SYLLABUS

Module-I: Magnetic fields and magnetic circuits (7 Hours)

Review of magnetic circuits - MMF, flux, reluctance, inductance; review of Ampere Law and Biot Savart Law; Visualization of magnetic fields produced by a bar magnet and a current carrying coil -through air and through a combination of iron and air; influence of highly permeable materials on the. magnetic flux lines.

Module-II: Electromagnetic force and torque (9 Hours)

B-H curve of magnetic materials; flux-linkage vs current characteristic of magnetic circuits; linear and nonlinear magnetic circuits; energy stored in the magnetic circuit; force as a partial derivative of stored energy with respect to position of a moving element; torque as a partial derivative of stored energy with respect to angular position of a rotating element. Examples - galvanometer coil, relay contact, lifting magnet, rotating element with eccentricity or saliency

Module-III: DC machines (9 Hours)

Basic construction of a DC machine, magnetic structure - stator yoke, stator poles, pole-faces or shoes, air gap and armature core, visualization of magnetic field produced by the field winding excitation with armature winding open, air gap flux density distribution, flux per pole, induced EMF in an armature coil. Armature winding and commutation - Elementary armature coil and commutator, lap and wave windings, construction of commutator, linear commutation Derivation of back EMF equation, armature MMF wave, derivation of torque equation, armature reaction, air gap flux density distribution with armature reaction.

Module-IV DC machine - motoring and generation (8 Hours)

Armature circuit equation for motoring and generation, Types of field excitations – separately excited, shunt and series. Open circuit characteristic of separately excited DC generator, back EMF with armature reaction, voltage build-up in a shunt generator, critical field resistance and critical speed. V-I characteristics and torque-speed characteristics of separately excited, shunt and series motors. Speed control through armature voltage. Losses, load testing and back-to-back testing of DC machines

Module-V Transformers (12 Hours)

Principle, construction and operation of single-phase transformers, equivalent circuit, phasor diagram, voltage regulation, losses and efficiency Testing - open circuit and short circuit tests, polarity test, back-to-back test, separation of hysteresis and eddy current losses Three-phase transformer - construction, types of connection and their comparative features, Parallel operation of single-phase and three-phase transformers, Autotransformers - construction, principle, applications and comparison with two winding transformer, Magnetizing current, effect of nonlinear B-H curve of magnetic core material, harmonics in magnetization current, Phase conversion - Scott connection, three-phase to six-phase conversion, Tap-changing transformers - No-load and on-load tap-changing of transformers, Three-winding transformers. Cooling of transformers.

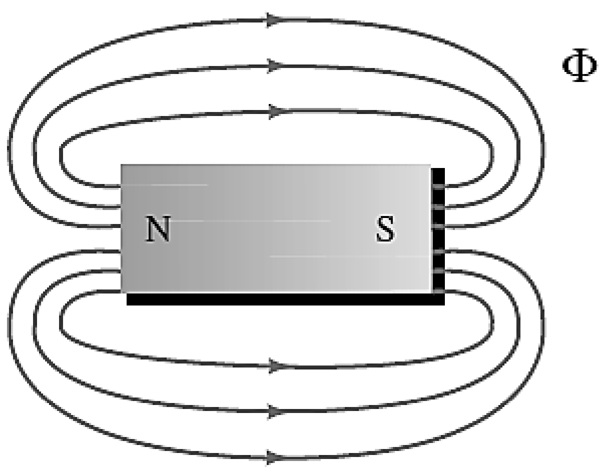
MODULE-I

MAGNETIC FIELD & MAGNETIC CIRCUITS

Magnetism and Magnetic Circuits:

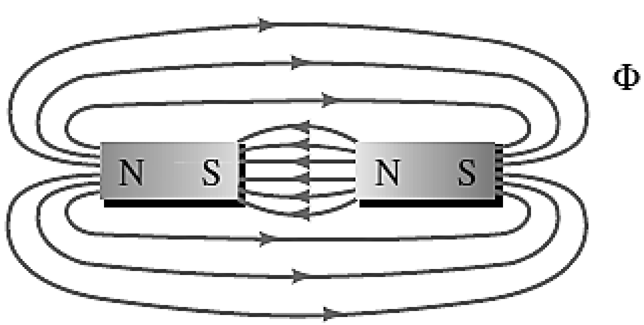
The Nature of a Magnetic Field:

- Magnetism refers to the force that acts between magnets and magnetic materials. We know, for example, that magnets attract pieces of iron, deflect compass needles, attract or repel other magnets, and so on.
- The region where the force is felt is called the "field of the magnet" or simply, its magnetic field. Thus, a magnetic field is a force field.
- Using Faraday's representation, magnetic fields are shown as lines in space. These lines, called flux lines or lines of force, show the direction and intensity of the field at all points.
- The field is strongest at the poles of the magnet (where flux lines are most dense), its direction is from north (N) to south (S) external to the magnet, and flux lines never cross. The symbol for magnetic flux as shown is the Greek letter (phi).



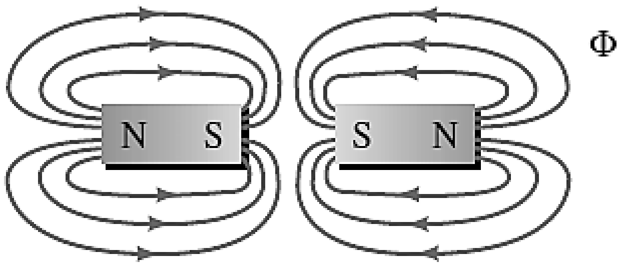
What happens when two magnets are brought close together?

- If unlike poles attract, and flux lines pass from one magnet to the other.



(a) Attraction

- If like poles repel, and the flux lines are pushed back as indicated by the flattening of the field between the two magnets.

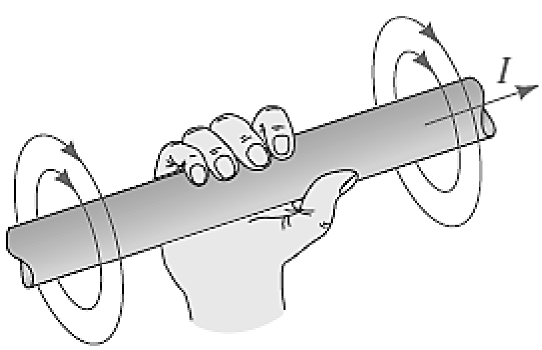


(b) Repulsion

- Ferromagnetic Materials (magnetic materials that are attracted by magnets such as iron, nickel, cobalt, and their alloys) are called ferromagnetic materials. Ferromagnetic materials provide an easy path for magnetic flux.
- The flux lines take the longer (but easier) path through the soft iron, rather than the shorter path that they would normally take. Note, however, that nonmagnetic materials (plastic, wood, glass, and so on) have no effect on the field.

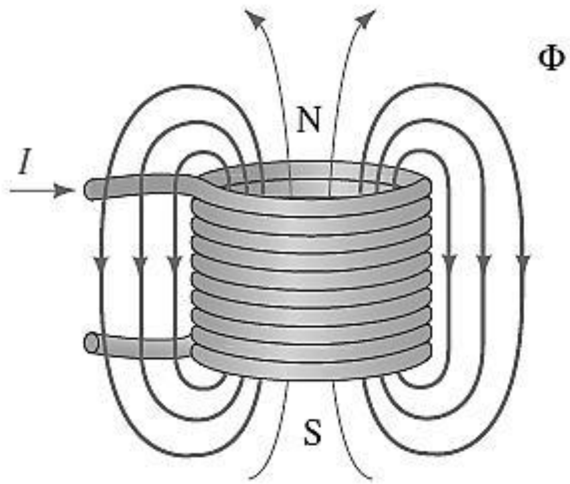
Electromagnetism:

Most applications of magnetism involve magnetic effects due to electric currents. The current, I, creates a magnetic field that is concentric about the conductor, uniform along its length, and whose strength is directly proportional to I. Note the direction of the field. It may be remembered with the aid of the right-hand rule, imagine placing your right hand around the conductor with your thumb pointing in the direction of current. Your fingers then point in the direction of the field. If you reverse the direction of the current, the direction of the field reverses.

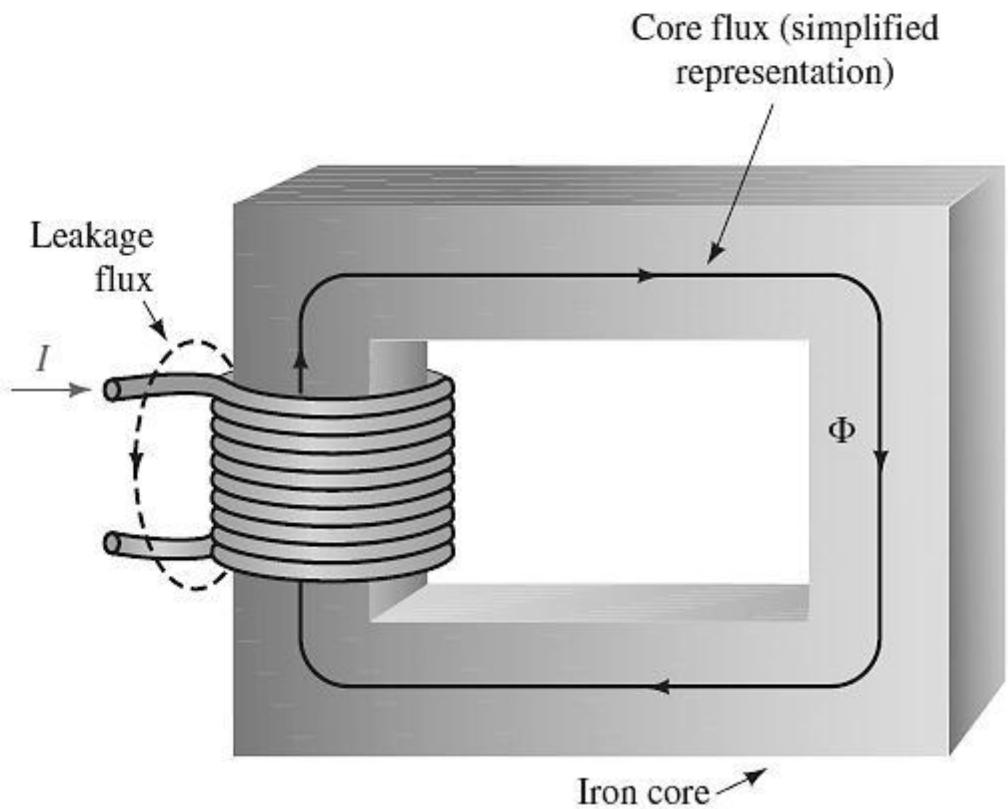


Right-hand rule

If the conductor is wound into a coil(Provided no ferromagnetic material is present) , the fields of its individual turns combine, producing a resultant field as in Figure. The direction of the coil flux can also be remembered by means of a simple rule: curl the fingers of your right hand around the coil in the direction of the current and your thumb will point in the direction of the field. If the direction of the current is reversed, the field also reverses. Provided no ferromagnetic material is present, the strength of the coil's field is directly proportional to its current.



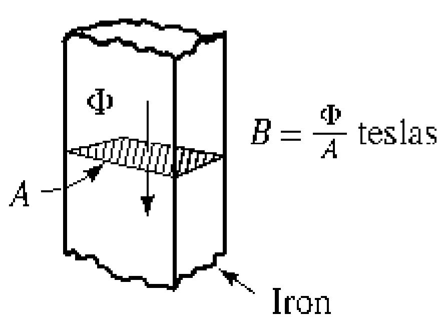
If the coil is wound on a ferromagnetic core as in Figure below (transformers are built this way), almost all flux is confined to the core, although a small amount (called stray or leakage flux) passes through the surrounding air. However, now that ferromagnetic material is present, the core flux is no longer proportional to current.



Flux and Flux Density:

The magnetic flux is represented by the symbol □. In the SI system, the unit of flux is the weber (Wb). However, we are often more interested in flux density B (i.e., flux per unit area) than in total flux □.

Since flux □ is measured in Wb and area A in m2, flux density is measured as Wb/m2, the unit of flux density is called the tesla (T) where 1 T = 1 Wb/m2. Flux density is found by dividing the total flux passing perpendicularly through an area by the size of the area is,



$$\boldsymbol{B = \frac{\Phi}{A}} \quad (\boldsymbol{Tesla, T})$$

PERMEABILITY:

If cores of different materials with the same physical dimensions are used in the electromagnet, the strength of the magnet will vary in accordance with the core used. This variation in strength is due to the greater or lesser number of flux lines passing through the core. Materials in which flux lines can readily be set up are said to be magnetic and to have high permeability. The permeability (μ) of a material It is similar in many respects to conductivity in electric circuits. The permeability of free space (vacuum) is.

$$\mu_o = 4\pi \times 10^{-7} \frac{Wb}{A.m}$$

The permeability of all nonmagnetic materials, such as copper, aluminum, wood, glass, and air, is the same as that for free space. Materials that have permeabilities slightly less than that of free space are said to be diamagnetic, and those with permeabilities slightly greater than that of free space are said to be paramagnetic. Materials with these very high permeabilities are referred to as ferromagnetic.
The ratio of the permeability of a material to that of free space is called its relative permeability; that is,

$$\mu_r = \frac{\mu}{\mu_o}$$

In general, for ferromagnetic materials, $\mu_r \geq 100$, and for nonmagnetic materials, $\mu_r = 1$.

RELUCTANCE:

The resistance of a material to the flow of charge (current) is determined for electric circuits by the equation,

$$R = \rho \frac{l}{A} \qquad (Ohms)$$

The reluctance of a material to the setting up of magnetic flux lines in the material is determined by the following equation:

$$\mathbb{R} = \frac{\ell}{\mu A} \quad (\frac{At}{Wb})$$

where R is the reluctance, and L is the length of the magnetic path, and A is the cross-sectional area. The units At/Wb is the number of turns of the applied winding. More is said about ampere-turns (At).

MMF: The Source of Magnetic Flux:

Current through a coil creates magnetic flux. The greater the current or the greater the number of turns, the greater will be the flux. This flux-producing ability of a coil is called its magnetomotive force (mmf). Magnetomotive force is given the symbol F and is defined as

$$\mathcal{F} = mmf = NI \qquad (amper - turn, At)$$

Ohm's Law for Magnetic Circuits:

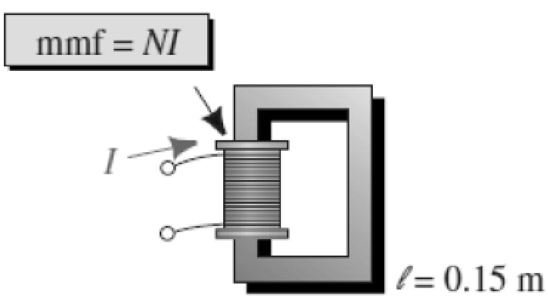
The relationship between flux, mmf, and reluctance is

$$\Phi = \frac{\mathcal{F}}{\mathbb{R}} \qquad (Wb)$$

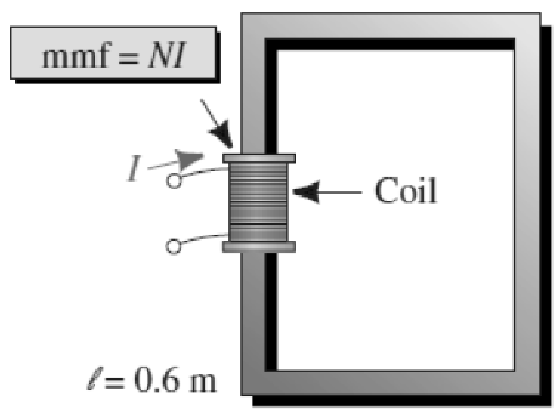
Magnetic Field Intensity and Magnetization Curves :

We now look at a more practical approach to analyzing magnetic circuits. First, we require a quantity called magnetic field intensity, H (also known as magnetizing force). It is a measure of the mmf per unit length of a circuit. We can define magnetic field intensity as the ratio of applied mmf to the length of path that it acts over. Thus,

$$H = \frac{\mathcal{F}}{\ell} = \frac{NI}{\ell} \qquad \left(\frac{AT}{m}\right)$$



(b) A short path



(a) A long path

The Relationship between B and H:

The flux density and the magnetizing force are related by the following equation:

$$\mathcal{B} = \mu H$$

Biot-Savart law

- We know that any current carrying conductor produces a magnetic field. A magnetic field $\mathfrak{R}$ is characterized either by H → , the magnetic field intensity or by B → , the magnetic flux density vector.

These two vectors are connected by a rather simple relation: $\vec{B} = \mu_0 \mu_r \vec{H}$; where $\mu_0 = 4\pi \times 10^{-7}$ H/m is called the *absolute permeability* of free space and μ_r, a dimensionless quantity called the *relative permeability* of a medium (or a material). For example the value of μ_r is 1 for free space or could be several thousands in case of ferromagnetic materials.

Biot-Savart law is of fundamental in nature and tells us how to calculate dB or $\vec{dH}$ at a given point with position vector r, due to an elemental current $i\,\vec{dl}$ and is given by:

$$\vec{dB} = \frac{\mu_0 \mu_r}{4\pi} \frac{i\,\vec{dl} \times \vec{r}}{r^3}$$

If the shape and dimensions of the conductor carrying current is known then field at given point can be calculated by integrating the RHS of the above equation.

$$\vec{B} = \frac{\mu_0 \mu_r}{4\pi} \int_{\text{length}} \frac{i\,\vec{dl} \times \vec{r}}{r^3}$$

where, length indicates that the integration is to be carried out over the length of the conductor. However, it is often not easy to evaluate the integral for calculating field at any point due to any arbitrary shaped conductor. One gets a nice closed form solution for few cases such as:

1. Straight conductor carries current and to calculate field at a distance d from the conductor.
2. Circular coil carries current and to calculate field at a point situated on the axis of the coil.

Ampere's circuital law

This law states that line integral of the vector along any arbitrary closed path is equal to the current enclosed by the path. Mathematically:

$$\oint \vec{H} \cdot \vec{dl} = I$$

For certain problems particularly in *magnetic circuit problems* Ampere's circuital law is used to calculate field instead of the more fundamental *Biot Savart law* for reasons going to be explained below. Consider an infinite straight conductor carrying current i and we want to calculate field at a point situated at a distance d from the conductor. Now take the closed path to be a circle of radius d. At any point on the circle the magnitude of field strength will be constant and direction of the field will be tangential. Thus LHS of the above equation simply becomes $H \times 2\pi d$. So field strength is

$$H = \frac{I}{2\pi d} \text{ A/m}$$

It should be noted that in arriving at the final result no integration is required and it is obtained rather quickly. However, one has to choose a suitable path looking at the distribution of the current and arguing that the magnitude of the field remains constant through out the path before applying this law with advantage.

MODULE-II

ELECTROMAGNETIC FOURCE & TORQUE

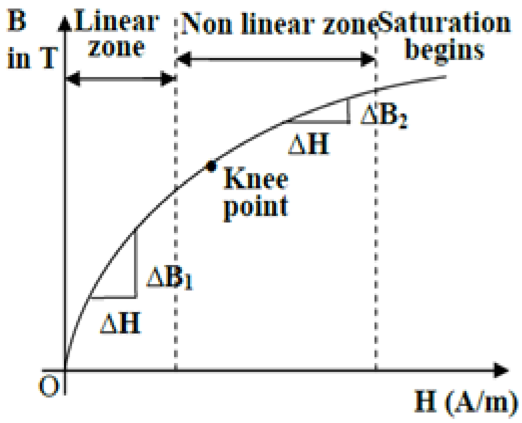
B-H Characteristics:

A magnetic material is identified and characterized by its $B - H$ characteristic. In free space or in air the relationship between the two is *linear* and the constant of proportionality is the permeability μ_0. If B is plotted against H, it will be straight a line. However, for most of the materials the relationship is not linear.

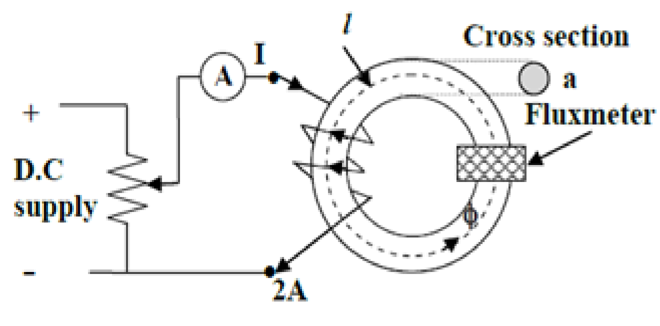
Let,

Number of turns	=	N
Mean length of the flux path	=	l in m.
Cross sectional area	=	a in m^2
Reading of the ammeter	=	I in A
Reading of the flux meter	=	ϕ in Wb

Now corresponding to this current, calculate $H = \frac{NI}{l}$ and $B = \frac{\phi}{a}$ and tabulate them. Thus we have several pair of H & B values for different values of currents. Now by choosing H to be the x axis B to be the y axis and plotting the above values one gets a *typical* B-H curve as shown in Figure 21.7 below.



A typical B-H curve



Experimental
determination of B-H curve

Different zones of B-H characteristic

The initial portion of the B-H curve is nearly a straight line and called *linear zone*. After this zone the curve gradually starts deviating from a straight line and enters into the nonlinear zone. The slope of the curve *dB/dH* starts gradually decreasing after the linear zone. A time comes when there is practically no increase in *B* in spite of the fact that *H* is further increased. The material is then said to be *saturated*. The rise in the value of B in the linear zone is much more than in the nonlinear or saturation zone for *same* ΔH. This can be ascertained from the B-H curve by noting $\Delta B1 > \Delta B2$ for same ΔH.

For this lesson, a brief qualitative explanation for the typical nature of the B-H curve is given. In a ferromagnetic material, very large number of tiny magnets (*magnetic dipoles*) are present at the atomic/molecular level. The material however does not show any net magnetic property at macroscopic level due to random distribution of the dipoles and eventual cancellation of their effects. In presence of an external field $\vec{H}$, these dipoles start aligning themselves along the direction of the applied field. Thus the more and more dipoles get aligned (resulting into more B) as the H i.e., current in the exciting coil is increased. At the initial phase, increase in B is practically proportional to H. However rate of this alignment gets reduced after a definite value of H as number of randomly distributed dipoles decreases. This is reflected in the nonlinear zone of the figure 2.1. Obviously if we further increase H, a time will come when almost all the dipoles will get aligned. Under such circumstances we should not expect any rise in B even if H is increased and the core is said to be *saturated*. At the saturation zone, the characteristic becomes almost parallel to the H axis.

Different materials will have different B-H curves and if the characteristics are plotted on same graph paper, one can readily decides which of them is better than the other. Referring to Figure 21.9, one can easily conclude that material-3 is better over the other two as flux produced in material-3 is the highest for same applied field H.

From the above discussion it can be said that there is no point in operating a magnetic circuit deep into saturation zone as because large exciting current will put extra overhead on the source supplying power to the coil. Also any desire to increase B by even a small amount in this zone will call for large increase in the value of the current. In case of transformers and rotating machines operating point is chosen close to the *knee point* of the B-H characteristic in order to use the magnetic material to its true potential. To design a constant value of *inductance,* the operating point should be chosen in the linear zone.

