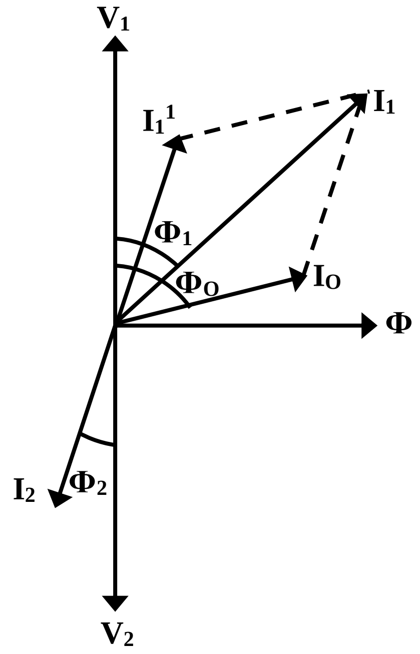
$\therefore \quad V_1 = -E_1 + I_1 Z_1$

and $V_2 = E_2 - I_2 Z_2$

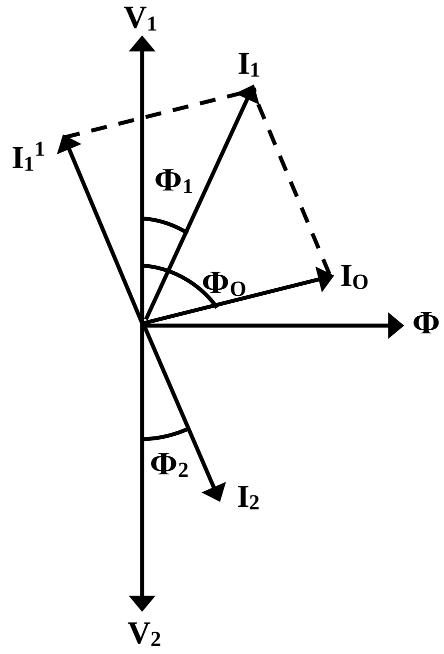
The phasor diagram for the working of a transformer with different varieties of loads are shown below -



PHASOR DIAGRAM FOR TRANSFORMER WITH RESISTIVE LOAD
Fig. - 5



PHASOR DIAGRAM FOR TRANSFORMER WITH R-L LOAD
Fig. - 6



PHASOR DIAGRAM FOR TRANSFORMER WITH R-C LOAD
Fig. - 7

The applied voltage V_1 leads the magnetic flux ϕ by 90° and the secondary voltage V_2 is equal and opposite to V_1. Let a R-L load be considered which draws a secondary current I_2 lagging V_2 by an angle ϕ_2 The current I_1^1 represents the primary current that neutralizes the demagnetizing effect of secondary current I_2. But $I_1^1 = KI_2$ is opposite to I_2. I_O is the no-load current of the transformer which lags the applied voltage by an angle ϕ_O . The primary current I_1 is the phasor sum of I_O and I_1^1 which lags the applied voltage V_1 by an angle ϕ_1. The load power factor = $\cos\phi_2$, The primary power factor = $\cos\phi_1$

The input power to the transformer, $P_1 = V_1 I_1 \cos\phi_1$

The output power of the transformer, $P_2 = V_2 I_2 \cos\phi_2$

The phasor diagram for a transformer with resistive load is shown in fig.- 5, and phasor diagram for a transformer with R-L load is shown in fig.- 6. The phasor diagram for a transformer with R-C load is shown in fig.- 7.