Approach to solve a magnetic circuit problem will be different for *linear* and *nonlinear* cases. In the following section let us discuss those approaches followed by equivalent electrical circuit representation of the magnetic circuits. It is instructive to draw *always* the equivalent representation of a magnetic circuit for the following reasons:

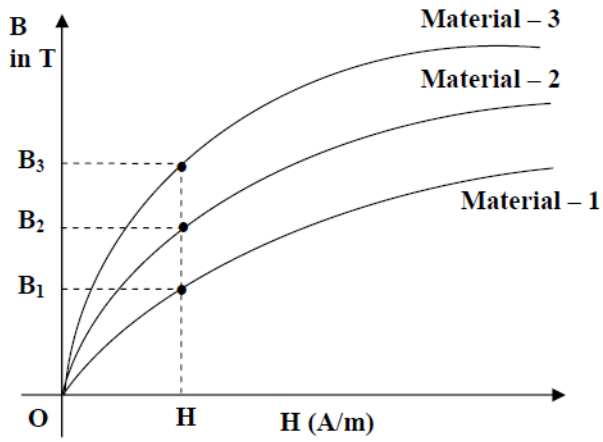


Figure-2.1

The various equations which will hold good are written below:

$$\phi = \phi_1 + \phi_2$$

$$NI = Hl + H_1 l_1 + H_g l_g = \Re\phi + (\Re_1 + \Re_g)\phi_1 \text{ balance in loop1}$$

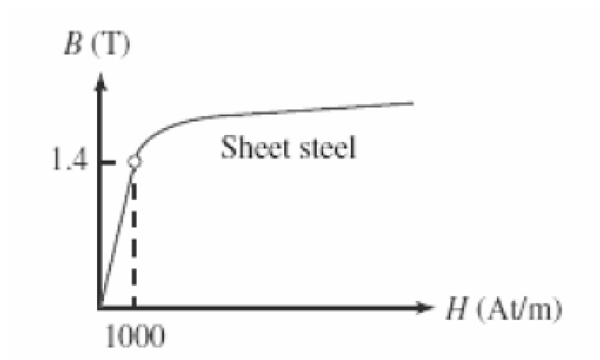
$$(\Re_1 + \Re_g)\phi_1 = \Re_2\phi_2 \text{ mmf balance in loop2}$$

$$H_1 l_1 + H_g l_g = H_2 l_2 \text{ mmf balance in loop2}$$

$$NI = Hl + H_2 l_2 \text{ mmf balance in the outer loop.}$$

<u>EXAMPLE :</u> If B =1.4 T for sheet steel, what is H?

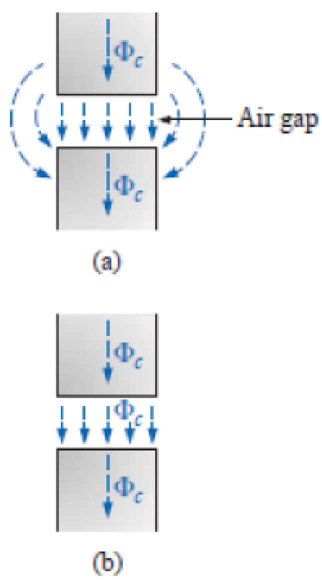
Sol/



For sheet steel, H = 1000 At/m, when B = 1.4 T.

Air Gaps, Fringing, and Laminated Cores:

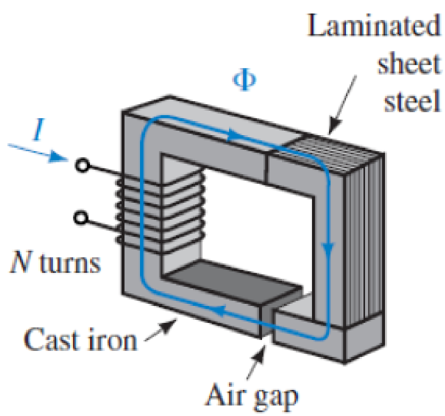
The spreading of the flux lines outside the common area of the core for the air gap in Figure(a) is known as fringing. For our purposes, we shall neglect this effect and assume the flux distribution to be as in Figure (b) .For magnetic circuits with air gaps, fringing occurs, causing a decrease in flux density in the gap. For short gaps, fringing can usually be neglected. Alternatively, correction can be made by increasing each cross-sectional dimension of the gap by the size of the gap to approximate the decrease in flux density.



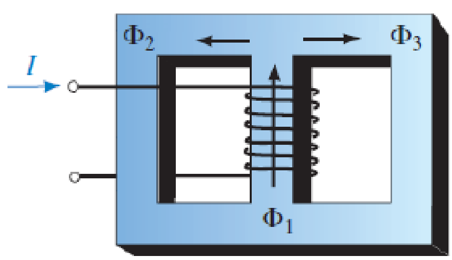
Air gaps: (a) with fringing; (b) ideal.

Series Elements and Parallel Elements:

Magnetic circuits may have sections of different materials. For example, the circuit of Figure has sections of cast iron, sheet steel, and an air gap. For this circuit, flux is the same in all sections. Such a circuit is called a series magnetic circuit. Although the flux is the same in all sections, the flux density in each section may vary, depending on its effective cross-sectional area as you saw earlier.



A circuit may also have elements in parallel (Figure). At each junction, the sum of fluxes entering is equal to the sum leaving. This is the counterpart of Kirchhoff's current law. Thus



$$\Phi_1 = \Phi_2 + \Phi_3$$

Series Magnetic Circuits: Given Φ, Find NI

You now have the tools needed to solve basic magnetic circuit problems. This type can be solved using four basic steps:

1) **Compute *B* for each section using $B = \frac{\Phi}{A}$.**
2) **Determine *H* for each magnetic section from the *B-H* curves. Use $H_g = 7.96 \times 10^5 B_g$ for air gaps.**
3) **Compute *NI* using Ampere's circuital law.**
4) **Use the computed *NI* to determine coil current or turns as required**

PRACTICAL NOTES...

Magnetic circuit analysis is not as precise as electric circuit analysis because

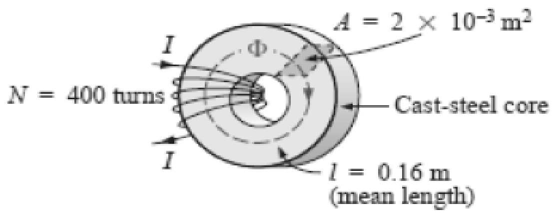
- ✓ **The assumption of uniform flux density breaks down at sharp corners.**
- ✓ **The B-H curve is a mean curve and has considerable uncertainty.**

Although the answers are approximate, they are adequate for most purposes.

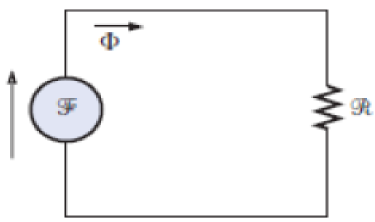
<u>EXAMPLE</u> : For the series magnetic circuit of Figure

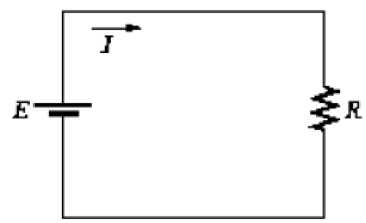
a) **Find the value of I required to develop a magnetic flux of $\Phi = 4 \times 10^{-4} Wb$.**

b) **Determine μ and μ_r for the material under these conditions.**



Sol/ $\Phi = 4 \times 10^{-4} Wb$, $A = 2 \times 10^{-3} m^2$,
$N = 400\ turns$, $\ell = 0.16\ m$





The flux density B is

$$B = \frac{\Phi}{A} = 0.2\ T$$

Using the B-H curves, we can determine the magnetizing force H:

$$H(Cast\ steel) = 170\ At/m$$

Applying Ampère's circuital law yields:

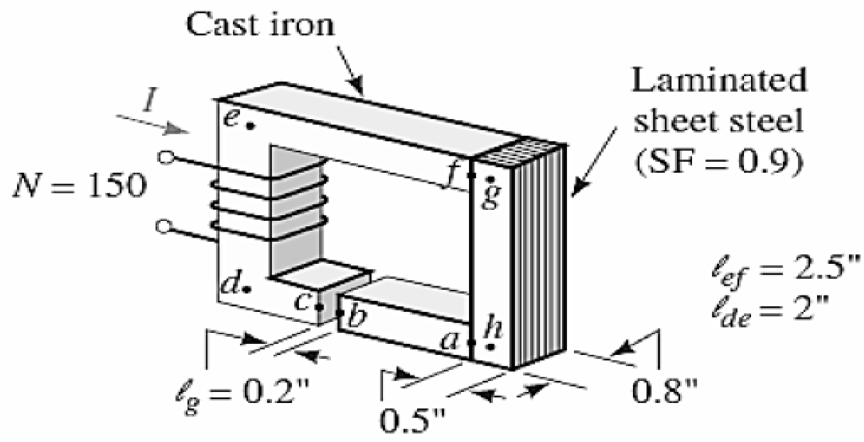
$$NI = H\ell, \qquad I = \frac{H\ell}{N} = 68\ mA$$

b. The permeability of the material can be found,

$$\mu = \frac{B}{H} = 1.17 \times 10^{-3} \frac{Wb}{A * m}$$

$$\mu_r = \frac{\mu}{\mu_o} = 935.83$$

Example: **The laminated sheet steel section of Figure ha a stacking factor of 0.9. Compute the current required t establish a flux of $\Phi = 1.4 \times 10^{-4}\ Wb$. Neglect fringing.**



Cross section = 0.5" × 0.8" (all members)
$\Phi = 1.4 \times 10^{-4}$ Wb

Sol/ Convert all dimensions to metric.

Cast iron:

$$\ell_{iron} = \ell_{ab} + \ell_{cdef} = 2.5 + 2 + 2.5 - 0.2 = 6.8\ in$$

$$\ell_{iron} = \frac{6.8}{39.37} = 0.173\ m$$

$$A_{iron} = (0.5 \times 0.8) = 0.4\ in^2 = 0.258 \times 10^{-3}\ m^2$$

$$B_{iron} = \frac{\Phi}{A_{iron}} = 0.54\ T$$

From B-H curve (Cast iron)

$$H_{iron} = 1850\ At\ /m$$

Sheet steel:

$$\ell_{steel} = \ell_{fg} + \ell_{gh} + \ell_{ha} = 0.25 + 2 + 0.25 = 2.5\ in$$
$$= 6.35 \times 10^{-2} m$$

$$A_{steel} = (0.9)(0.258 \times 10^{-3}) = 0.232 \times 10^{-3} m^2$$

$$B_{steel} = \frac{\Phi}{A_{steel}} = 0.6\ T$$

From B-H curve (Sheet steel)

$$H_{steel} = 125\ \frac{At}{m}$$

Air gap:

$$\ell_g = 0.2\ in = 5.08 \times 10^{-3} m$$

$$B_g = B_{iron} = 0.54T$$

$$H_g = (7.96 \times 10^5)(0.54) = 4.3 \times 10^5\ At/m$$

Ampere's law

$$NI = H_{iron}\ell_{iron} + H_{steel}\ell_{steel} + H_g\ell_g = 2512\ At$$

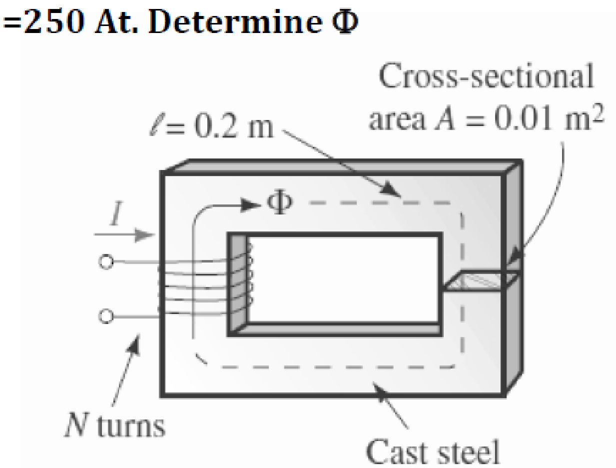
$$I = \frac{2512}{N} = 16.7\ Amps.$$

Series-Parallel Magnetic Circuits:

Series-parallel magnetic circuits are handled using the sum of fluxes principle and Ampere's law.

Example: For the circuit of Figure , NI =250 At. Determine Φ

sol/



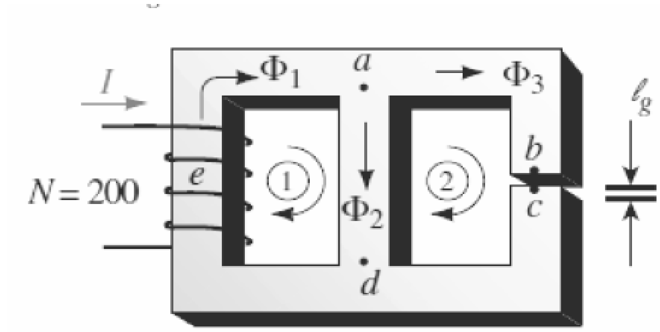
$$NI = H\ell \ \rightarrow H = \frac{NI}{\ell} = 1250\ At/m$$

From B-H curve(cast steel)

B= 1.2T , therefore

$$\Phi = BA = 1.24 \times 10^{-4} Wb$$

<u>Example :</u> The core of Figure below is cast steel. Determine the current to establish an air-gap flux $\Phi_g = 6 \times 10^{-3} Wb$. Neglect fringing.



<u>Cast steel</u>

$$\ell_{ab} = \ell_{cd} = 0.25\, m$$

$$\ell_g = \ell_{bc} = 0.25 \times 10^{-3} m$$

$$\ell_{da} = 0.2\, m$$

$$\ell_{dea} = 0.35\, m$$

$$A = 2 \times 10^{-2} m^2$$

$$\Phi_g = \Phi_3$$

Sol/ Air Gap

$$B_g = \frac{\Phi_g}{A_g} = 0.3T$$

$$H_g = (7.96 \times 10^5)(0.3) = 2.388 \times 10^5\ At\ /m$$

<u>Sections ab and cd</u>

$$B_{ab} = B_{cd} = B_g = 0.3T$$

From B-H curve

$$H_{ab} = H_{cd} = 250\ At\ /m$$

Ampere's Law (Loop 2), $\sum_{\circlearrowright} NI = \sum_{\circlearrowright} H\ell$

$$0 = H_{ab}\ell_{ab} + H_g\ell_g + H_{cd}\ell_{cd} - H_{da}\ell_{da}$$

$$0 = 62.5 + 59.7 + 62.5 - 0.2\, H_{da}$$

$$H_{da} = 925\ At \backslash m$$

MODULE-III

DC MACHINES

D.C Generator

An electrical Generator is a machine which converts mechanical energy (or power) into electrical energy (or power). The generator operates on the principle of the production of dynamically induced emf i.e., whenever flux is cut by the conductor, dynamically induced emf is produced in it according to the laws of electromagnetic induction, which will cause a flow of current in the conductor if the circuit is closed.

Hence, the basic essential parts of an electric generator are:

- A magnetic field and
- A conductor or conductors which can so move as to cut the flux

In dc generators the field is produced by the field magnets which are stationary. Permanent magnets are used for very small capacity machines and electromagnets are used for large machines to create magnetic flux. The conductors are situated on the periphery of the armature being rotated by the prime-mover.

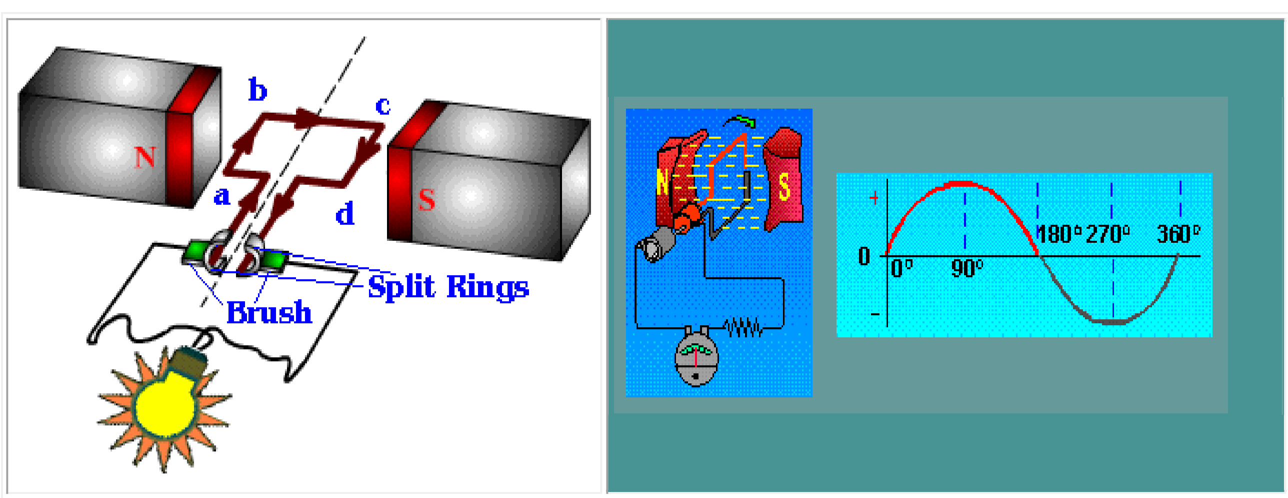


Fig. 3.1 Basics of dc generators

Practical DC generator construction

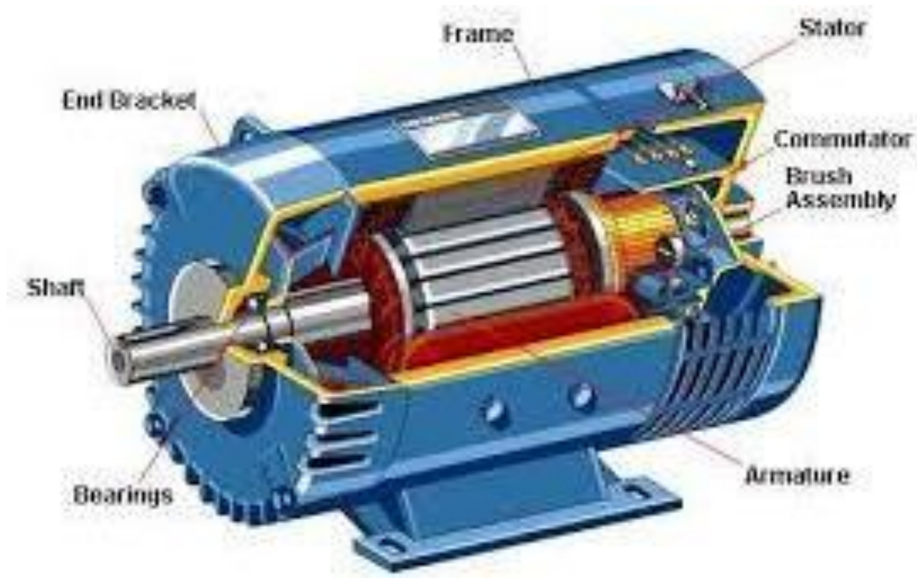


Fig. 3.2 Cut-away view of dc practical generators

The actual DC generator consists of the following essential parts:

- Magnetic frame or Yoke
- Pole Cores and Pole Shoes
- Pole Coils or Field Coils
- Armature Core
- Armature Windings or Conductors
- Commutator
- Brushes and Bearings

a) Magnetic frame or Yoke

Purpose of Yoke is

1. It act as a protecting cover for whole machine

2. It provides mechanical support for poles

3. It carries the magnetic flux produced by poles

b) Pole Cores and Pole Shoes

The field magnets consist of pole cores and pole shoes. The Pole shoes serve two purposes:

1. They spread out the flux in the air gap

2. They support the exciting coils

c) Armature

When current is passed through field coils, they electro-magnetize the poles which produce the necessary flux.

The Armature serves two purposes:

1. Armature houses the armature conductors or coils
2. It provides low reluctance path for flux

It is drum shaped and is built up of laminations made sheet steel to reduce eddy current loss. Slots are punched on the outer periphery of the disc. The Armature windings or conductors are wound in the form of flat rectangular coils and are placed in the slots of the Armature. The Armature windings are insulated from the armature body by insulating materials.

d) Commutator and brushes

The function of Commutator is to facilitate collection of current from the armature conductors and converts the alternating current induced in the armature conductors into unidirectional current in the external load circuit. The commutator is made up of insulated copper segments. Two brushes are pressed to the commutator to permit current flow. The Brushes are made of carbon or Graphite. Bearings are used for smooth running of the machine.

E.M.F. equation

Let, ϕ =flux per pole in weber

z = total number of armature conductors=no. of slots$\times$ no. of conductors/slot

P = no. of generator poles

A = no. of parallel paths in armature

N = armature rotation in revolutions per minute (rpm)

E = emf induced in any parallel path in armature

Generated emf, E_g = emf generated in any one of the parallel path i.e. E

Average emf generated/conductor $= \frac{d\phi}{dt}$ volts, $\because n = 1$

Now, flux cut per conductor in one revolution,

$d\phi = \phi P$ weber

No. of revolutions per second $= \frac{N}{60}$

Time for one revolution, $dt = \frac{60}{N}$ second

Hence, according to Faradays laws of Electromagnetic induction,

EMF generated/conductor $= \frac{d\phi}{dt} = \frac{\phi PN}{60}$ volts

For a simplex lap-wound generator:

No. of parallel paths $= P$

No. of conductors in one path $= \frac{z}{P}$

Hence, EMF generated/path $= \frac{\phi PN}{60} \times \frac{z}{P} = \frac{\phi zN}{60}$ volts

For a simplex wave-wound generator:

No. of parallel paths = 2

No. of conductors in one path $= \frac{z}{2}$

Hence, EMF generated/path $= \frac{\phi PN}{60} \times \frac{z}{2} = \frac{\phi zNP}{120}$ volts

In general generated EMF, $E_g = \frac{\phi zN}{60} \times \frac{P}{A}$

Types of generator

DC generators are usually classified according to the way in which their fields are excited. DC generators may be divided into, (a) separately excited dc generators, and (b) self excited dc generators.

a) separately excited dc generators

Separately excited generators are those whose field magnets are energized from an independent external source of dc current.

b) self excited dc generators

Self excited generators are those whose field magnets are energized by the current produced by the generators themselves. Due to residual magnetism, there is always present some flux in the poles. When the armature is rotated, some emf and hence some current flows which is partly or fully passed through the field coils thereby strengthening the residual pole flux.

There are three types of self excited dc generators named according to the manner in which their field coils (or windings) are connected to the armature. In shunt the two windings, field and armature are in parallel while in series type the two windings are in series. In compound type the part of the field winding is in parallel while other part in series with the armature winding.

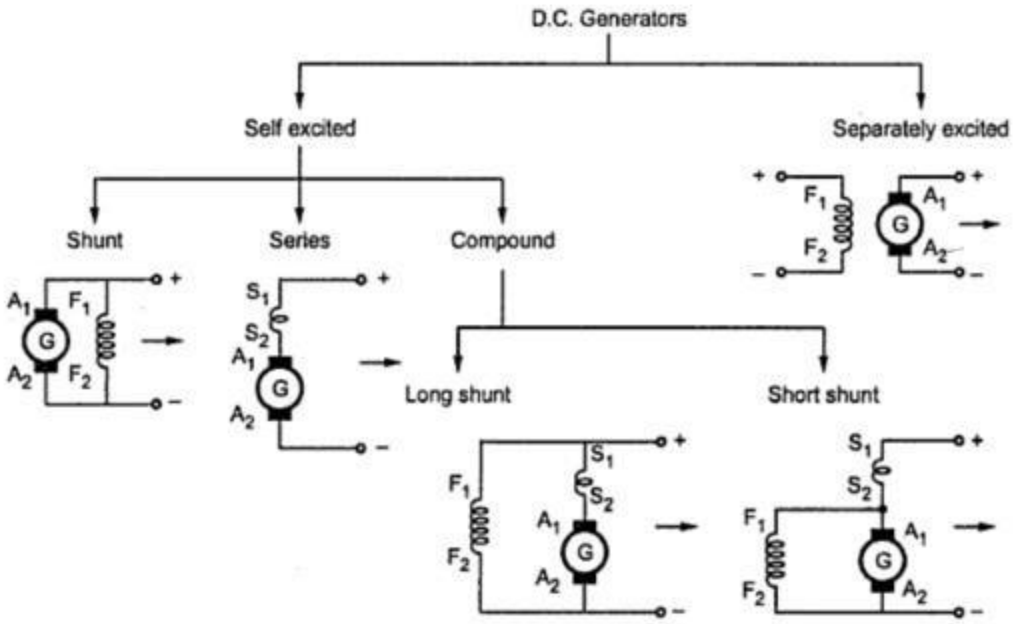


Fig.3.3 DC generators classification

Armature Reaction

The action of magnetic field set up by armature current on the distribution of flux under main poles of a DC machine is called armature reaction.

When the armature of a DC machines carries current, the distributed armature winding produces its own mmf. The machine air gap is now acted upon by the resultant mmf distribution caused by the interaction of field ampere turns (AT_f) and armature ampere turns (AT_a). As a result the air gap flux density gets distorted.

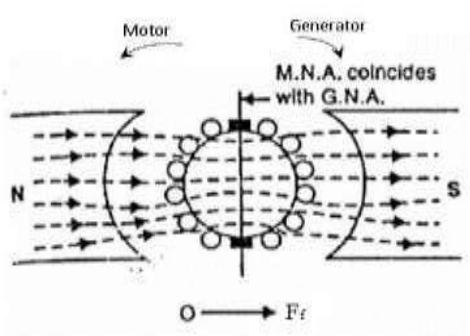


Fig. a

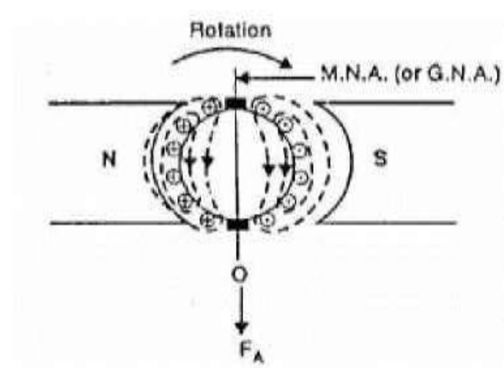


Fig. b

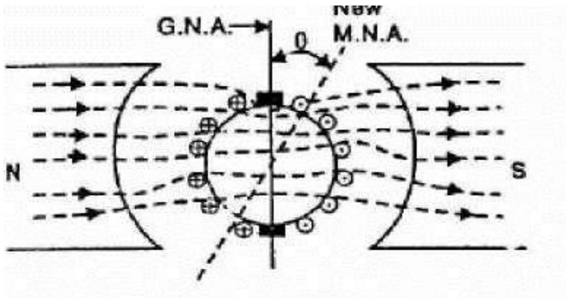


Fig. c

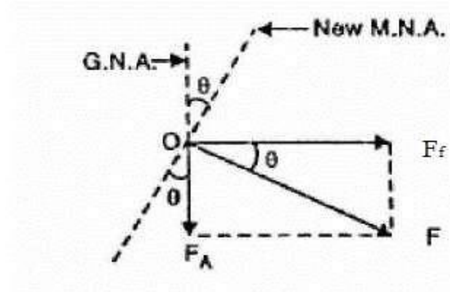


Fig. d

Figure a shows a two pole machine with single equivalent conductor in each slot and the main field mmf (Ff) acting alone. The axis of the main poles is called the direct axis (d-axis) and the interpolar axis is called quadrature axis (q-axis). It can be seen from the Figure b that armature mmf (Fa) is along the interpolar axis. Fa which is at 90^0 to the main field axis is known as cross magnetizing mmf.

Figure c shows the practical condition in which a DC machine operates when both the Field flux and armature flux are existing. Because of both fluxes are acting simultaneously, there is a shift in brush axis and crowding of flux lines at the trailing pole tip and flux lines are weakened or thinned at the leading pole tip. (The pole tip which is first met in the direction of rotation by the armature conductor is leading pole tip and the other is trailing pole tip).

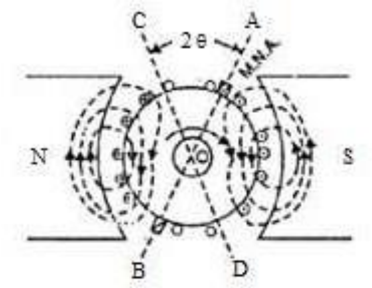
If the iron in the magnetic circuit is assumed unsaturated, the net flux/pole remains unaffected by the armature reaction though the air gap flux density distribution gets distorted. If the main pole excitation is such that the iron is in the saturated region of magnetization (practical case) the increase in flux density at one end of the poles caused by armature reaction is less than the decrease at the other end, so that there is a net reduction in the flux/pole. This is called the demagnetizing effect. Thus it can be summarized that the nature of armature reaction in a DC machine is

1. Cross magnetizing with its axis along the q-axis.

2. It causes no change in flux/pole if the iron is unsaturated but causes reduction in flux/pole in the presence of iron saturation. This is termed as demagnetizing effect. The resultant mmf ‘F’ is shown in figure d.

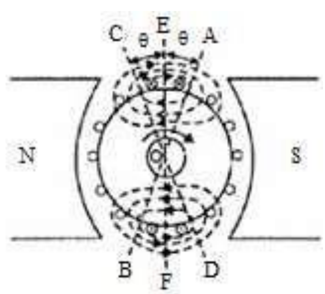
Cross Magnetizing Ampere Turns/pole(AT_c)

If the brush is shifted by an angle θ as shown in figure 1.23 then the conductors lying in between the angles BOC and DOA are carrying the current in such a way that the direction of the flux is downwards i.e., at right angles to the main flux. This results is the distortion in the main flux. Hence, these conductors are called cross magnetizing or distorting ampere conductors.



Demagnetizing Ampere Turns /pole (AT_d)

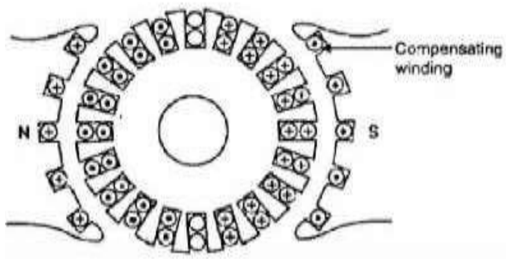
The exact conductors which produce demagnetizing effect are shown in Fig 1.24, Where the brush axis is given a forward lead of θ so as to lie along the new axis of M.N.A. The flux produced by the current carrying conductors lying in between the angles AOC and BOD is such that, it opposes the main flux and hence they are called as demagnetizing armature conductors.

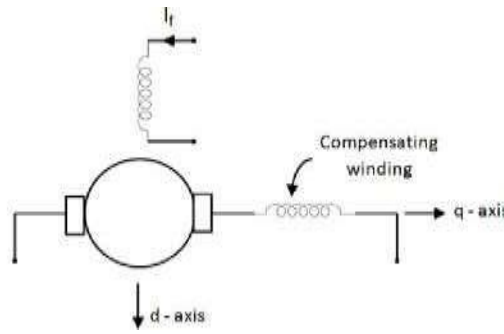


Compensating Winding

Due to armature reaction flux density wave get distorted and reduced. Due to distortion of flux wave the peak flux density increases to such a high value that it creates high induced emf. If this emf is higher than the breakdown voltage across adjacent segments, a spark over could result which can easily spread over the whole commutator, and there will be a ring of fire, resulting in the complete short circuit of the armature.

To protect armature from such adverse condition armature reaction must be neutralized. To neutralize the armature reaction ampere-turns by compensating winding placed in the slots cut out in pole face such that the axis of the winding coincides with the brush axis as shown figure.





The compensating windings neutralize the armature mmf directly under the pole which is the major portion because in the interpole region the air gap will be large. Compensating windings are connected in series with armature so that it will create mmf proportional to armature mmf.

The number of ampere-turns required in the compensating windings is given by

Commutation

The process of reversal of current in the short circuited armature coil is called 'Commutation'. This process of reversal takes place when coil is passing through the interpolar axis (q-axis), the coil is short circuited through commutator segments and brush.

The process of commutation of coil 'CD' is shown Fig. 3.4 In sub figure 'c' coil 'CD' carries 20A current from left to right and is about to be short circuited in figure 'd' brush has moved by a small width and the brush current supplied by the coil are as shown. In figure 'e' coil 'CD' carries no current as the brush is at the middle of the short circuit period and the brush current in supplied by coil 'AB' and coil 'EF'. In sub figure 'f' the coil 'CD' which was carrying current from left to right carries current from right to left. In sub fig 'g' spark is shown which is due to the reactance voltage. As the coil is embedded in the armature slots, which has high permeability, the coil possess appreciable amount of self inductance. The current is changed from +20 to –20. So due to self inductance and variation in the current from +20 to –20, a voltage is induced in the coil which is given by L dI/dt. This emf opposes the change in current in coil ‘CD’ thus sparking occurs.

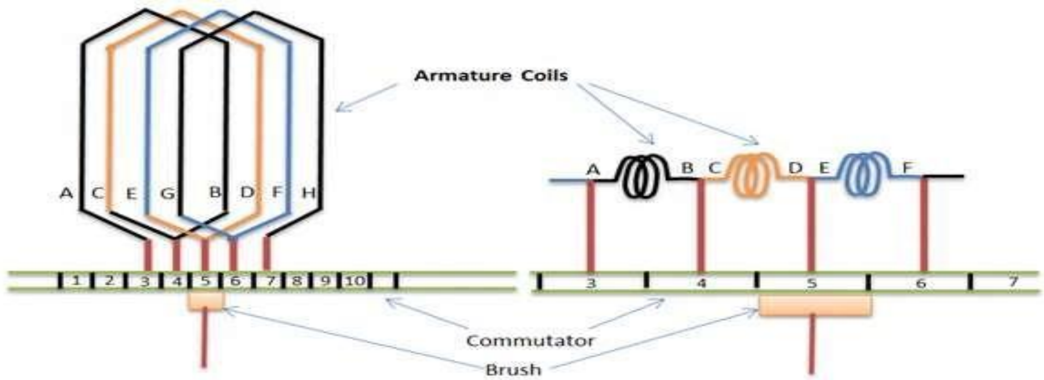


Fig a

Fig b

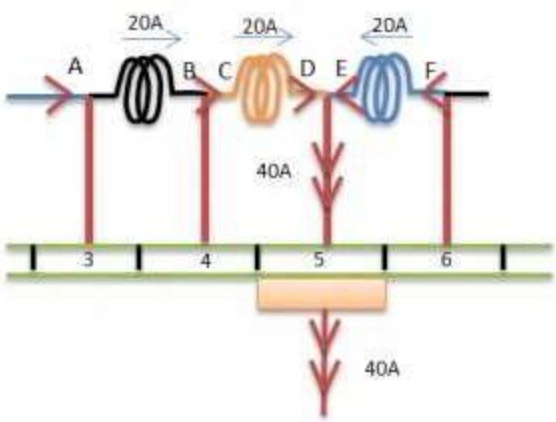


Fig.c

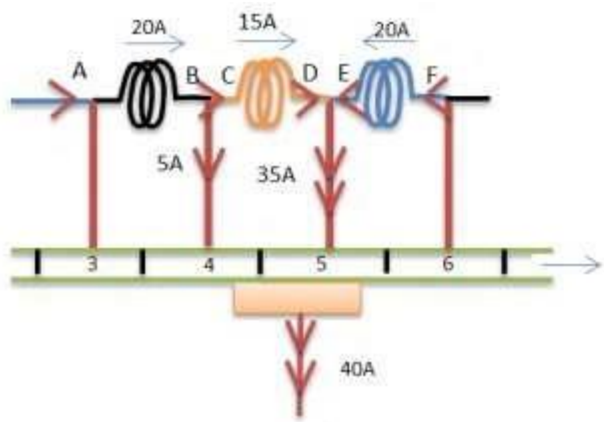


Fig.d

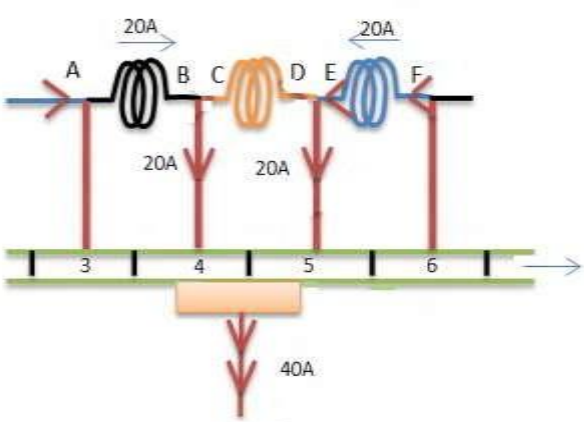


Fig.e

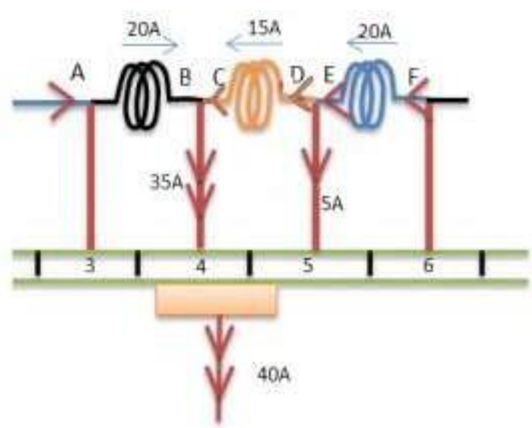


Fig.f

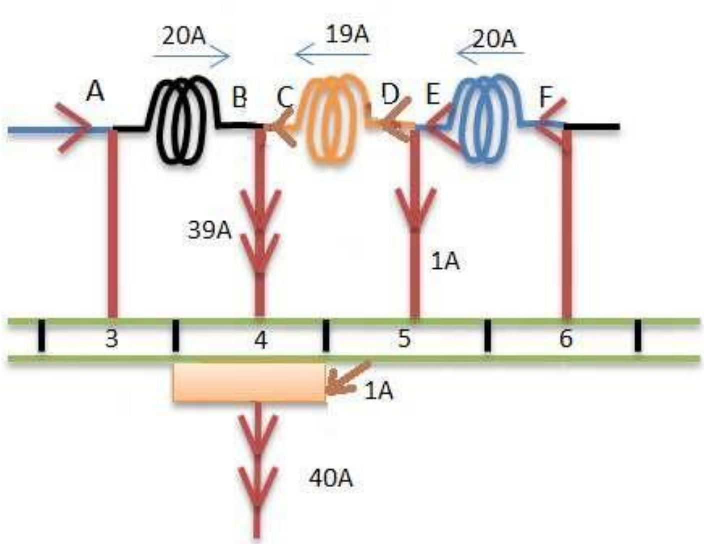


Fig.g

Fig.3.4 a-g shows the process of commutation

Reactance Voltage

During commutation sparking occurs in the commutator segment and brush due to presence of reactance voltage. This voltage is generated due to change of current in the commutating coil for its self- inductance and also due to mutual inductance of the adjacent coils. This voltage is called reactance voltage and according to Lenz's law this induced voltage oppose its cause of production. Here the cause of production is the change in current in the coil under commutation. Thus the commutation becomes poorer.

Method of Improving Commutation

Commutation can be improved in two ways by (i) Resistance commutation

(ii) E.M.F commutation.

Resistance Commutation

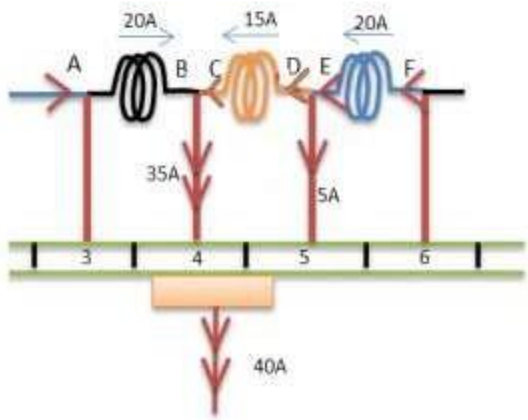


Fig. 3.5

In this method the resistance of the brushes are increased by changing then from copper brush to carbon brush. From the above figure 3.5 it is seen that when current ‘20A’ from coil ‘EF’ reaches the commutator segment ‘5’, it has two parallel paths opened to it. The first path is straight from bar ‘5’ to the brush and the other is via short circuited coil ‘CD’ to bar ‘4’ and then to brush. If copper brushes are used the current will follow the first path because of its low contact resistance. But when carbon brushes having high resistance are used, then current ‘20A’ will prefer the second path because the resistance r1 of first path will increase due to reducing area of contact with bar ‘5’ and the resistance r2 of second path decreases due to increasing area of contact with bar ‘4’. Hence carbon brushes help in obtaining sparkles commutation. Also, carbon brushes lubricate and polish commutator. But, because of high resistance the brush contact drop increases and the commutator has to be made larger to dissipate the heat due to loss. Carbon brushes require larger brush holders because of lower current density.

E.M.F commutation:

To neutralize sparking caused by reactance voltage in this method an emf is producied whichacts in opposite direction to that of reactance voltage, so that the reactance voltage is completely eliminated. The neutralization of emf may be done in two ways (i) by giving brush a forward lead sufficient enough to bring the short circuited coil under the influence of next pole of opposite polarity or (ii) by using interpoles or compoles. The second method is commonly employed.

Interpoles or Compoles

These are small poles fixed to the yoke and placed in between the main poles as shown in figure 3.6 They are wound with few turns of heavy gauge copper wire and are connected in series with the armature so that they carry full armature current. Their polarity in case of generator is that of the main pole ahead in the direction of rotation. Their polarity in case of motor is that of the main pole behind in the direction of rotation. The function of interpoles is (i) to induce an emf which is equal and opposite to that of the reactance voltage. Interpoles neutralize the cross magnetizing effect of armature reaction.

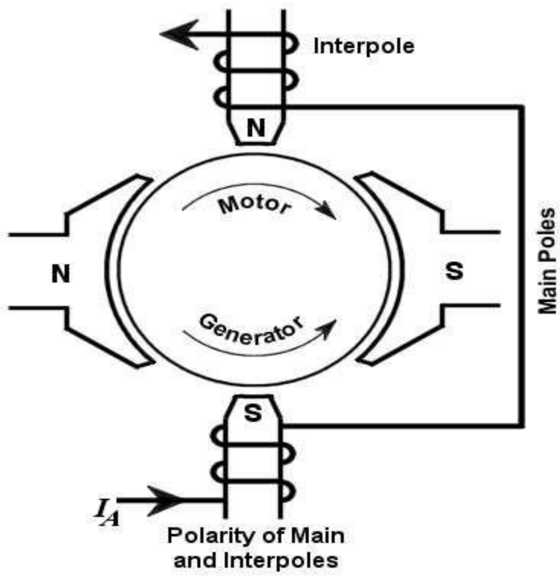


Fig-3.6

MODULE-IV

DC MACHINES-Characteristics & Motoring

Build-up of E.M.F in DC Generator:

When the armature is rotating with armature open circuited, an emf is induced in the armature because of the residual flux. When the field winding is connected with the armature, a current flows through the field winding (in case of shunt field winding, field current flows even on No-load and in case of series field winding only with load) and produces additional flux. This additional flux along with the residual flux generates higher voltage. This higher voltage circulates more current to generate further higher voltage. This is a cumulative process till the saturation is attained.

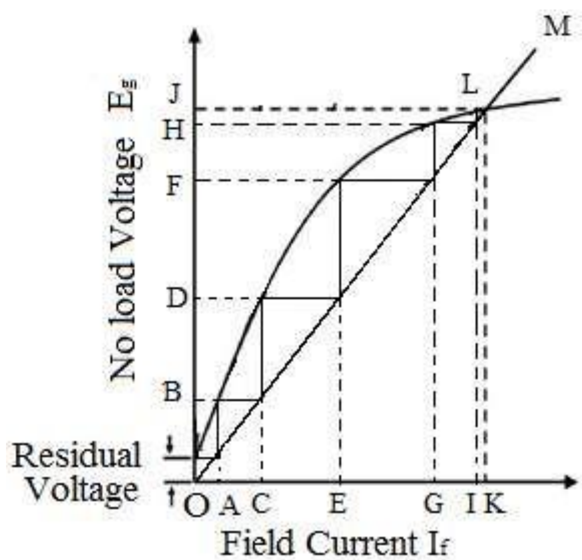


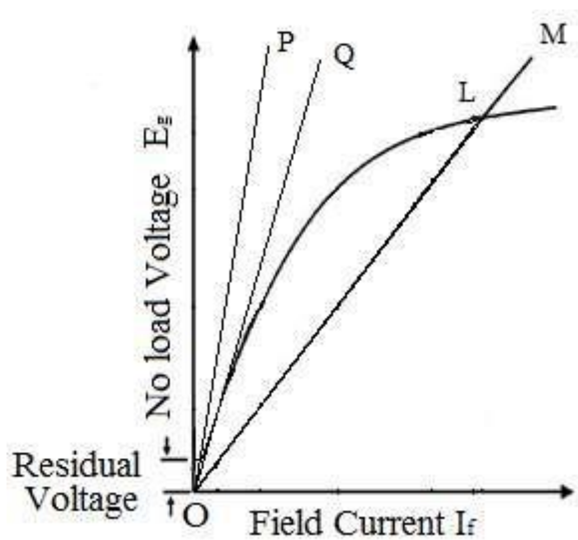
Fig. 4.1 Process of voltage build-up in DC generator

Here OM is the field resistance curve in Fig. 4.1. Initially there will be residual voltage which will create OA field current. This field current will increase the existing magnetic field and the induced voltage will increase up-to OB. This OB voltage will further applied to the field winding and increase the field current to OC. This process will continue upto the point L where the emf curve intersect with field resistance and finally the induced voltage will be OJ. This way voltage builds-up in dc generator.