Equivalent circuit of transformer:

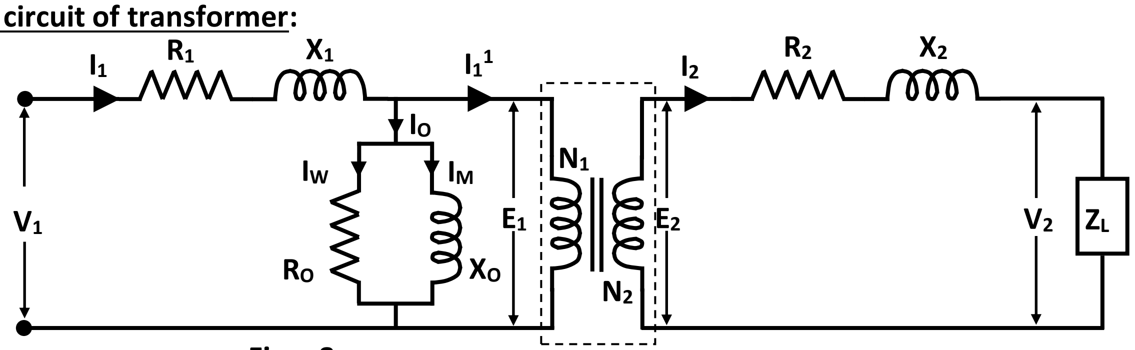


Fig. - 8

IDEAL TRANSFORMER

An actual transformer has two electric circuits linked by a magnetic circuit. To simplify calculations, a transformer is often represented by its equivalent circuit as shown in fig. - 8.The effects of the core and the windings are represented by equivalent basic circuit elements and the transformer gets reduced to a simple circuit. An equivalent circuit is merely a circuit interpretation of the equations that describe the behavior of the device. The transformer windings are shown as ideal. The resistance and leakage reactance of the primary and secondary are shown separately in the primary and secondary circuits. The effect of magnetising current is represented by a reactance X_O connected in parallel across the winding. The effect of core loss is represented by a non-inductive resistance R_O. The no-load current I_O in a transformer is only 1 to 3 % of its rated primary current; hence, it may be neglected, as it is not going to cause any serious error.

Approximate equivalent circuit of transformer: If theno-load current is neglected, we get the approximate equivalent circuit of the transformer. The equivalent circuit can be simplified by transferring the secondary resistance and reactance to the primary side in such a way that the ratio of E_2 to E_1 is not affected in magnitude or phase. If all the secondary quantities are referred to the primary, resistance and reactance are divided by K^2, voltages are divided by K and currents are multiplied by K.

We get the equivalent circuit of the transformer referred to primary as shown in fig. - 9.

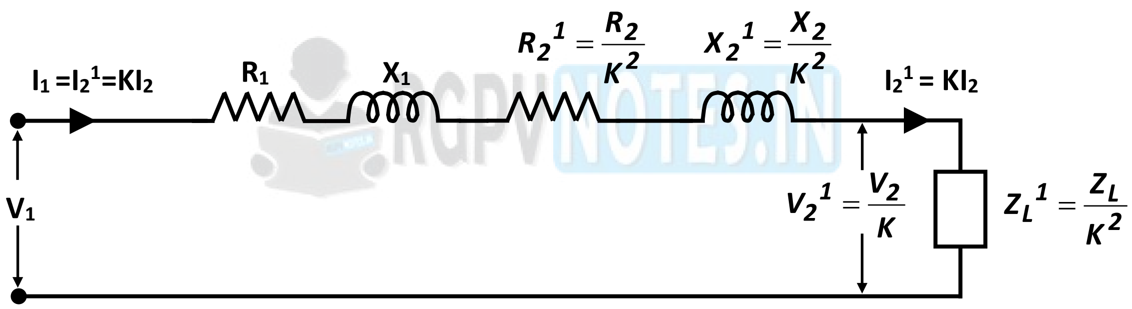


Fig. - 9

If all the primary quantities are referred to secondary, we get the equivalent circuit of the transformer referred to secondary. When primary quantities are referred to secondary, resistance and reactance are multiplied by K^2, voltages are multiplied by K and currents are divided by K.

Voltage regulation of a transformer: It is defined as the change in the output terminal voltage of the transformer from no-load to load condition, expressed as a fraction or percentage of the no-load terminal voltage.

$$\% \text{ Voltage Regulation} = \frac{oV_2 - V_2}{oV_2} \times 100$$

Where $oV_2$is the no-load secondary voltage and $V_2$is the secondary voltage on load.

Losses in transformer: The losses occurring in a transformer are of two types-

1. Iron loss
2. Copper loss.

These losses appear in the form of heat and produce an increase of temperature and drop in efficiency.