Critical Resistance:-

The voltage to which it builds is decided by the resistance of the field winding as shown in the figure 4.2. If field circuit resistance is increased such that the resistance line does not cut OCC like 'OP' in the figure 4.2 , then the machine will fail to build up voltage to the rated value. The slope of the air gap line drawn as a tangent (OQ) to the initial linear portion of the curve represents the maximum resistance that the field circuit can have beyond which the machine fails to build up voltage. This value of field circuit resistance is called critical field resistance. The field circuit is generally designed to have a resistance value less than this so that the machine builds up the voltage to the rated value.

Fig. 4.2 Field current vs No-load voltage for different field resistances



Critical field resistance is defined as the maximum field circuit resistance for a given speed with which the shunt generator would excite. The shunt generator will build up voltage only if field circuit resistance is less than critical field resistance.

Critical Speed:

Voltage of a dc generator is proportional to its speed. Thus when speed will be reduced then the induced voltage will reduced. There can be such situation occur when the speed will be so low that the existing field winding resistance voltage bulid up will not occur. The speed of the generator can be lowered upto a certain level. This minimum value of the speed of the generator for which the generator can excite is called critical speed. It can also define as that speed of a generator for which the existing field resistance of generator becomes its critical field resistance.

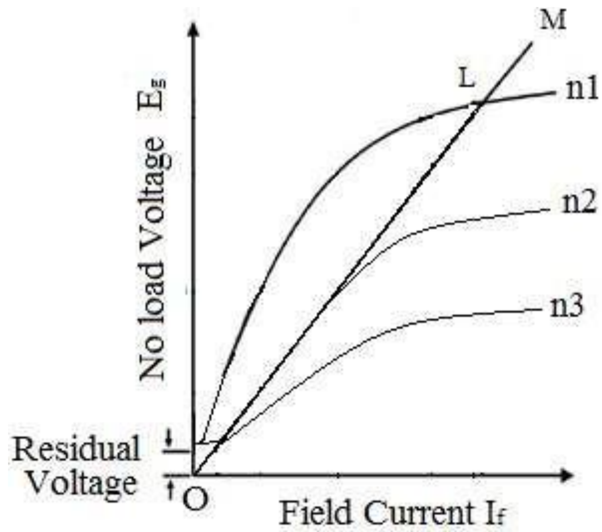


Fig. 4.3 Field current vs No-load voltage for different speed

In the above figure it is showing that when speed of the generator changes from n1 to n2 and then n3 emf production changes accordingly. Here n1>n2>n3. For speed n3 voltage build-up is not possible. The speed n2 is the critical speed. As shown in the figure at speed n2 generator field resistance become its critical field resistance.

Causes for failure to self-excite and its remedial

i. The field poles may not have residual magnetism. Then the generator will fail to excite. Then to restore residual magnetism field winding should be connected to an external dc voltage source. This is called flashing of field.

ii. When the direction of rotation is not proper such that flux produced by the field current reinforces the residual magnetism. The rotation of the machine has to be reversed.

iii. The field winding resistance is more than critical resistance then the machine will fail to excite. The field winding resistance should be less than critical field resistance.

iv. When the speed of the machine is less than critical speed. The machine's speed should be more than critical speed.

DC Machines Characteristics

The main characteristics of dc machines are

i. No-load characteristics or Open Circuit Characteristics

ii. Load characteristics

(i)No-load characteristics or Open Circuit Characteristics of separately excited generator

In this type of generator field winding is excited from a separate source, hence field current is independent of armature terminal voltage as shown on figure 4.4. The generator is driven by a prime mover at rated speed, say N rpm. With switch *S* in opened condition, field is excited via a potential divider connection from a separate d.c source and field current is gradually increased. The field current will establish the flux per pole □ . The voltmeter V connected across the armature terminals of the machine will record the generated emf. As Field current will increase Eg will increase.

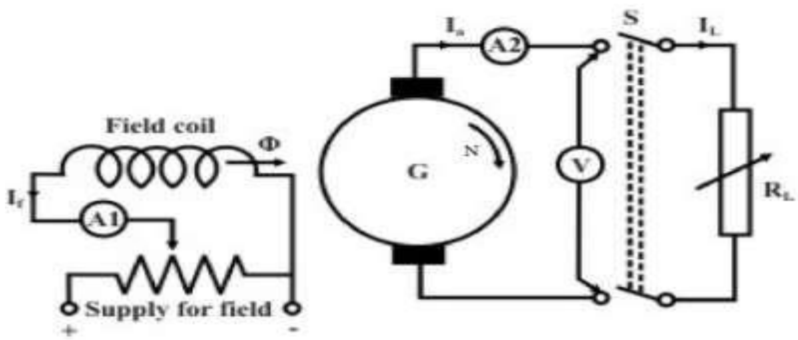
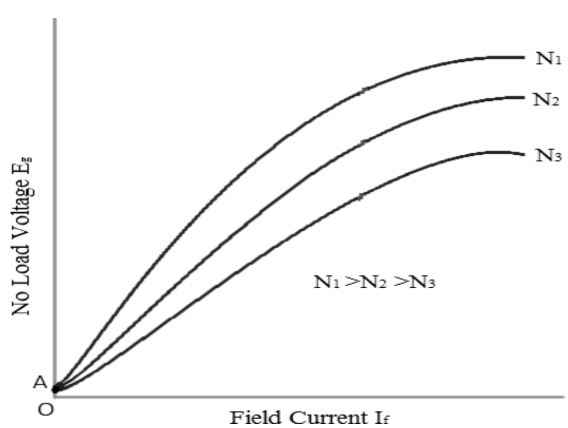


Fig.4.4



Load characteristic of separately excited generator

Load characteristic is the characteristics in between terminal voltage V_T with load current I_L of a generator with constant speed and constant field current. For $I_L = 0$, $V_T = E_g$ should be the first point on the load characteristic. With increase of load current the terminal voltage will drop due to armature resistance and reaction drop. In the figure below the rated load current shown by point A. Hence the load characteristic will be drooping in nature as shown in figure 4.5.

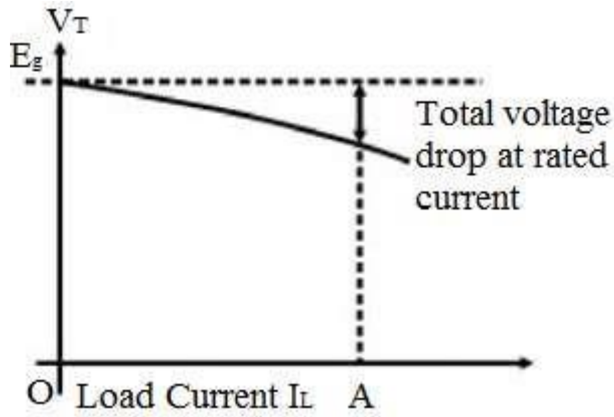


Fig 4.5 Load characteristics of DC separately excited generator

Characteristics of a shunt generator

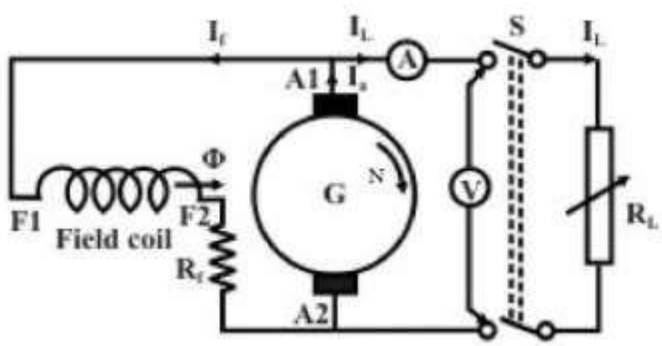


Fig 4.6 Connection diagram to obtain no-load and load characteristic

To obtain OCC of DC shunt generator the above circuit will be used with switch S kept open in fig.

4.6. As this machine is self-excited thus there is no need to use separate dc source for producing field current. The voltage build up process is described earlier. The open nature of the OCC will be similar to separately excited machine.

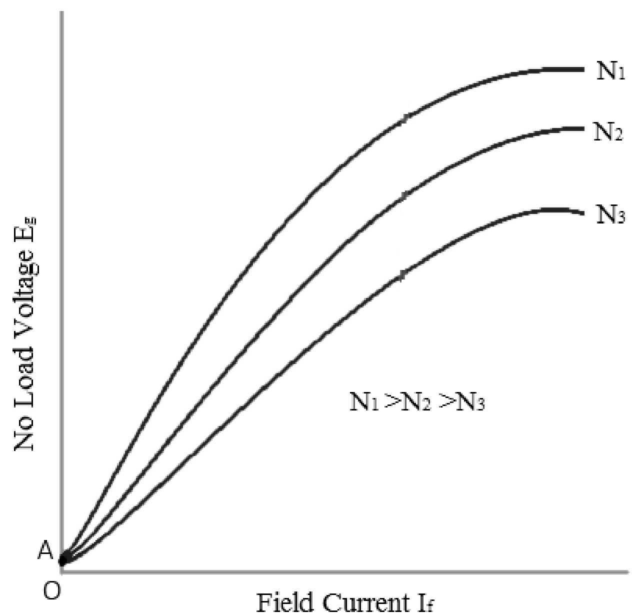


Fig. 4.7 Open circuit characteristics of DC shunt generator

Load characteristic of shunt generator

With switch S in open condition in fig. 4.6, the generator is practically under no load condition as field current is pretty small. The voltmeter reading will be E_g as shown in figures below. In other words, $V_T = E_g$, $I_L = 0$ is the first point in the load characteristic. To load the machine S is closed and the load resistances decreased so that it delivers load current IL. Unlike separately excited motor, here $I_L \neq I_a$. In fact, for shunt generator, $I_a = I_L - I_f$. So increase of IL will mean increase of I_a as well. The drop in the terminal voltage will be caused by the usual $I_a r_a$ drop, brush voltage drop and armature reaction effect. Apart from these, in shunt generator, as terminal voltage decreases, field current hence ϕ also decreases causing additional drop in terminal voltage. Remember in shunt generator, field current is decided by the terminal voltage by virtue of its parallel connection with the armature. Figure 4.8 gives the plot of terminal voltage versus load current which is called the load characteristic.

As the load resistance is decreased (load current increased), the terminal voltage drops until point B is reached. If load resistance is further decreased, the load current increases momentarily. This momentary increase in load current produces more armature reaction thus causing a reduction in the terminal voltage and field current. The net reduction in terminal voltage is so large that the load current decreases and the characteristic turns back. In case the machine is short circuited, the curve terminates at point H. Here OH is the load current due to the voltage generated by residual flux.

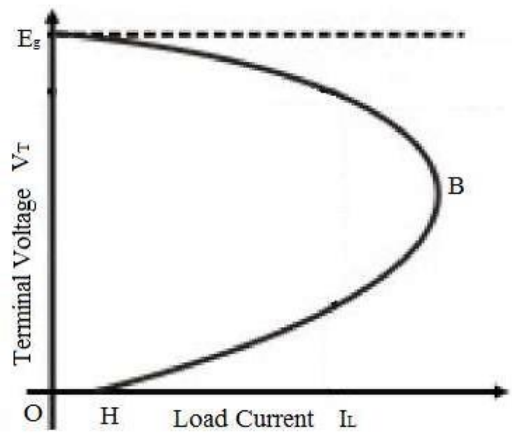
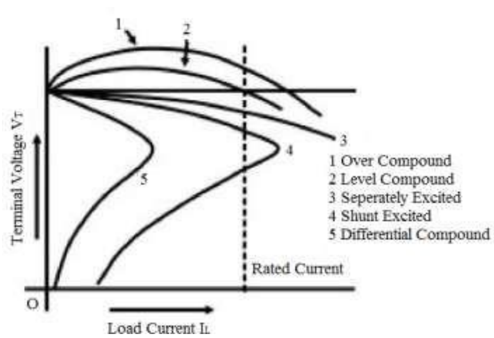


Fig. 4.8 Load characteristics of DC shunt generator

Compound generator

As introduced earlier, compound machines have both series and shunt field coils. Series field coil may be connected in such a way that the mmf produced by it aids the shunt field mmf-then the machine is said to be cumulative compound machine, otherwise if the series field mmf acts in opposition with the shunt field mmf – then the machine is said to be differential compound machine.

Fig. 4.9 Load characteristics of DC compound generator



In a compound generator, series field coil current is load dependent. Therefore, for a cumulatively compound generator, with the increase of load, flux per pole increases. This in turn increases the generated emf and terminal voltage. Unlike a shunt motor, depending on the strength of the series field mmf, terminal voltage at full load current may be same or more than the no load voltage. When the terminal voltage at rated current is same that at no load condition, then it is called a level compound generator. If however, terminal voltage at rated current is more than the voltage at no load, it is called a over compound generator. The load characteristic of a cumulative compound generator will naturally be above the load characteristic of a shunt generator as depicted in figure 4.9. At load current higher than the rated current, terminal voltage starts decreasing due to saturation, armature reaction effect and more drop in armature and series field resistances.

D.C. Motor

An electric motor is a machine which converts electrical energy into mechanical energy.

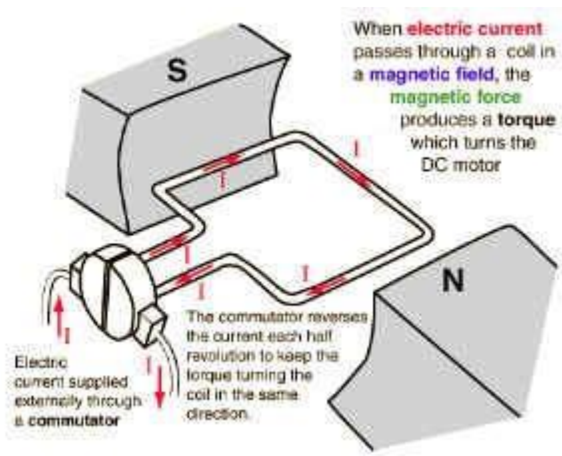
Principle of operation

It is based on the principle that when a current-carrying conductor is placed in a magnetic field, it experiences a mechanical force whose direction is given by Fleming's Left-hand rule and whose magnitude is given by

Force, **F = B I l** newton

Where B is the magnetic field in weber/m^2. I is the current in amperes and l is the length of the coil in meter.

Fleming's left hand rule says that if we extend the index finger, middle finger and thumb of our left hand in such a way that the current carrying conductor is placed in a magnetic field (represented by the index finger) is perpendicular to the direction of current (represented by the middle finger), then the conductor experiences a force in the direction (represented by the thumb) mutually perpendicular to both the direction of field and the current in the conductor.



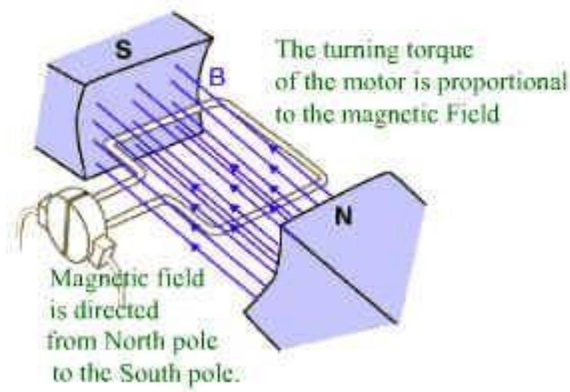
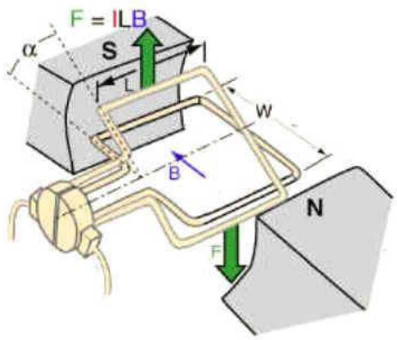


Figure 2.1: Force in DC Motor **Figure 2.2 : Magnetic Field in DC Motor**



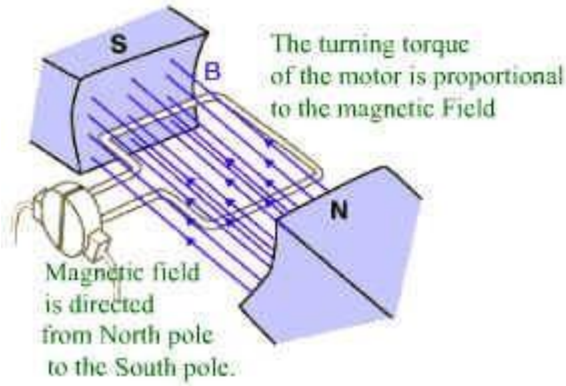


Figure 2.3 : Torque in DC Motor **Figure 2.4 : Current Flow in DC Motor**

Constructionally, there is no basic difference between a dc generator and motor. In fact, the same dc machine can be used interchangeably as a generator or as a motor. The basic construction of a dc motor contains a current carrying armature which is connected to the supply end through commutator segments and brushes and placed within the north south poles of a permanent or an electro-magnet.

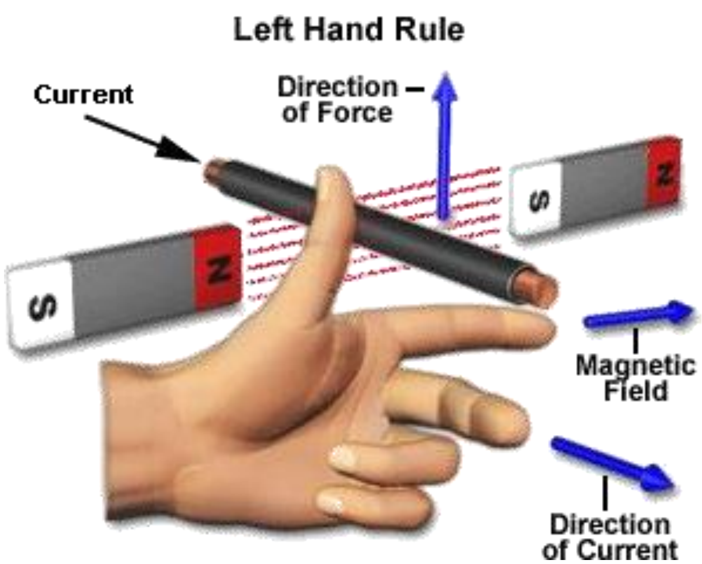


Fig. 2.5 Flemings Left hand rule

Back E.M.F

When the motor armature rotates, the conductors also rotate and hence cut the flux. In accordance with the laws of electromagnetic induction, emf is induced in them whose direction, as found by Fleming's Right hand Rule, is in opposition to the applied voltage. Because of its opposing direction, it is referred to as counter emf of back emf E_b. V has to drive I_a against the opposition of E_b. The power required to overcome this opposition is $E_b I_a$.

Voltage Equation of a Motor

The voltage V applied across the motor armature has to,

(a) Overcome the back emf E

(b) Supply the armature ohmic drop $I_a R_a$

Hence, $V = E_b + I_a R_a$

Where, VI_a =Electrical power input to the armature

$E_b I_a$ = Electrical equivalent of mechanical power developed in the armature

$I_a^2 R_a$ = copper loss in the armature

Condition for maximum efficiency

The gross mechanical power developed by motor is, $P = VI - I^2 R$

Differentiating both side with respect to I_a and equating the result to zero, we get

$$\frac{dP_m}{dI_a} = V - 2I_a R_a = 0$$

Hence, $I_a R_a = V / 2$

As, $V = E_b + I_a R_a$ and $I_a R_a = V / 2$

Hence, $E_b = V/2$

Thus gross mechanical power developed by a motor is maximum when back emf is equal to half the supply voltage. This condition is, however, not realized in practice, because in that case current would be much beyond the normal current of the motor. Moreover, half the input would be wasted in the form of heat and taking other losses (mechanical and magnetic) into consideration, the motor efficiency will be well below 50 percent.

Torque

The turning or twisting moment of a force about an axis is called torque. It is measured by the product of the force and the radius at which this force acts.

Consider a pulley of radius r meter acted upon by a circumferential force of F newton which causes it to rotate at N rpm.

Then torque $T = F \times r$ newton-metre(N-m

Work done by this force in one revolution

=Force$\times$ distance

$= F \times 2\pi r$ joule

Power developed $= F \times 2\pi r \times N$ joule/second or watt $= (F \times r) \times 2\pi N$ watt

Now, $2\pi N =$ angular velocity ω in radian per second and $F \times r$ =torque T

Hence, power developed $= T \times \omega$ watt or $P = T\omega$ watt

Torque

$T = F \times r$ N.m.

work done by the force in one revolution

$= F \times$ distance $= F \times 2\pi r$ · Joule.

Power developed.

$= F \times 2\pi r \times n$ Joule/sec. or watt. $n \rightarrow rps$.

$= (F \times r) 2\pi n$ watt

$2\pi n = \omega$ = Angular velocity.

$F \times r = T$.

So Power developed $= T \times \omega$ (watt)

So $P = T\omega$ watt.

if

So $\omega = 2\pi n = \frac{2\pi N}{60}$.

So $\boxed{P = \frac{2\pi N T}{60}}$.

Armature Torque of a Motor :-

T_a is the Torque developed by the Armature.

So $P = T_a \times \frac{2\pi N}{60}$ watt — (1)

Electrical power developed $= E_b I_a$ watt

So $T_a \times 2\pi N = E_b I_a$

$$\Rightarrow T_a \times \frac{2\pi N}{60} = \frac{P\phi Z N}{60A} \cdot I_a$$

$$\Rightarrow T_a = \frac{1}{2\pi} \phi Z I_a \left(\frac{P}{A}\right) \text{ N.m.}$$

$$\boxed{T_a = 0.159 \cdot \phi Z I_a (P/A) \text{ N.m}}$$

Shaft Torque :-

The Armature Torque which is generated is not avialable for doing useful work. because some losses occurs. (iron & friction losses).

The Torque avialable for doing useful work is "T_{sh}".

So $O/P = T_{sh} \times \frac{2\pi N}{60}$.

$$\Rightarrow T_{sh} = \frac{(O/P)60}{2\pi N} \text{ N.m.}$$

$$\boxed{T_{sh} = 9.55 \left(\frac{O/P}{N}\right) \text{ N.m.}}$$

The diff. $(T_a - T_{sh})$ is known as the Loss Torque.

DC Motor

DC Electrical Energy $\longrightarrow$ Mechanical Energy (Torque).

Back emf. $(E_b) = \frac{P\phi ZN}{60A}$

for DC Shunt Motor = $\boxed{V - I_a R_a = E_b}$ (Voltage eqn)

Torque Eqn :-

$T_a = 0.159\, \phi Z I_a \left(\frac{P}{A}\right)$ N.m.
(Armature Torque)

$T_{sh} = 9.55 \cdot \left(\frac{O/P}{N}\right)$ N.m.
(Shaft Torque)

$(T_a - T_{sh})$ is known as the LOSS Torque.

Speed eqn :-

$E_b = \frac{P\phi ZN}{60A} \Rightarrow N = \frac{60 A E_b}{P\phi Z}$

$\Rightarrow \boxed{N \propto \frac{E_b}{\phi}} = K \cdot \frac{E_b}{\phi}$

$K = \frac{60A}{PZ}$

$\Rightarrow \boxed{N = K \cdot \frac{(V - I_a R_a)}{\phi}}$

DC Motor Characteristics :-

1) Torque and Armature Current - ($T_a \sim I_a$) - Electrical char.

2) Speed and Armature Current - ($N \sim I_a$)

3). Speed and Torque ($N \sim T_a$) - mechanical char.

$T_a = 0.159 \phi Z I_a \left(\frac{P}{A}\right)$ N.m. , $N = K \cdot \frac{E_b}{\phi}$ (where $K = \frac{60A}{PZ}$)

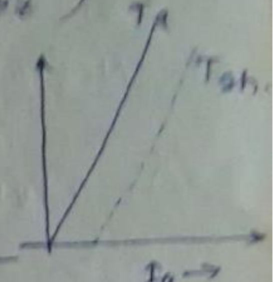
$\Rightarrow T_a \propto \phi I_a$

(i). Char. of Shunt Motor :-

1). $T_a \sim I_a$:-

→ ~~As~~ ϕ is practically Const. for Shunt Motor.

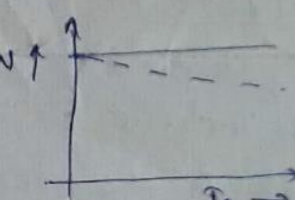
→ As $T_a \propto \phi I_a \Rightarrow$ for Shunt Motor $T_a \propto I_a$



(2). $N \sim I_a$:-

$N \propto \frac{E_b}{\phi}$ ⇒ ϕ is constant - & As E_b is also Practically constant, Shunt Motor is a constant-Speed Motor.

→ But ~~for~~ with increasing Load, E_b & ϕ decreases but E_b decreases slightly more than "ϕ". So ~~Speed~~ there is some decrease in Speed.



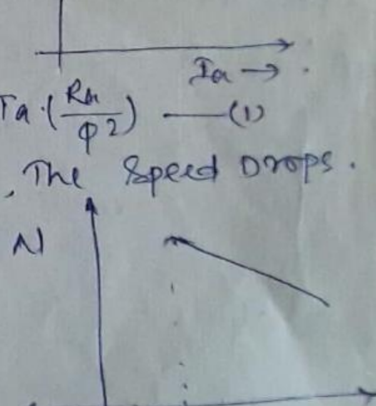
(3) $N \sim T_a$:- $N = K\frac{E_b}{\phi}$, $T_a = K_1 \phi I_a$

$\Rightarrow I_a = \frac{T_a}{K_1 \phi}$

~~As $T_a \propto \phi I_a$, & $N \propto \frac{1}{\phi}$~~

So $N = K \cdot \frac{(V - \frac{T_a}{K_1 \phi} R_a)}{\phi} \Rightarrow N = \frac{KV}{\phi} - \frac{K}{K_1} T_a \cdot \left(\frac{R_a}{\phi^2}\right)$ —— (1)

So from eqn. (1), with the increase of "T_a", The Speed Drops.

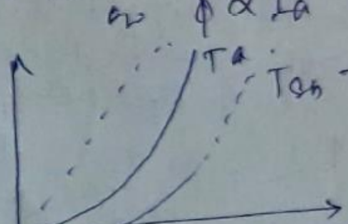


(ii). Char. of Series Motor :-

(1) ($T_a \sim I_a$) :- $T_a \propto \phi I_a$.

As here the field winding also carry the "I_a".

or $\phi \propto I_a \Rightarrow \boxed{T_a \propto I_a^2}$



→ At light loads I_a is small But As I_a increases T_a increase as the square of "I_a". So Curve Parabolic.

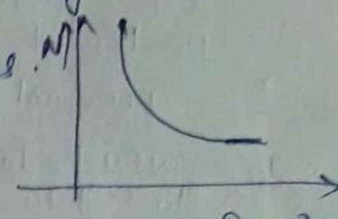
→ ~~So~~ So at heavy loads a Series Motor exerts a Torque Proportional to the square of Armature Current. So for high Starting Torque requirements like electric trains, traction trains, Series Motors used.

→ In Labs always Series Motors ~~Stop~~ will be Started with load.

2) $N \sim I_a$:- $N \propto \frac{E_b}{\phi}$ → change in E_b, for various Load currents is small and Hence may be neglected so E_b is Constant.

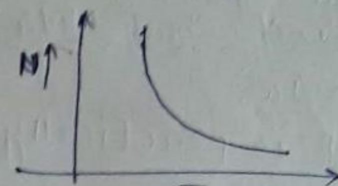
→ with increase in "i_a", ϕ also increases.

So $I_a \propto \phi$ So $\underline{N \propto \frac{1}{I_a}}$



3) $\underline{N \sim T_a}$ As $N \propto \frac{1}{I_a}$ & $T_a \propto I_a^2$

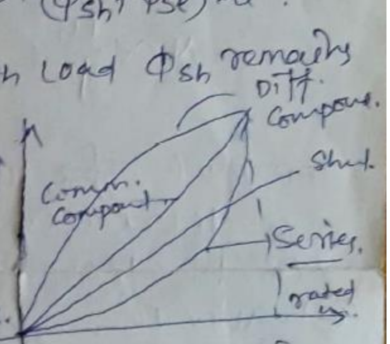
⇒ $\underline{N \propto \frac{1}{T_a}}$



(iii) Char. of Compound Motors :-

1) Cumulative Compound :- (Long shunt) 1) $\underline{T \sim I_a}$ $T_a \propto \phi I_a$ ⇒ $T_a \propto (\phi_{sh} + \phi_{se}) I_a$.

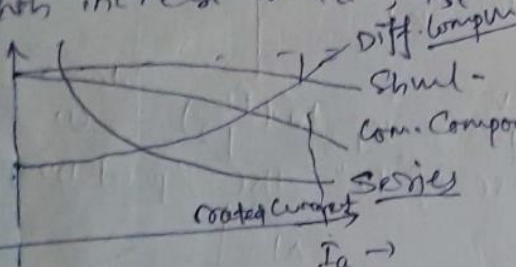
at no Load $I_a = 0$, $\phi_{se} = 0$ and So $T_a = 0$ with Load ϕ_{sh} remains cons. But As the Armature Current rises but ϕ_{se} rises So T_a rises.



2) $\underline{N \sim I_a}$. $V = E_b + I_a(R_a + R_{se})$

$N = K \frac{E_b}{(\phi_{sh} + \phi_{se})}$

with increase in I_a, ϕ_{se} increases & speed drops.



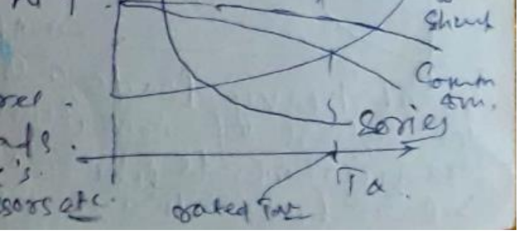
3) $N \sim T_a$:- $N = K \cdot \frac{V - I_a(R_a + R_{se})}{(\phi_{se} + \phi_{sh})}$

& $I_a = \frac{T_a}{K_1(\phi_{sh} + \phi_{se})}$

Diff. Compound :- → As fluxes oppose each other the char. is opposite to Comm. Compound. Applications in research & testing

$$\Rightarrow N = K \cdot \frac{V - \frac{T_a}{K_1(\phi_{sh} + \phi_{se})}(R_a + R_{se})}{(\phi_{se} + \phi_{sh})} = \frac{KV}{\phi_{se} + \phi_{sh}} - \frac{K\,T_a(R_a + R_{se})}{K_1(\phi_{se} + \phi_{sh})^2}$$

with the increase in motor Torque, Armature Current rises and ϕ_{se} rises. So in the equ^n the first term gets reduced and 2nd Term becomes somewhat more. So speed drops more than a shunt DC Motor



→ Comm. Compound motors has greatest application with loads that require high starting Torque or pulsating loads.

Ex:- drives elevators, metal stamping m/c's, reciprocating Pumps, hoists & compressors etc.

Speed Control of DC Motor

Speed control means intentional change of the drive speed to a value required for performing the specific work process. Speed control is a different concept from speed regulation where there is natural change in speed due to change in load on the shaft. Speed control is either done manually by the operator or by means of some automatic control device.

One of the important features of dc motor is that its speed can be controlled with relative ease. We know that the expression of speed control dc motor is given as

The speed of a dc motor is given by

$$N \propto \frac{E_b}{\phi}$$

or

$$N = K\frac{(V - I_a R)}{\phi} \text{ r.p.m.}$$

where $R = R_a$ for shunt motor

$= R_a + R_{se}$. for series motor

i) **Flux Control**: By varying the flux per pole.

ii) **Armature Control**: By varying the resistance in the armature circuit.

iii) **Voltage Control**: By varying the applied voltage.

Therefore speed (N) of 3 types of dc motor – SERIES, SHUNT AND COMPOUND can be controlled by changing the quantities on RHS of the expression. So speed can be varied by changing

(i) terminal voltage of the armature V ,

(ii) armature circuit resistance R and

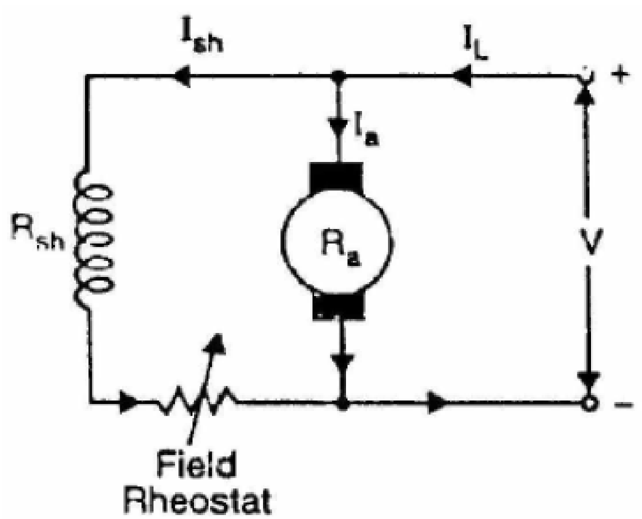
(iii) flux per pole ϕ .

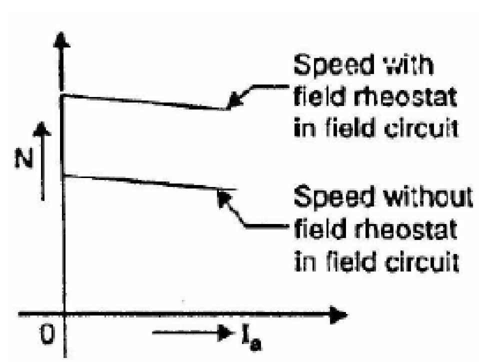
The first two cases involve change that affects armature circuit and the third one involves change in magnetic field. Therefore speed control of dc motor is classified as

1) Armature control methods and

2) Flux control methods.

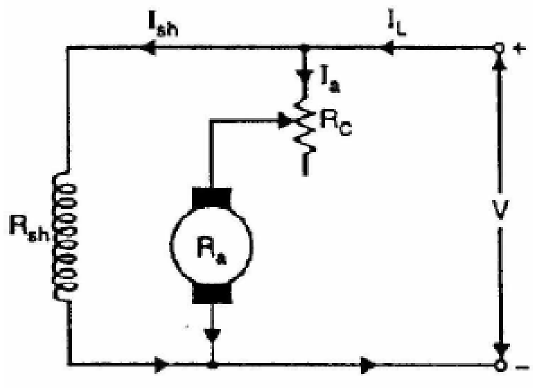
Flux Control Method

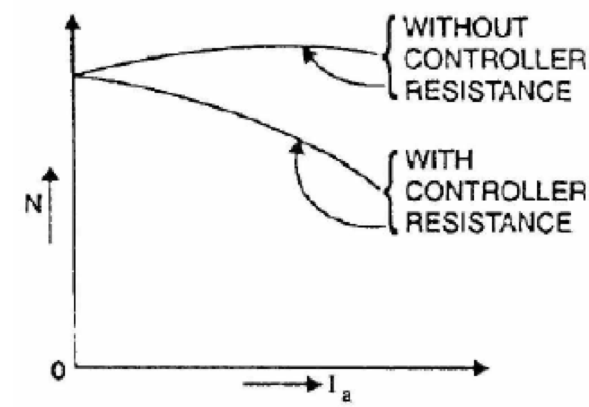




It is based on the fact that by varying the flux f, the motor speed (N) can be changed and hence the name flux control method. In this method, a variable resistance is placed in series with shunt field winding.

Armature Control Method





$$N \propto V - I_a(R_a + R_C)$$

This method is based on the fact that by varying the voltage available across the armature, the back e.m.f and hence the speed of the motor can be changed. This is done by inserting a variable resistance in series with the armature.

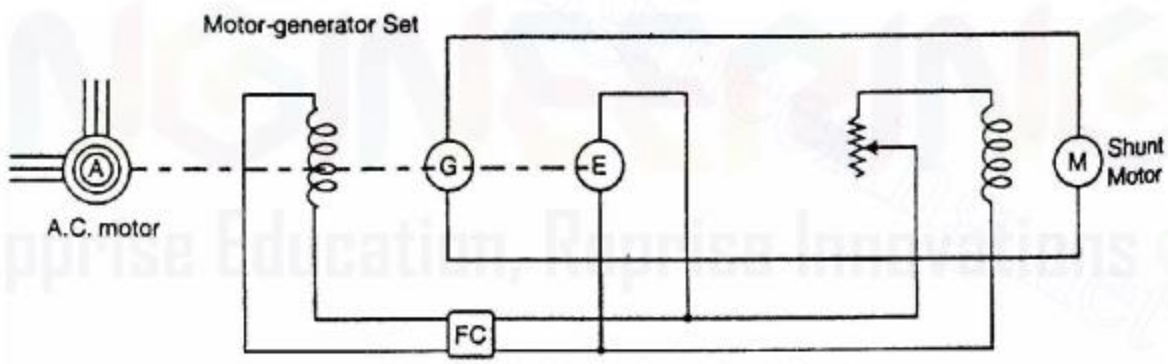
3. Voltage control method

In this method, the voltage source supplying the field current is different from that which supplies the armature. This method avoids the disadvantages of poor speed regulation and low efficiency as in armature control method. However, it

is quite expensive. Therefore, this method of speed control is employed for large size motors where efficiency is of great importance.

(i) **Multiple voltage control**. In this method, the shunt field of the motor is connected permanently across a-fixed voltage source. The armature can be connected across several different voltages through a suitable switchgear. In this way, voltage applied across the armature can be changed. The speed will be approximately proportional to the voltage applied across the armature. Intermediate speeds can be obtained by means of a shunt field regulator.

(ii) **Ward-Leonard system**. In this method, the adjustable voltage for the armature is obtained from an adjustable-voltage generator while the field circuit is supplied from a separate source. This is illustrated in Fig. (5.5). The armature of the shunt motor M (whose speed is to be controlled) is connected directly to a d.c. generator G driven by a constant-speed a.c. motor A. The field of the shunt motor is supplied from a constant-voltage exciter E. The field of the generator G is also supplied from the exciter E. The voltage of the generator G can be varied by means of its field regulator. By reversing the field current of generator G by controller FC, the voltage applied to the motor may be reversed. Sometimes, a field regulator is included in the field circuit of shunt motor M for additional speed adjustment. With this method, the motor may be operated at any speed upto its maximum speed.



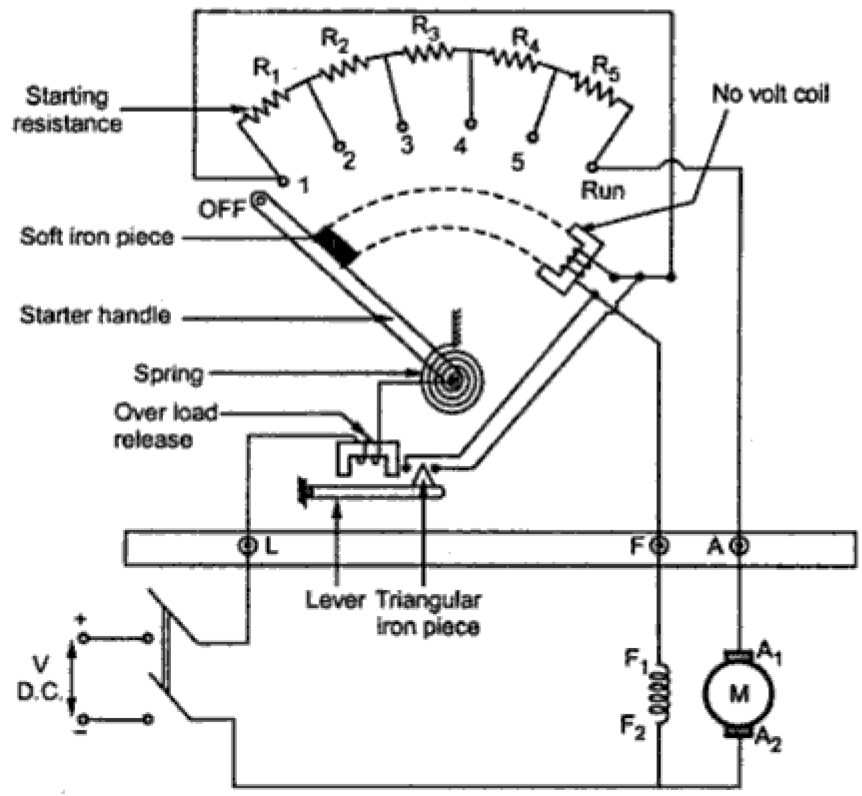
Ward-Leonard speed-control system.

Motor starters

The starting of DC motor is somewhat different from the starting of all other types of electrical motors. This difference is credited to the fact that a dc motor unlike other types of motor has a very high starting current that has the potential of damaging the internal circuit of the armature winding of dc motor if not restricted to some limited value. This limitation to the starting current of dc motor is brought about by means of the starter. Thus the distinguishing fact about the starting methods of dc motor is that it is facilitated by means of a starter. Or rather a device containing a variable resistance connected in series to the armature winding so as to limit the starting current of dc motor to a desired optimum value taking into consideration the safety aspect of the motor.

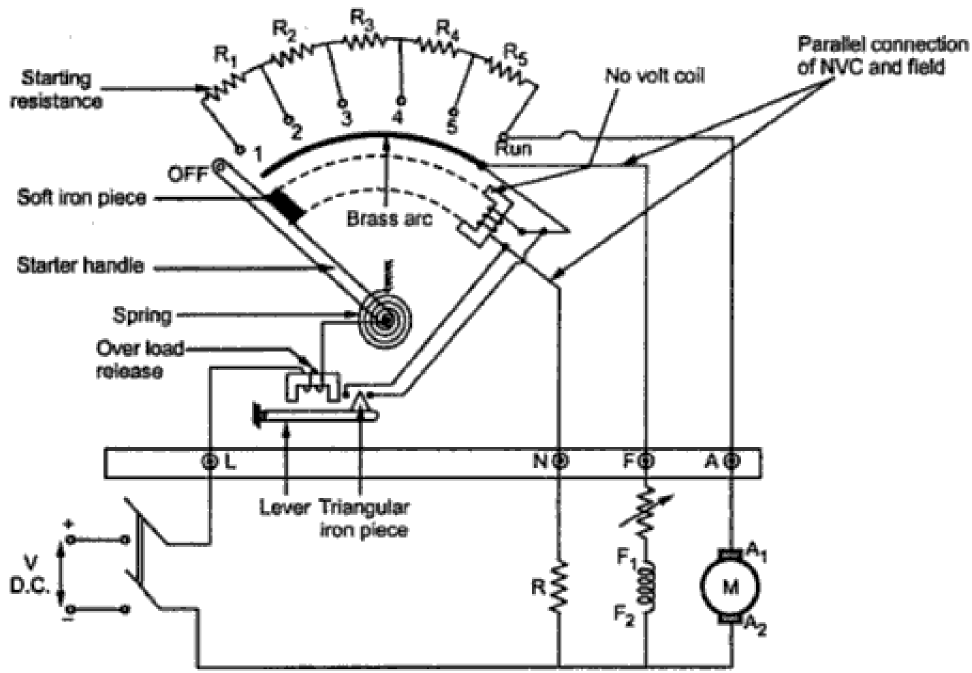
Starters can be of several types and requires a great deal of explanation and some intricate level understanding. But on a brief over-view the main types of starters used in the industry today can be illustrated as:-

1. 3 point starter.
2. 4 point starter.



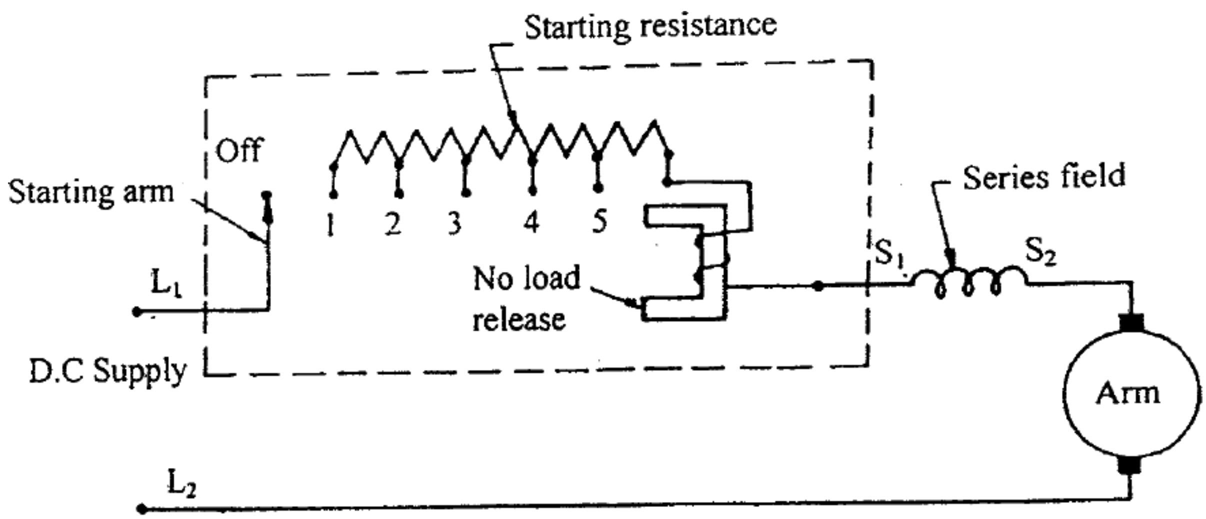
<u>3 point Starter</u>

Fig. 2.6



4 point Starter

Fig. 2.7

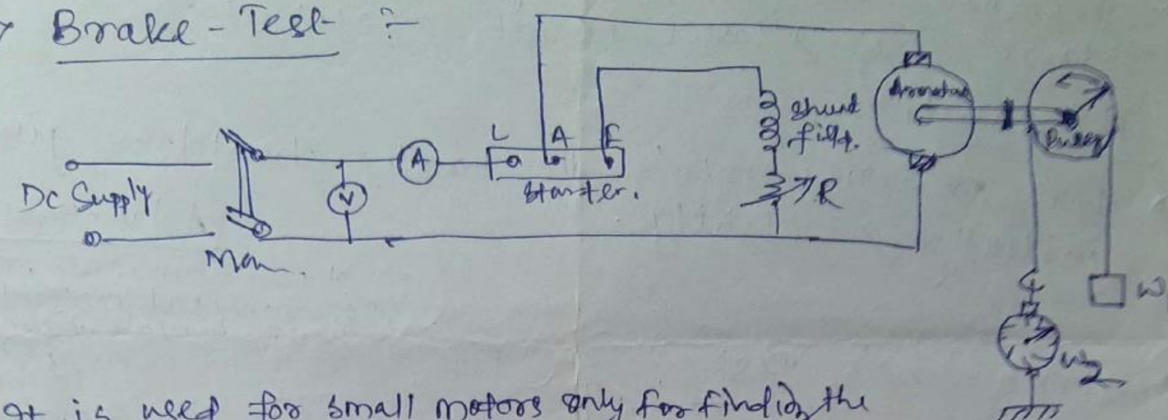


Series motor starter, no-load release.