Core or Iron Losses: It comprises of Hysteresis and Eddy current losses and occur in the transformer core due to the alternating flux. We have Hysteresis loss = $P_h = K_h B_m^{1.6} f V$ watts,

and Eddy current loss = $P_e = K_e B_m^2 t^2 f^2 V$ watts

Where K_h and Ke are constants, 'f' is the frequency of the supply, 'B_m' is the Maximum flux density in the core, 'V' is the volume of magnetic material and 't' is the thickness of the lamination.

Both the losses depend on frequency and maximum flux density in the core. Since transformers are connected to constant frequency and constant supply voltage, both 'f' and 'B_m' are constant. Hence, core or iron losses are practically the same at all loads.

Iron or core losses, P_i = Hysteresis loss + Eddy current loss = Constant losses.

Copper losses: These losses occur both in primary and secondary windings due to their ohmic resistance.

Copper loss = $P_c = I_1^2 R_1 + I_2^2 R_2$ = Variable losses

Where I_1 = Primary current, R_1 = Resistance of primary winding, I_2 = Secondary current,

R_2 = Resistance of secondary winding.

Total loss in Transformer = Iron loss + Copper loss = Constant loss + Variable loss = $P_i + P_c$

Efficiency of Transformer:

The efficiency of a transformer is defined as the ratio of out put power to the input power.

$$\therefore Efficiency = \frac{Output\ power}{Input\ power} = \frac{Output}{Output + Losses} \quad \text{or } Efficiency\ \eta_x = \frac{x.KVA.Cos\phi}{x.KVA.Cos\phi + P_i + x^2 P_c}$$

Where KVA is the out put power rating of the transformer and 'x' is load factor,

x = 1 for Full load, x = 0.5 for Half full load and x = 0.25 for Quarter full load.

As Iron losses are independent of load they are considered as constant.

As Copper losses are proportional to the square of the load current, the copper losses = $x^2 P_c$

$$\%\ \eta_x = \frac{x.KVA.Cos\phi}{(x.KVA.Cos\phi) + P_i + x^2 P_c} \times 100$$

Transformer tests: The efficiency and voltage regulation of a transformer can be determined by two simple tests - Open circuit test and Short circuit test. These tests provide the required information using which the performance of the transformer can be ascertained without actually loading the transformer.

Open circuit test or no-load test: In this test the secondary winding is kept open and the rated voltage of the transformer is applied to its primary winding. The voltmeter measures the applied voltage V_1. The ammeter measures the no-load current I_0 . The wattmeter measures the no-load input power W_0 . As the no-load current is very small and flows only in the primary, the copper losses due to it are negligible. Hence, the wattmeter reading practically gives the iron losses in the transformer.The circuit connection to perform this test is shown in fig. - 10.

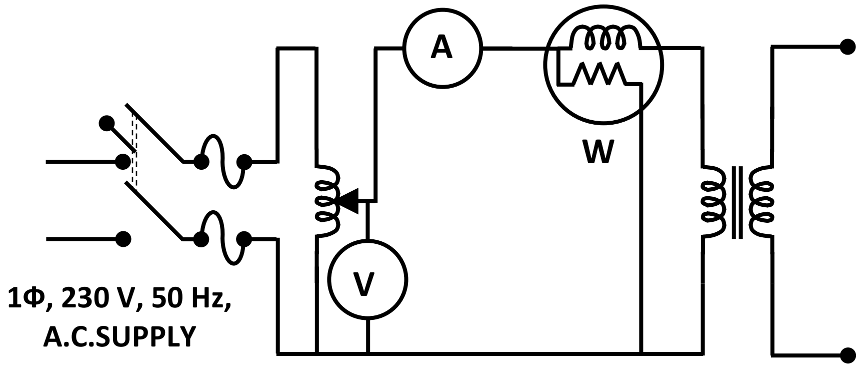


Fig. - 10

The input power on no-load = Iron losses = $P_i = W_O = V_1 I_O Cos\Phi_O$

$\textit{No load powerfactor},\quad Cos\Phi_O = \dfrac{W_O}{V_1 I_O}$

Magnetising component of the no-load current, $I_M = I_O Sin\Phi_O$

Working component of the no-load current, $I_W = I_O Cos\Phi_O$

$\textit{Core loss component resistance},\quad R_O = \dfrac{V_1}{I_W}\quad ;\quad \textit{Magnetising Reactance},\quad X_O = \dfrac{V_1}{I_M}$