Fig. 2.8

Testing of DC Machines :-

1) Brake - Test :-



→ It is used for small motors only for finding the efficiency & is known as a Direct Test.

→ A pulley is connected to the motor shaft and one end of Pulley connected to suspended wt. W_1 and other end (brake band) fixed to earth through Spring "S".

→ The diff. of W_1 and spring balance W_2 gives effective force on pulley.

Let I be the i/p current (Ammeter)
V " " Supply Volt (Voltm)
W_1 kg → Suspended wt.
W_2 kg → Spring balance reading.
N → Speed of rotation in rpm.
r → radius of Pulley in meter.
t → thickness of belt in meter.

So Motor o/p $= T \times \frac{2\pi N}{60}$. kg m/sec.

$$= (W_1 - W_2)\left(r + \frac{t}{2}\right) \cdot \frac{2\pi N}{60} \text{ . kg m/sec.}$$

As $T = (W_1 - W_2)\left(r + \frac{t}{2}\right)$

$$= (W_1 - W_2)\, r \cdot \frac{2\pi N}{60}$$ (Neglecting t as very small)

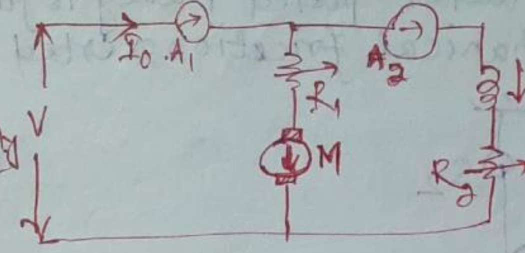
$$= (W_1 - W_2)\, r \times \frac{2\pi N}{60} \times 9.81 \text{ N m/sec or watt}$$

I/P to motor = VI watts.

$$\text{So } \eta_m = \frac{O/P}{I/P} = \frac{(W_1 - W_2) \cdot r \times \frac{2\pi N}{60} \times 9.81}{VI}$$

Swinburn's Test :-

→ It is an indirect method of finding losses and efficiency of a dc machine basically shunt & compound.



→ The m/c is running as a motor on no-load at its rated voltage & the rated speed.

→ The no-load current "I_0" is measured by A_1 and I_{sh} by A_2.

The no-load Armature Current $= I_0 - I_{sh} = I_{a0}$

Let V = Supply voltage

no load i/p $= VI_0$ watt.

Power i/p to Armature $= V(I_0 - I_{sh})$

" " to Shunt $= VI_{sh}$.

No Load power i/p to Armature supplies.

→ Iron Loss in the core

→ friction Loss

→ windage Loss

→ Armature Cu loss $(I_0 - I_{sh})^2 R_A$ $\left(\begin{array}{l} R_A \to \text{hot resistance of Armature} \\ R_a = 1.2 R_A \end{array}\right)$

So Constant Loss $(W_c) = VI_0 - (I_0 - I_{sh})^2 R_A$

"η" running as a Motor :-

$I_a = I - I_{sh}$; i/p $= VI$.

Armature Cu. Loss $= I_a^2 R_A = (I - I_{sh})^2 R_A$

So Total loss $= W_c + (I - I_{sh})^2 R_A$

So $\eta_m = \dfrac{\text{i/p} - \text{losses}}{\text{i/p}} = \dfrac{VI - (I - I_{sh})^2 R_A - W_c}{VI}$

Generator :-

o/p $= VI$, $I_a = I + I_{sh}$

Armature Cu loss $= (I + I_{sh})^2 R_A$

Total Loss $= (I + I_{sh})^2 R_A + W_c$

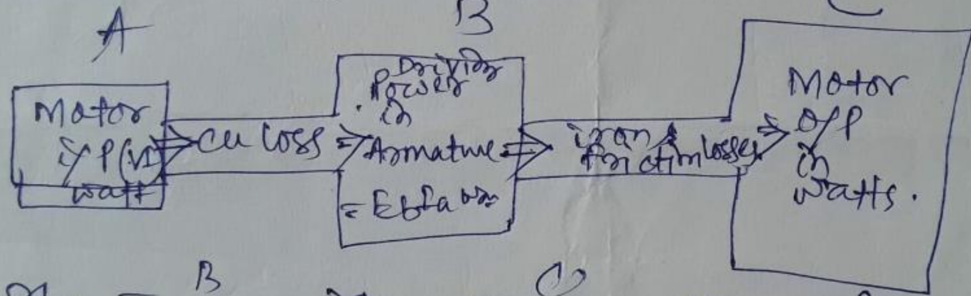
So $\eta_G = \dfrac{\text{o/p}}{\text{o/p} + \text{losses}} = \dfrac{VI}{VI + (I + I_{sh})^2 R_A + W_c}$

dis. Adv :-

→ No Calculation of change in iron losses from no load to full load.

→ Due to Armature rea? flux distorts at full load.

Power Stages of a DC Motor :-



$\eta_e = \frac{B}{A}$, $\eta_m = \frac{C}{B}$, $\eta_c = \frac{C}{A}$.

Condⁿ for maxᵐ η :-

Const loss = Variable loss.

Comparision between Diff. types of dc motors :-

Shunt	Series	Commulative Compound
→ Const. speed	→ Variable speed.	→ Variable speed.
→ Medium starting Torque.	→ high starting torque	→ high starting Torque.
→ for driving Const speed m/c's and Lathes.	→ for traction work.	→ For intermittent high torque loads.
→ Centifugal pumps.	→ Electric Locomotives.	→ For shears & punces.
→ Machine tools	→ Trolley, Cars, Cranes, and hoists.	→ Elevators.
→ Blowers & fans.	conveyors.	→ conveyors.
→ Reciprocating pump		→ Heavy planers.
		→ Rolling mills.
		→ Ice machines,
		→ Printing m/c.
		→ Air Compressors.

MODULE-V

Single phase Transformer

Principle of operation and construction

A transformer is a static or stationary piece of apparatus by means of which electric power in one circuit is transformed into electric power of the same frequency in another circuit. Although transformers have no moving parts, they are essential to electromechanical energy conversion. They make it possible to increase or decrease the voltage so that power can be transmitted at a voltage level that results in low costs, and can be distributed and used safely. In addition, they can provide matching of impedances, and regulate the flow of power (real or reactive) in a network.

- The physical basis of a transformer is mutual induction between two circuits linked by a common magnetic field.
- In its simplest form, it consists of two inductive coils which are electrically separated but magnetically linked through a path of low reluctance. The two coils passes high mutual inductance.
- If one coil is connected to a source of alternating voltage, an alternating flux is set up in the laminated core, most of which is linked with the other coil in which it produces mutually induced emf.

Constructionally, the transformers are of two general types, distinguished from each other merely by the manner in which the primary and secondary coils are placed around the laminated core.

a) Core type

b) Shell type

In the so-called core type transformer, the windings surround a considerable part of the core whereas in shell-type transformer, the core surrounds considerable portions of the winding.

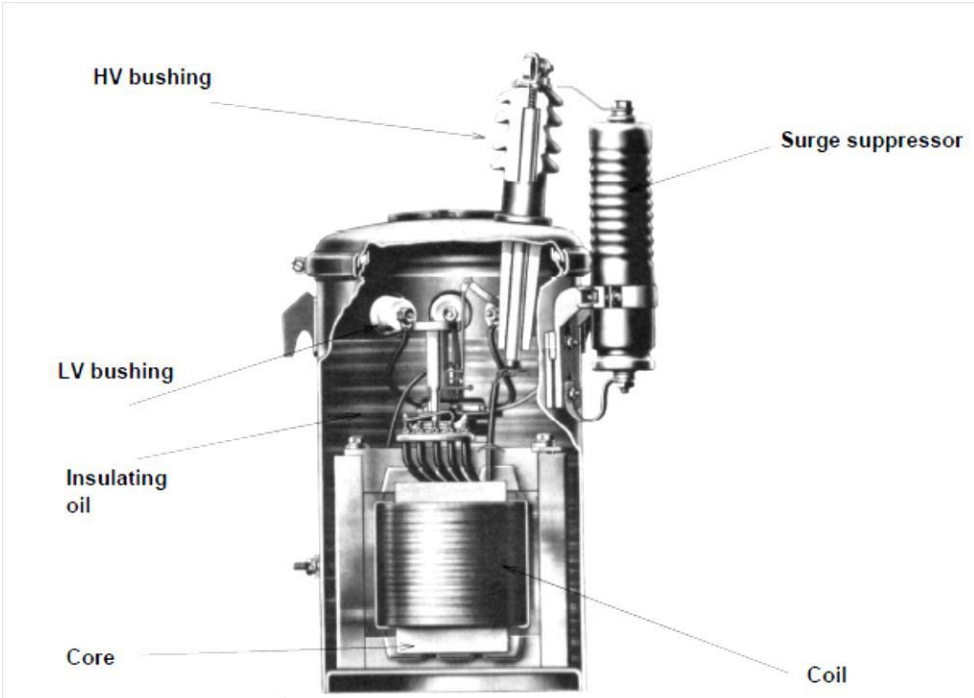


Fig.5.1 Physical diagram of a transformer

Elementary theory of an ideal transformer

An ideal transformer is one which has no losses i.e. its windings have no ohmic resistance, there is no magnetic leakage and hence which has no copper and core losses. An ideal transformer consists of two purely inductive coils wound on a loss free core.

In its simplest form it consist of, two inductive coils which are electrically separated but magnetically linked through a path of low reluctance. If one coil (primary) is connected to a source of alternating voltage, an alternating flux is set up in the laminated core, most of which is linked with the other coil in which it produces mutually-induced e.m.f. according to Faraday's Laws of Electromagnetic Induction. If the second coil (secondary circuit) is closed, a current flows in it and so electric energy is transferred (entirely magnetically) from the first coil to the second coil.

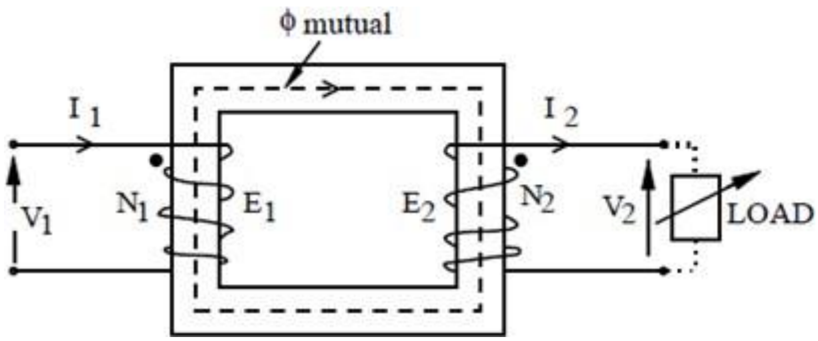


Fig.5.2 Elementary Transformer

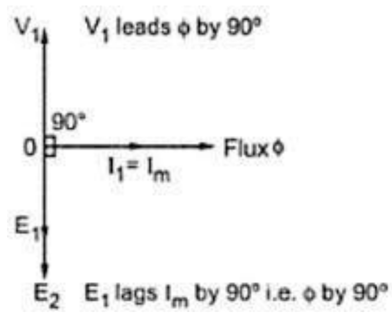


Fig.5.3 Vector representation of applied voltage, induced emf flux and magnetizing current of a single phase transformer

E.M.F. equation

Let, N_1 = No. of turns in primary

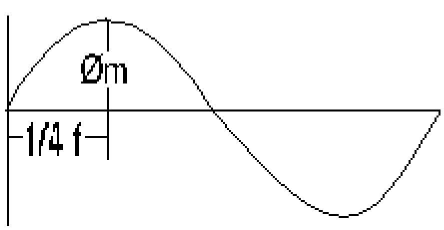
N_2 = No. of turns in secondary

ϕ_m =Maximum flux in core in webers = $B_m \times A$

B_m =Maximum flux density

A = Area

f = Frequency of ac input in Hz



The flux increases from its zero value to maximum value ϕ_m in one quarter of the cycle i.e. in $1/4f$ second.

The average rate of change of flux $= \dfrac{\phi_m}{1/4f} = 4f\phi_m$ wb/sec or volts

Now, rate of change of flux per turn means induced emf in volts.

Hence, average EMF/turn = $4f\phi_m$ volts

If flux varies sinusoidally, then rms value of induced emf is obtained by multiplying the average value with form factor.

$$Form\_factor = \frac{rms\_value\_of\_ac\_quantity}{average\_value\_of\_ac\_quantity} = 1.11$$

Hence, rms value of EMF/turn = $1.11 \times 4f\phi_m = 4.44f\phi_m$ volts

Now, r.m.s value of induced e.m.f in the whole of primary winding

= (induced e.m.f. / turn) x No. of primary winding

$E_1 = 4.44f\phi_m N_1$ ------------------- (i)

Similarly, r.m.s. value of e.m.f. induced in secondary is,

$E_2 = 4.44 f \phi_m N_2$ ……………………………(ii)

Voltage transformation ratio

E2/E1=V2/V1=K

This constant K is known as voltage transformation ratio.

(i) If K>1, then the transformer is called step-up transformer.

(ii) If K<1, then the transformer is called step-down transformer.

Transformer with losses but no magnetic leakage.

There are two cases, (i) when a transformer is on no load and (ii) when it is loaded.

Actual and approximate equivalent circuits

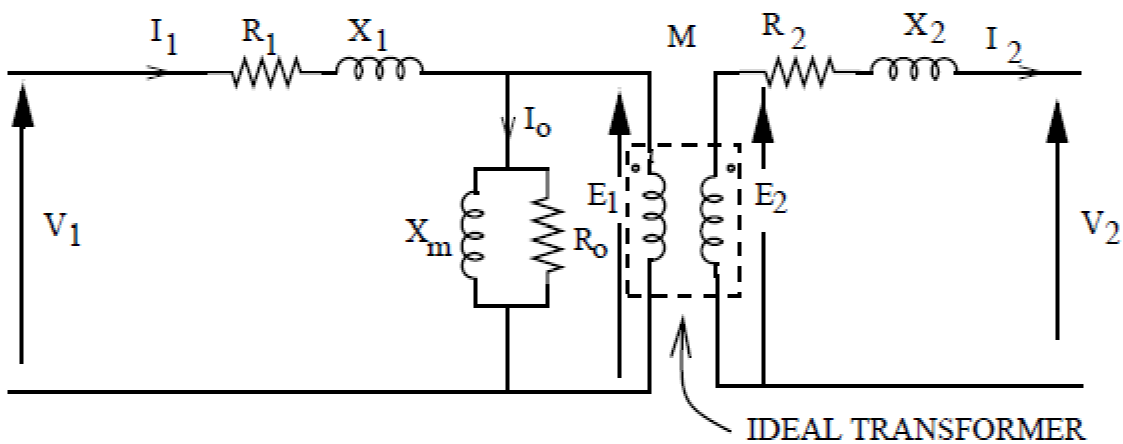


Fig. 5.4(a)

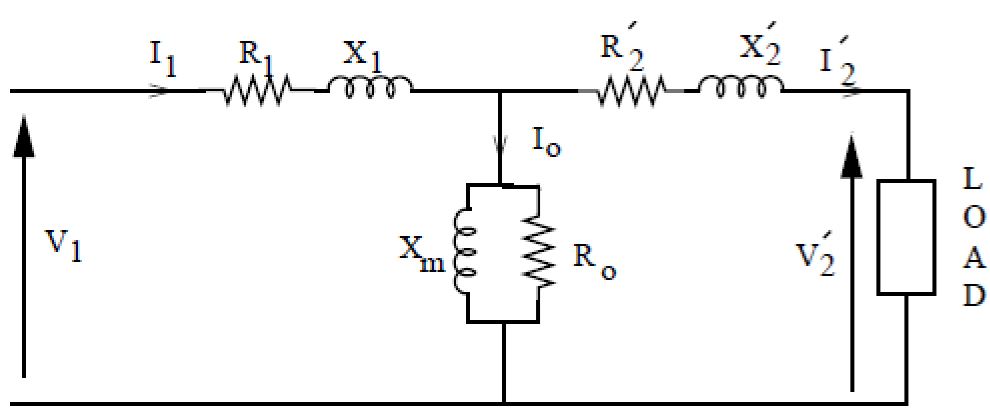
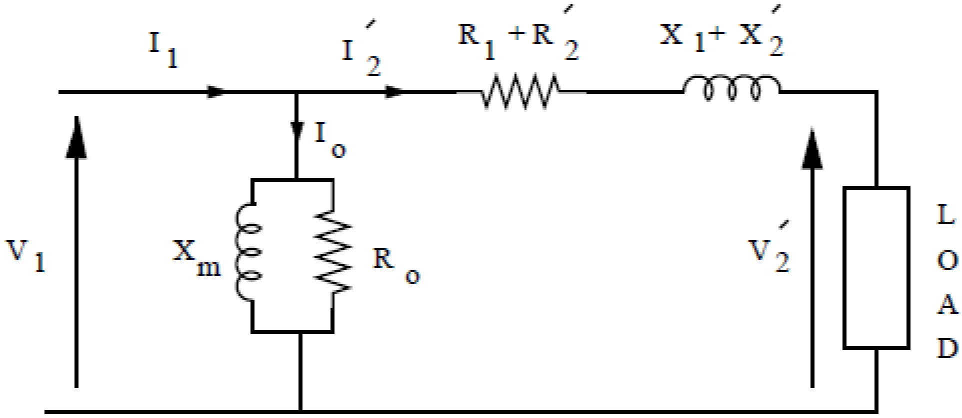


Fig. 5.4(b)

Fig.5.4 Approximate equivalent circuit of transformer



Open and short circuit tests

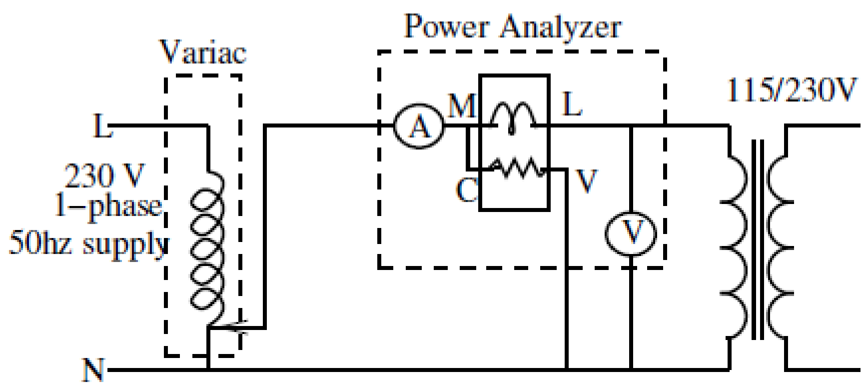


Fig.5.5 Circuit Diagram for No−Load Test

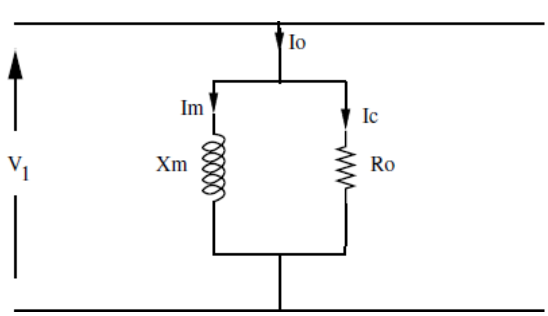


Fig.5.6 (a) Equivalent Circuit on No−Load

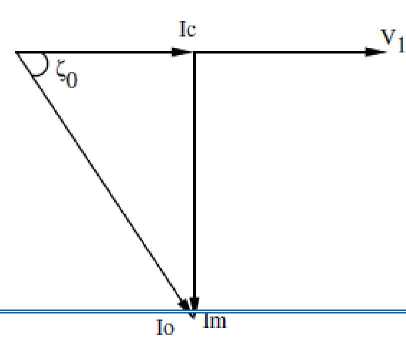


Fig.5.7 (b) Phasor Diagram on No−Load

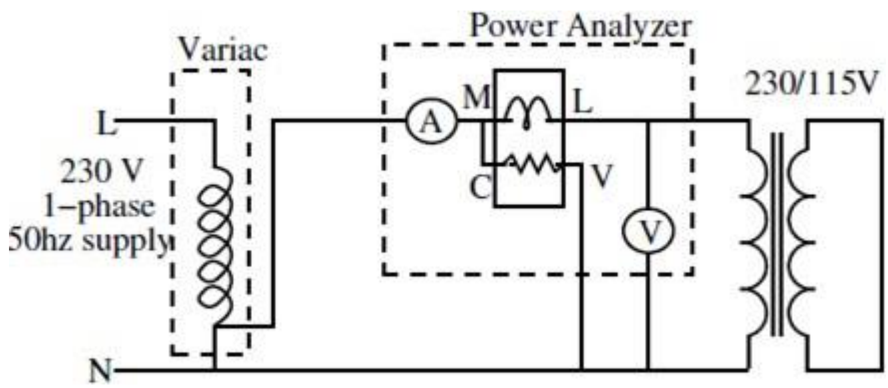


Fig.5.8 (a) Circuit Diagram for Short−Circuit Test

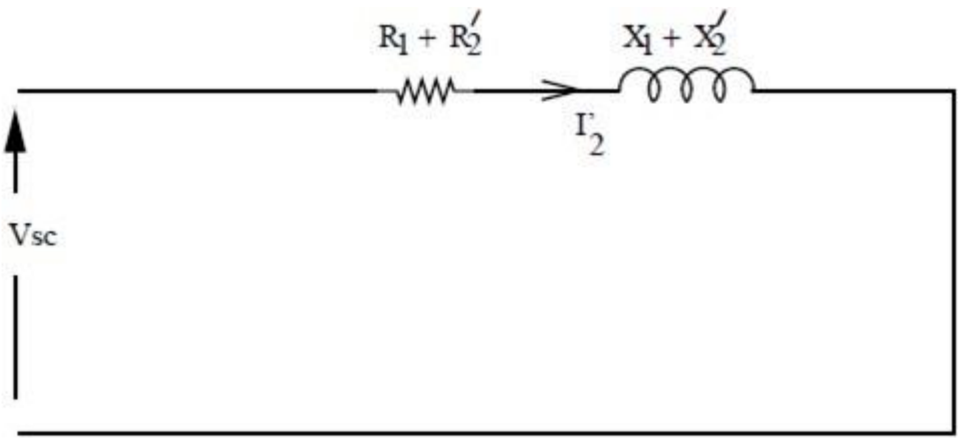


Fig.5.9 (b) Equivalent Circuit on Short Circuit

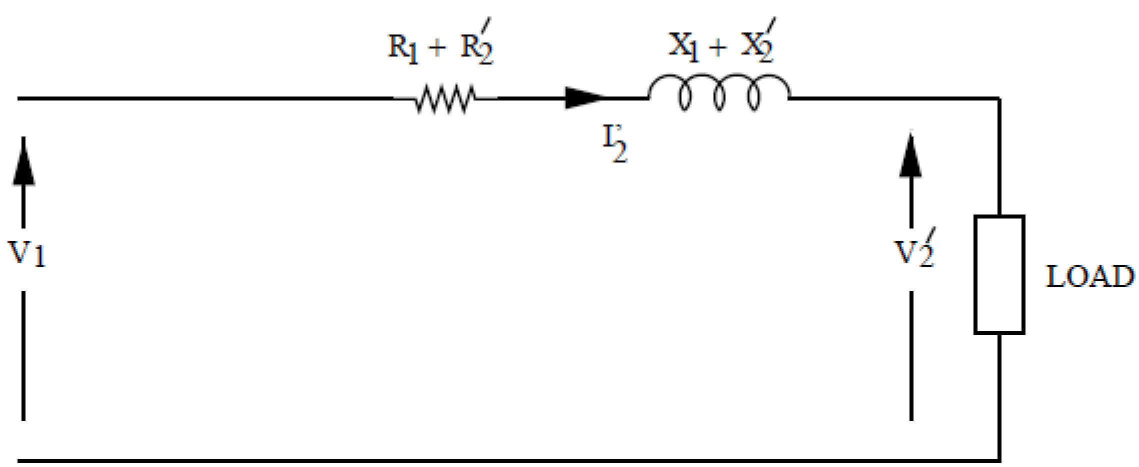
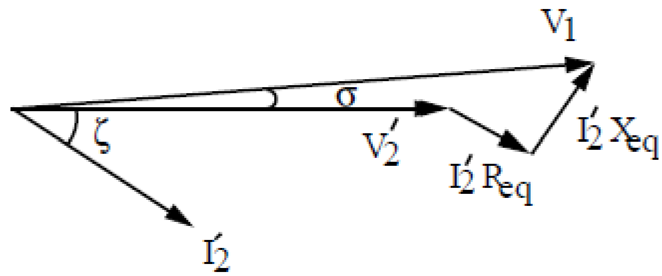
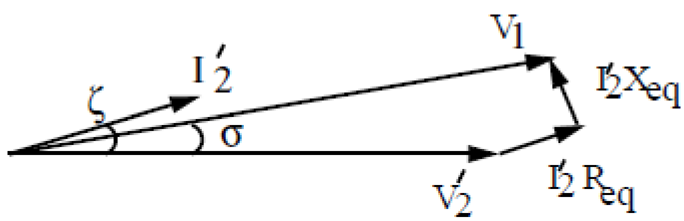


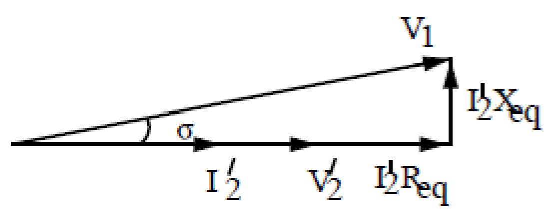
Fig.5.10 Equivalent Circuit to determine Regulation



(a) Lagging Power Factor



(b) Leading Power Factor



(c) Unity Power Factor

Fig.5.11 Vector diagram for various load conditions

Current Ratio

Current ratio is the ratio of current flow through the primary winding (I_1) to the current flowing through the secondary winding (I_2). In an ideal transformer -

Apparent input power = Apparent output power.

$$V_1 I_1 = V_2 I_2$$

$$\frac{I1}{I2} = \frac{V2}{V1} = \frac{N2}{N1} = K$$

Volt-Ampere Rating

i) The transformer rating is specified as the products of voltage and current (VA rating).

ii) On both sides, primary and secondary VA rating remains same. This rating is generally expressed in KVA (Kilo Volts Amperes rating).

$$\frac{V1}{V2} = \frac{I2}{I1} = K$$

$$V_1I_1 = V_2I_2$$

$$\text{KVA Rating of a transformer} = \frac{V1I1}{1000} = \frac{V2I2}{1000} \text{ (1000 is to convert KVA to VA)}$$

V_1 and V_2 are the V_t of primary and secondary by using KVA rating we can calculate I_1 and I_2 Full load current and it is safe maximum current.

$$I_1 \text{ Full load current} = \frac{KVA\ Rating\ X\ 1000}{V1}$$

$$I_1 \text{ Full load current} = \frac{KVA\ Rating\ X\ 1000}{V2}$$

Transformer on No-load

a) Ideal transformer

b) Practical transformer

a) *Ideal Transformer*

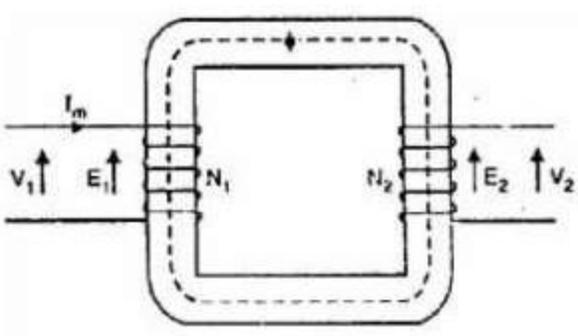
An ideal transformer is one that has

(i) No winding resistance

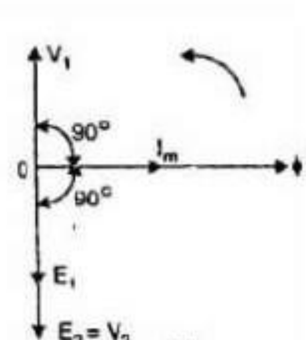
(ii) No leakage flux i.e., the same flux links both the windings

(iii) No iron losses (i.e., eddy current and hysteresis losses) in the core

Although ideal transformer cannot be physically realized, yet its study provides a very powerful tool in the analysis of a practical transformer. In fact, practical transformers have properties that approach very close to an ideal transformer.



(i)



(ii)

Fig: 2.4

Consider an ideal transformer on no load i.e., secondary is open-circuited as shown in *Fig.2.4 (i)*. under such conditions, the primary is simply a coil of pure inductance. When an alternating voltage V_1 is applied to the primary, it draws a small magnetizing current Im which lags behind the applied voltage by 90°. This alternating current Im produces an alternating flux ϕ which is proportional to and in phase with it. The alternating flux ϕ links both the windings and induces e.m.f. E1 in the primary and e.m.f. E_2 in the secondary. The primary e.m.f. E1 is, at every instant, equal to and in opposition to V_1 (Lenz's law). Both e.m.f.s E_1 and E2 lag behind flux ϕ by 90°.However, their magnitudes depend upon the number of primary and secondary turns. *Fig. 2.4 (ii)* shows the phasor diagram of an ideal transformer on no load. Since flux ϕ is common to both the windings, it has been taken as the reference phasor. The primary e.m.f. E1 and secondary e.m.f. E2 lag behind the flux ϕ by 90°. Note that E_1 and E_2 are in phase. But E1 is equal to V1 and 180° out of phase with it.

Phasor Diagram

$$\boxed{\frac{E2}{E1} = \frac{V2}{V1} = K}$$

i) Φ (flux) is reference

ii) Im produce φ and it is in phase with φ, V_1 Leads Im by 90˚

iii) E1 and E2 are in phase and both opposing supply voltage V1, winding is purely inductive

So current has to lag voltage 90˚.

iv) The power input to the transformer

$P = V_1.I_1. \cos(90^\circ)$................................. $(\cos 90^\circ = 0)$

P= 0 (ideal transformer)

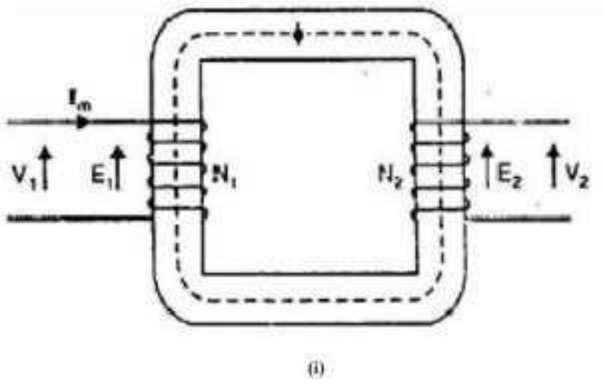
***b)i) Practical Transformer* on no load**

A practical transformer differs from the ideal transformer in many respects. The practical transformer has (i) iron losses (ii) winding resistances and (iii) Magnetic leakage

(i) Iron losses. Since the iron core is subjected to alternating flux, there occurs eddy current and hysteresis loss in it. These two losses together are known as iron losses or core losses. The iron losses depend upon the supply frequency, maximum flux density in the core, volume of the core etc. It may be noted that magnitude of iron losses is quite small in a practical transformer.

(ii) Winding resistances. Since the windings consist of copper conductors, it immediately follows that both primary and secondary will have winding resistance. The primary resistance R_1 and secondary resistance R_2 act in series with the respective windings as shown in Fig. When current flows through the windings, there will be power loss as well as a loss in voltage due to IR drop. This will affect the power factor and E_1 will be less than V_1 while V_2 will be less than E_2.

Consider a practical transformer on no load i.e., secondary on open-circuit as Shown in Fig 2.5.



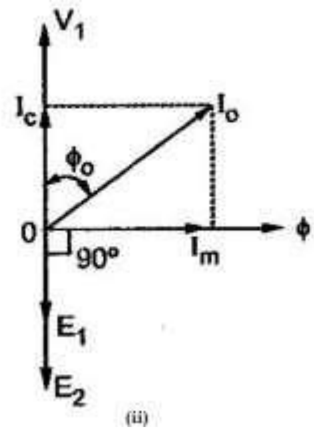


Fig: 2.5 Phasor diagram of transformer at noload

Here the primary will draw a small current I_0 to supply -

(i) the iron losses and
(ii) a very small amount of copper loss in the primary.

Hence the primary no load current I0 is not 90° behind the applied voltage V_1 but lags it by an angle ϕ_0 < 90° as shown in the phasor diagram. No

load input power, $W_0 = V_1 I_0 \cos \phi 0$

As seen from the phasor diagram in Fig.2.5 (ii), the no-load primary current I_0

(i) The component I_c in phase with the applied voltage V_1. This is known as active or working or iron loss component and supplies the iron loss and a very small primary copper loss.

$I_c = I_0 \cos \varphi_0$

The component Im lagging behind V_1 by 90° and is known as magnetizing component. It is this component which produces the mutual flux ϕ in the core.

$I_m = I_0 \sin \varphi_0$

Clearly, Io is phasor sum of Im and I_c,

$$I_o = \sqrt{Im^2 + Ic^2}$$

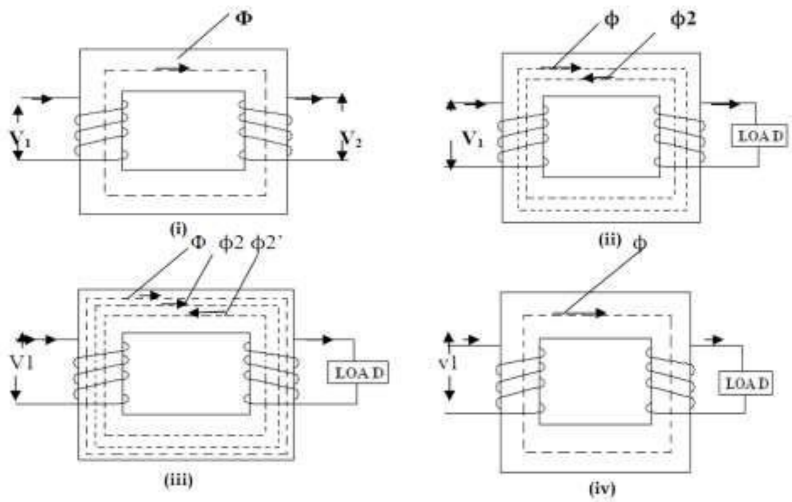
$$\text{No load P.F.,} \quad \cos\phi o = \frac{Ic}{Io}$$

The no load primary copper loss (i.e. Io^2R1) is very small and may be neglected.

Therefore, the no load primary input power is practically equal to the iron loss in the transformer i.e.,

No load input power, $W_0 = V_1 I_o \cos\phi_o = P_i$ = Iron loss

ii)Practical Transformer on Load **Fig: 2.6**



At no load, there is no current in the secondary so that $V_2 = E_2$. On the primary side, the drops in R_1 and X_1, due to I_0 are also very small because of the smallness of I_0. Hence, we can say that at no load, $V_1 = E_1$.

i) When transformer is loaded, the secondary current I_2 is flows through the secondary winding.

ii) Already I_m magnetizing current flow in the primary winding fig. 2.6(i).

iii) The magnitude and phase of I_2 with respect to V_2 is determined by the characteristics of the load.

a) I_2 in phase with V_2 (resistive load)

b) I_2 lags with V_2 (Inductive load)

c) I_2 leads with V_2 (capacitive load)

iv) Flow of secondary current I_2 produce new Flux φ_2 fig.2.6 (ii)

v) Φis main flux which is produced by the primary to maintain the transformer as constant

magnetising component.

vi) Φ_2 opposes the main flux φ, the total flux in the core reduced. It is called demagnetising Ampere-turns due to this E_1 reduced.

vii) To maintain the φ constant primary winding draws more current (I_2') from the supply (load component of primary) and produce φ_2' flux which is oppose φ_2 (but in same direction as φ), to maintain flux constant flux constant in the core fig.2.6 (iii).

viii) The load component current I_2' always neutralizes the changes in the load.

ix) Whatever the load conditions, the net flux passing through the core is approximately the same as at no-load. An important deduction is that due to the constancy of core flux at all loads, the core loss is also practically the same under all load conditions fig.2.6 (iv).

$$\boxed{\Phi_2 = \phi_2' \quad N_2I_2 = N_1I_2' \quad I_2' = \frac{N2}{N1} XI_2 = KI_2}$$

Phasor Diagram

i) Take (ϕ) flux as reference for all load

ii) The no load I_o which lags by an angle ϕo. $Io = \sqrt{Ic^2 + Im^2}$.

iii) The load component I_2', which is in anti-phase with I_2 and phase of I_2 is decided by the load.

iv) Primary current I_1 is vector sum of I_o and I_2'

$$\vec{I_1} - \vec{I_o} + \vec{I_2'}$$

$$I_1 = \sqrt{Io^2 + I2'^2}$$

a) If load is Inductive, I_2 lags E_2 by φ_2, shown in phasor diagram fig 2.7 (a).

b) If load is resistive, I_2 in phase with E_2 shown in phasor diagram fig. 2.7 (b).

c) If load is capacitive load, I_2 leads E_2 by φ_2 shown in phasor diagram fig. 2.7 (c).

For easy understanding at this stage here we assumed E_2 is equal to V_2 neglecting various drops.

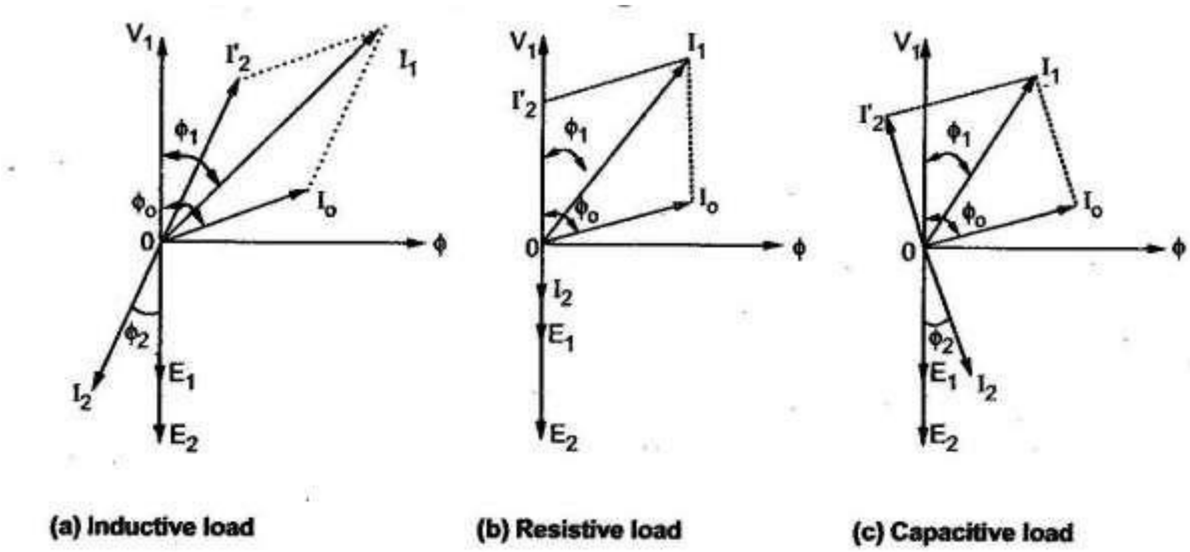


Fig..2.7 (a)

Now we going to construct complete phasor diagram of a transformer (shown in Fig: 2.7.b)

Effect of Winding Resistance

In practical transformer it process its own winding resistance causes power loss and also the voltage drop.

R_1 – primary winding resistance in ohms. R_2 –
secondary winding resistance in ohms.

The current flow in primary winding make voltage drop across it is denoted as I_1R_1 here supply voltage V_1 has to supply this drop primary induced e.m.f E_1 is the vector difference between V_1 and I_1R_1.

$$\vec{E_1} = \vec{V_1} - \vec{I_1R_1}$$

Similarly the induced e.m.f in secondary E_2, The flow of current in secondary winding makes voltage drop across it and it is denoted as I_2R_2 here E_2 has to supply this drop.

The vector difference between E_2 and I_2R_2

$$\vec{V_2} = \vec{E_2} - \vec{I_2R_2}$$ (Assuming as purely resistive drop here.)

Equivalent Resistance

1) It would now be shown that the resistances of the two windings can be transferred to any one of the two winding.

2) The advantage of concentrating both the resistances in one winding is that it makes calculations very simple and easy because one has then to work in one winding only.

3) Transfer to any one side either primary or secondary without affecting the performance of the transformer.

The total copper loss due to both the resistances.

$$\text{Total copper loss} = I_1^2R_1 + I_2^2R_2$$
$$= I_1^2[R_1 + \frac{I2^2}{I1^2}]$$
$$= I_1^2[R_1 + \frac{1}{K} R_2]$$

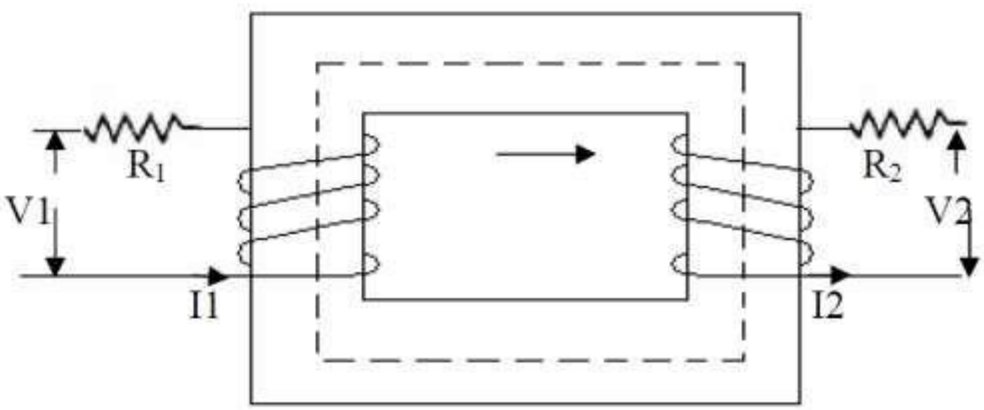
$\frac{R2}{K^2}$ is the resistance value of R_2 shifted to primary side and denoted as R_2'.

R_2' is the equivalent resistance of secondary referred to primary

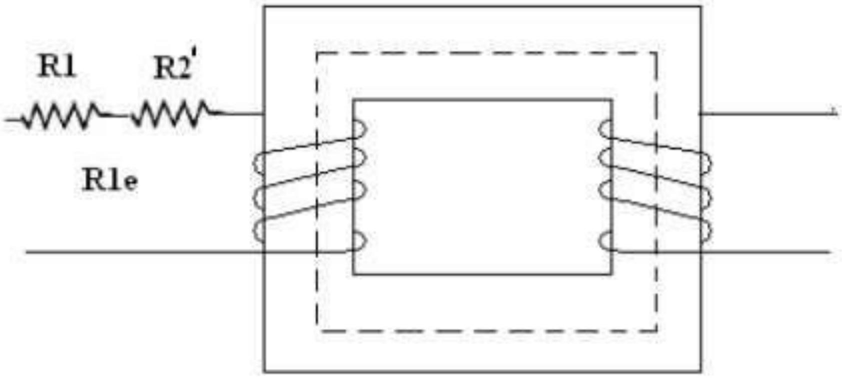
$$\boxed{R_2' = \frac{R2}{K^2}}$$

Equivalent resistance of transformer referred to primary fig (ii)

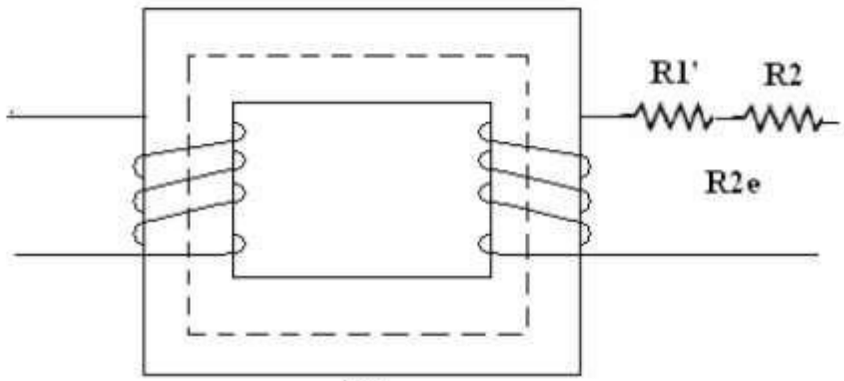
$$\boxed{R_{1e} = R_1 + R_2' = R_1 + \frac{R2}{K^2}}$$



(i)



(ii)



(iii)

Fig:2.8

Similarly it is possible to refer the equivalent resistance to secondary winding.

Note:

Note:

i) When a resistance is to be transferred from the primary to secondary, it must be multiplied by K^2, it must be divided by K^2 while transferred from the secondary to primary.

High voltage side ➡ low current side ➡ high resistance side

Low voltage side ➡ high current side ➡ low resistance side

<u>Effect of Leakage Reactance</u>

i) It has been assumed that all the flux linked with primary winding also links the secondary winding.

But, in practice, it is impossible to realize this condition.

ii) However, primary current would produce flux φ which would not link the secondary winding.