Short circuit or Impedance test: In this test the secondary winding is short circuited and the voltage across the primary winding is adjusted such that the rated current flows through the primary winding. The voltmeter measures the applied voltage V_{1SC}. The ammeter measures the full load primary current I_1. As the applied voltage is very small the iron losses in the core will be negligible. Under short circuit condition there is no output from the transformer. Hence, the wattmeter measures the full load copper losses W_S in the transformer windings. The circuit connection to perform this test is shown in fig. - 11

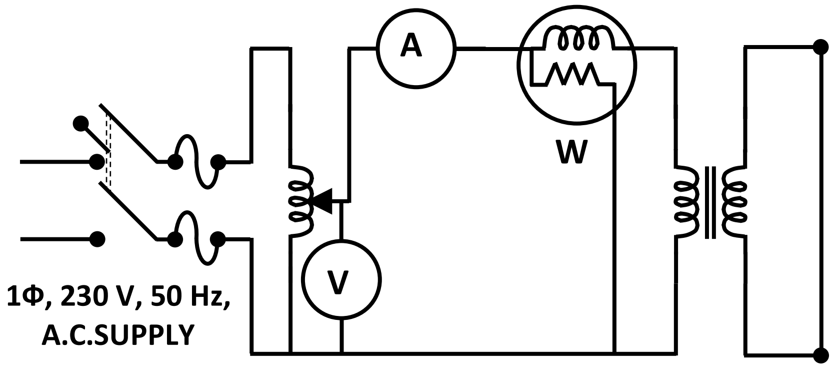


Fig. - 11

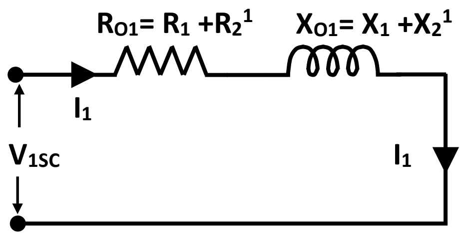


Fig. - 12

The equivalent circuit of a transformer on short circuit as referred to the primary is shown in fig. -12, as the no-load current is very small it is neglected.

The input power under short circuit condition = Copper losses = $P_C = W_S$

If total resistance of transformer referred to primary is R_{O1}; total reactance referred to primary is X_{O1}

Then total impedance referred to primary is Z_{O1}

$$\therefore R_{O1} = \frac{W_S}{I_1^2}\ ;\ Z_{O1} = \frac{V_{1SC}}{I_1}\ ;\ X_{O1} = \sqrt{Z_{O1}^2 - R_{O1}^2}\qquad \textit{Short circuit power factor},\ Cos_{\Phi 2} = \frac{W_S}{V_{1SC} I_1}$$

Relations for Efficiency and Voltage regulation: The efficiency of the transformer at any load factor 'x' and any power factor can be determined if the KVA rating of the transformer, Iron losses and the Full load copper losses are known. The relation given below helps in finding the efficiency from the OC and SC tests conducted on the transformer.

$$\% \ \eta_x = \frac{x.KVA.Cos\phi}{(x.KVA.Cos\phi) + P_i + x^2 P_c} \times 100$$

The voltage regulation of the transformer can be calculated by using the relation given below -

If the resistance and reactance of the transformer referred to the secondary side are known then

$$\% \ Voltage \ Regulation = \frac{I_2 \left(R_{O2} \, Cos\phi_2 \pm X_{O2} \, Sin\phi_2 \right)}{V_2} \times 100$$

(+ ve for lagging power factor and – ve for leading power factor)

V_2 is the secondary voltage of the transformer on no-load.