Similarly, current would produce some flux φ that would not link the primary winding.

iii) The flux φ_{L1} complete its magnetic circuit by passing through air rather than around the core, as shown in fig.2.9. This flux is known as primary leakage flux and is proportional to the primary ampere – turns alone because the secondary turns do not links the magnetic circuit of φ_{L1}. It induces an e.m.f e_{L1} in primary but not in secondary.

– The flux φ_{L2} complete its magnetic circuit by passing through air rather than around the core, as shown in fig. This flux is known as secondary leakage flux and is proportional to the secondary ampere turns alone because the primary turns do not links the magnetic circuit of φ_{L2}. It induces an e.m.f e_{L2} in secondary but not in primary.

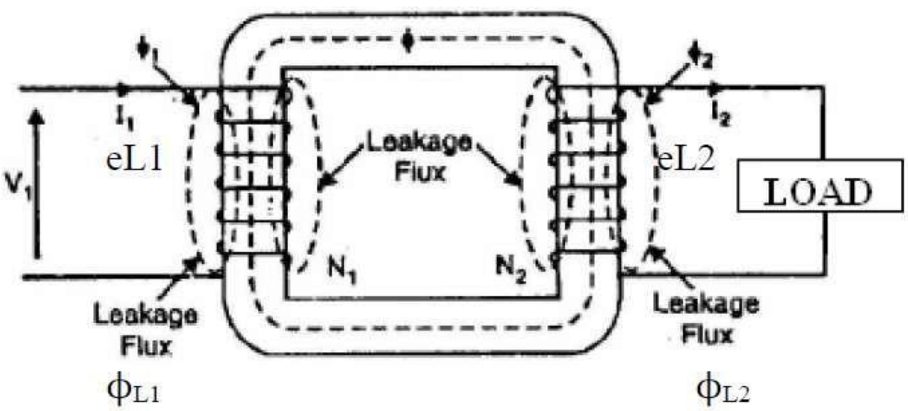


Fig: 2.9

ϕ_{L1} – primary leakage flux
ϕ_{L2} – secondary leakage flux
e_{L1} – self induced e.m.f (primary)
e_{L2} –self induced e.m.f (secondary)

Equivalent Leakage Reactance

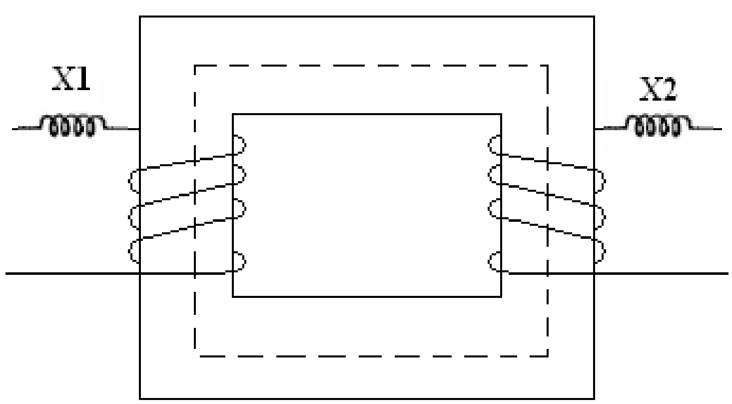


Fig: 2.10

Similarly to the resistance, the leakage reactance also can be transferred from primary to secondary. The relation through K^2 remains same for the transfer of reactance as it is studied earlier for the resistance

X_1 – leakage reactance of primary.

X_2 - leakage reactance of secondary.

Then the total leakage reactance referred to primary is X_{1e} given by

$$X_{1e} = X_1 + X_2'$$

$$X_2' = \frac{X2}{K^2}$$

The total leakage reactance referred to secondary is X_{2e} given by

$$X_{2e} = X_2 + X_1'$$
$$X_1' = K^2X_1$$

$$\boxed{\begin{aligned} X_{1e} &= X_1 + X_2' \\ X_{2e} &= X_2 + X_1' \end{aligned}}$$

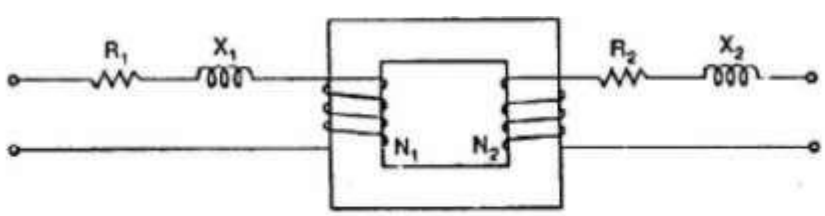
Equivalent Impedance

The transformer winding has both resistance and reactance (R_1, R_2, X_1,X_2).Thus we can say that the total impedance of primary winding isZ_1 which is,

$Z_1 = R_1 + jX_1$ ohms

On secondary winding, Z_2

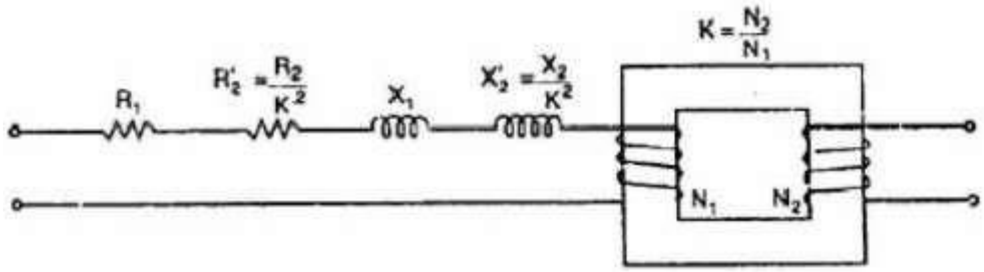
$= R_2 + jX_2$ ohms



Individual magnitude of Z1 and Z2 are

$$Z_1 = \sqrt{R1^2 + X1^2}$$
$$Z_2 = \sqrt{R2^2 + X2^2}$$

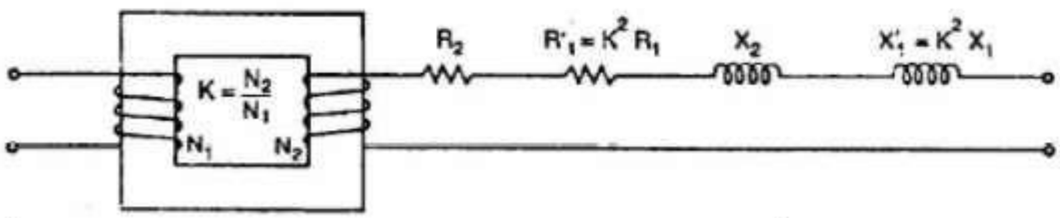
Similar to resistance and reactance, the impedance also can be referred to any one side,



Z_{1e} = total equivalent impedance referred to primary

$$Z_{1e} = R_{1e} + jX_{1e} = Z_1 + Z_2' = Z_1 + \frac{Z2}{K^2}$$

Z_{2e} = total equivalent impedance referred to secondary.



$$Z_{2e} = R_{2e} + jX_{2e} = Z_2 + Z_1' = Z_2 + K^2 Z_1$$

The magnitudes of Z1e and Z2e

$$Z_1 = \sqrt{R1e^2 + X1e^2}$$
$$Z_2 = \sqrt{R2e^2 + X2e^2}$$

It can be noted that

$Z_{2e} = K^2 Z_{1e}$ and $Z_{1e} = \frac{Z2e}{K^2}$

<u>Complete Phasor Diagram of a Transformer *(for Inductive Load or Lagging pf)*</u>

We now restrict ourselves to the more commonly occurring load i.e. inductive along with resistance

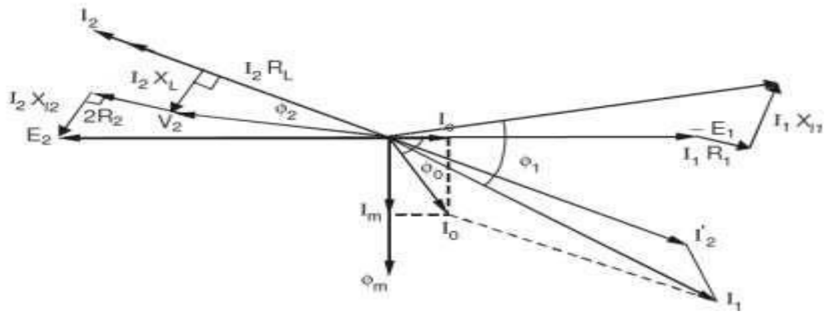
which has a lagging power factor.

For drawing this diagram, we must remember that

$$\overline{V_2} = \overline{E}_2 - \overline{I}_2\,(R_2 + j\,X_{l2})$$

and

$$\overline{V_1} = -\,\overline{E}_1 + \overline{I}_2\,(R_1 + j\,X_{l1})$$



Equivalent Circuit of Transformer

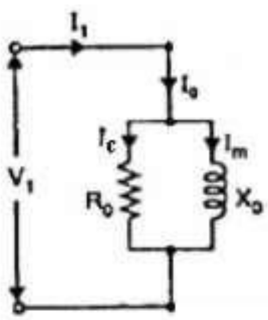


Fig:11

$I_m = I_o \sin \phi_o$ = magnetizing component
$I_c = Io \cos \phi_o$ = Active component

$R_o = \frac{V1}{Ic}$, $\quad X_o = \frac{V1}{Im}$

No load equivalent circuit

i) I_m produces the flux and is assumed to flow through reactance X_o called no load reactance while I_c is active component representing core losses hence is assumed to flow through the resistance R_0

ii) Equivalent resistance is shown in fig.2.12.

iii) When the load is connected to the transformer then secondary current I_2 flows causes voltage drop across R_2 and X_2. Due to I_2, primary draws an additional current.

$$I_2' = \frac{I2}{K}$$

I_1 is the phasor addition of I_o and I_2'. This I_1 causes the voltage drop across primary resistance R_1 and reactance X_1.

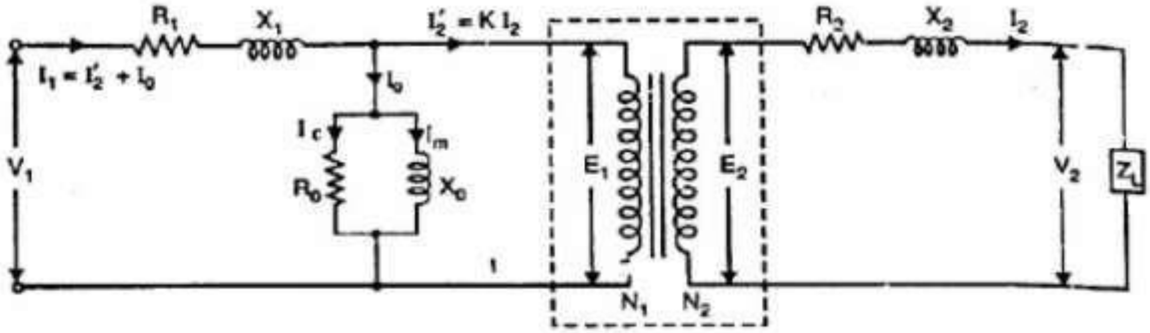


Fig: 2.12

To simplified the circuit the winding is not taken in equivalent circuit while transfer to one side.

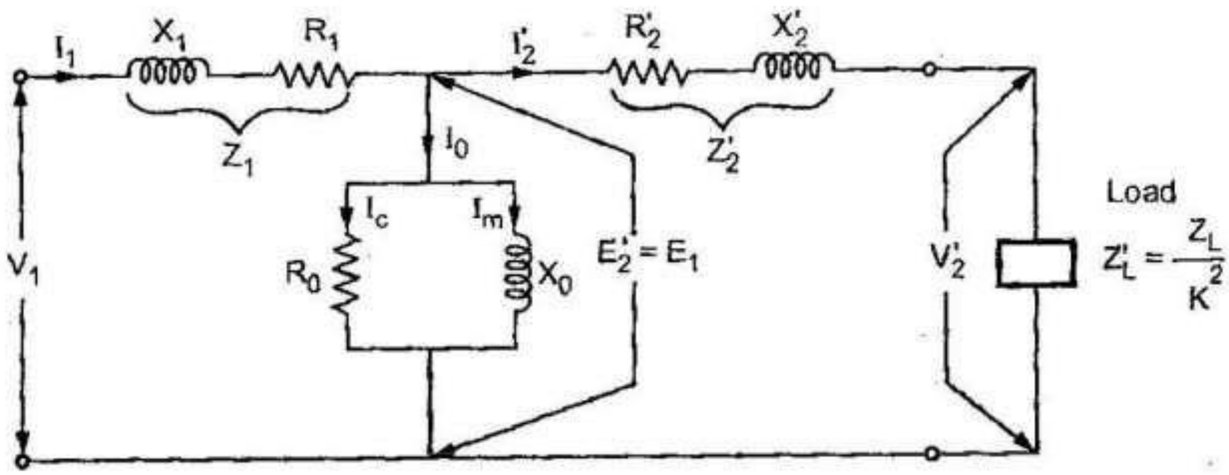


Fig: 2.13

Exact equivalent circuit referred to primary

Transferring secondary parameter to primary -

$$\boxed{R_2' = \frac{R2}{K^2},\ X_2' = \frac{X2}{K^2},\ Z_2' = \frac{Z2}{K^2},\ E_2' = \frac{E2}{K},\ I_2' = KI_2,\ K = \frac{N2}{N1}}$$

High voltage winding ➡ low current ➡ high impedance

Low voltage winding ➡ high current ➡ low impedance

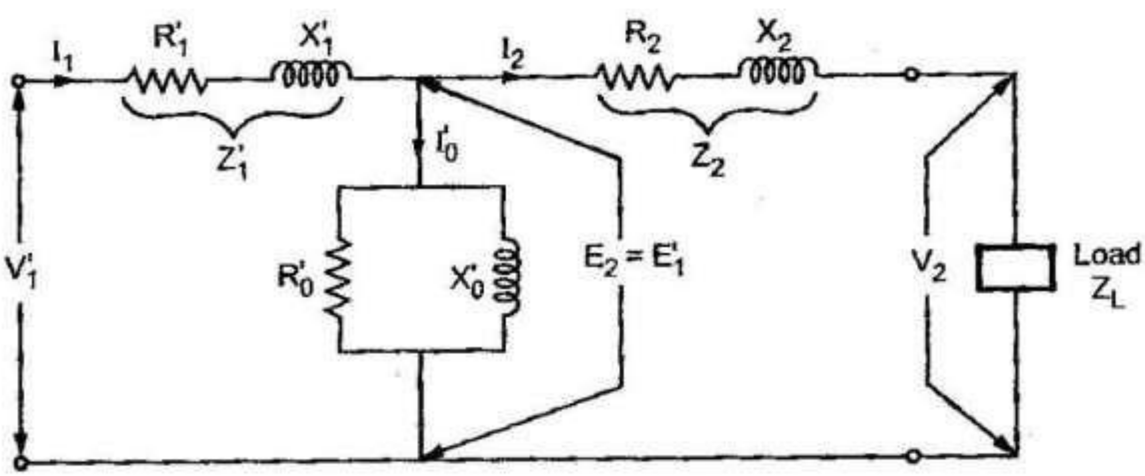


Fig: 2.14

Exact equivalent circuit referred to secondary

$$R_1' = R_1K^2,\ X_1' = K^2X_1\ ,\ E_1' = KE_1$$

$$Z_1' = K^2Z1\ ,\ I_1' = \frac{I1}{K'},\ I_o = \frac{Io}{K}$$

Now as long as no load branch i.e. exciting branch is in between Z_1 and Z_2', the impedances cannot be combined. So further simplification of the circuit can be done. Such circuit is called approximate equivalent circuit.

Approximate Equivalent Circuit

i) To get approximate equivalent circuit, shift the no load branch containing R_o and X_o to the left of R_1 and X_1.

ii) By doing this we are creating an error that the drop across R_1 and X_1 to I_o is neglected due to this circuit because simpler.

iii) This equivalent circuit is called approximate equivalent circuit Fig: 2.15 & Fig: 2.16.

In this circuit new R_1 and R_2' can be combined to get equivalent circuit referred to primary R_{1e},similarly

X_1 and X_2' can be combined to get X_{1e}.

$$R_{1e} = R_1 + R_2' = R_1 + \frac{R2}{K^2}$$

$$X_{1e} = X_1 + X_2' = X_1 + \frac{X2}{K^2}$$

$$Z_{1e} = R_{1e} + jX_1E, \qquad R_o = \frac{V1}{Ic}, \quad \text{and } X_o = \frac{V1}{Im}$$

$$I_c = I_o \cos\phi_o, \quad \text{and } I_m = I_o \sin\phi_o$$

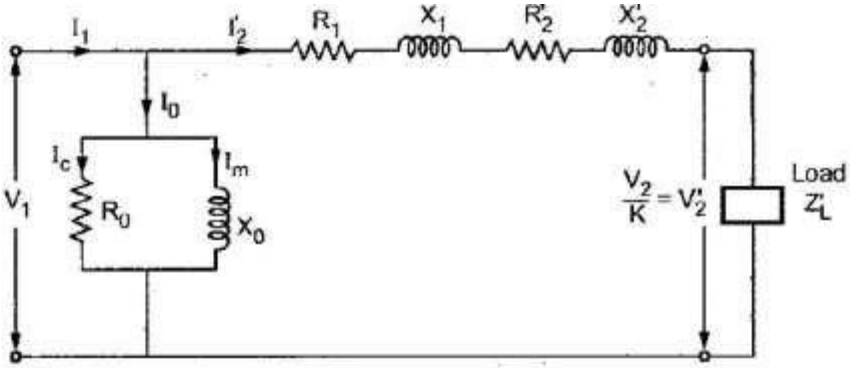


Fig:2.15Approximate equivalent circuit referred to primary

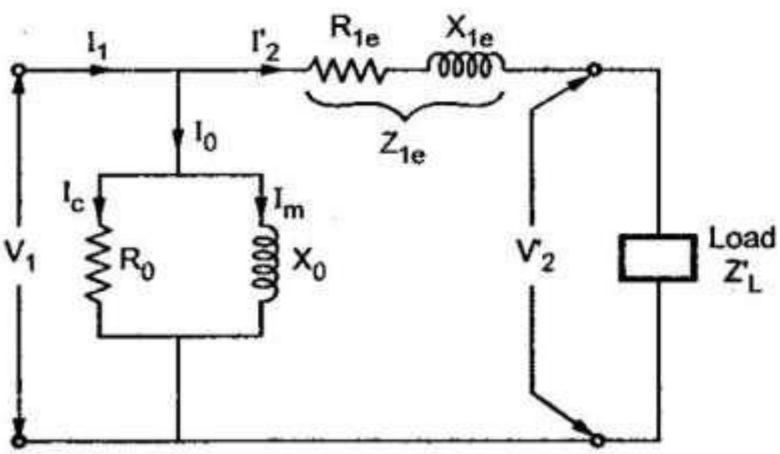
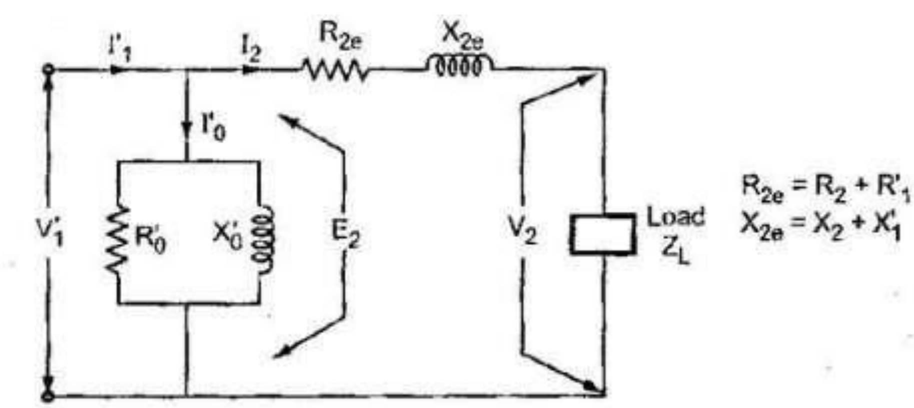


Fig:2.16Simplified equivalent circuit

Approximate Voltage Drop in a Transformer



$$\vec{E_2} = \overrightarrow{I_2 R_{2e}} + \overrightarrow{I_2 X_{2e}} + \vec{V_2} = \vec{V_2} + \vec{I_2}(R_{2e} + jX_{2e}), \quad \vec{E_2} = \vec{V_2} + \overrightarrow{I_2 Z_{2e}}$$

Fig. 2.17

Primary parameter is referred to secondary there are no voltage drop in primary. When there is no load, $I_2 = 0$ and we get no load terminal voltage drop in $V_{2o} = E_2$ = no load terminal voltage V_2 = terminal voltage on load

For Lagging P.F.

i) The current I_2 lags V_2 by angle φ_2

ii) Take V_2 as reference

iii) I_2R_{2e} is in phase with I_2 while I_2X_{2e} leads I_2 by 90°

iv) Draw the circle with O as centre and OC as radius cutting extended OA at M. as OA

= V_2 and now OM = E_2.

v) The total voltage drop is AM = I_2Z_{2e}.

vi) The angle α is practically very small and in practice M&N are very close to each other. Due to this the approximate voltage drop is equal to AN instead of AM

AN – approximate voltage drop.

To find AN by adding AD& DN AD

AB $\cos\phi = I_2R_{2e}\cos\phi$

DN = BL $\sin\phi = I_2X_{2e}\sin\phi$

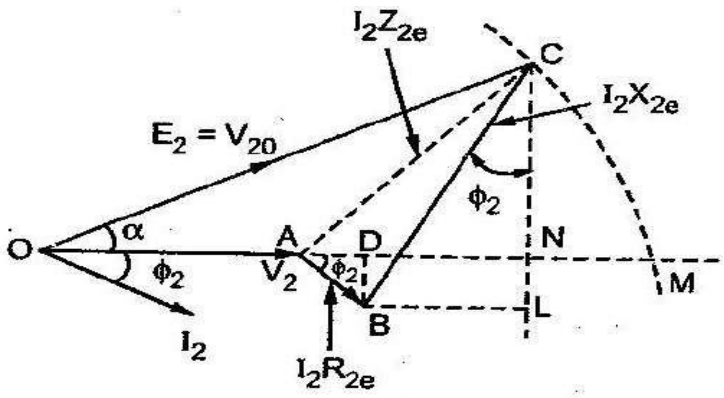
AN = AD + DN = $I_2R_{2e}\cos\varphi_2 + I_2X_{2e}\sin\varphi_2$

Assuming: $\varphi_2 = \varphi_1 = \varphi$

Approximate voltage drop = $I_2R_{2e}\cos\phi + I_2X_{2e}\sin\phi$ (referred to secondary) Similarly:

Approximate voltage drop = $I_1R_{1e}\cos\phi + I_1X_{1e}\sin\phi$ (referred to primary)

Fig:2.18



For Leading P.F Loading

I_2 leads V_2 by angle φ

Approximate voltage drop = $I_2R_{2e}\cos\phi - I_2X_{2e}\sin\phi$ (referred to secondary) Similarly:

Approximate voltage drop = $I_1R_{1e}\cos\phi - I_1X_{1e}\sin\phi$ (referred to primary)

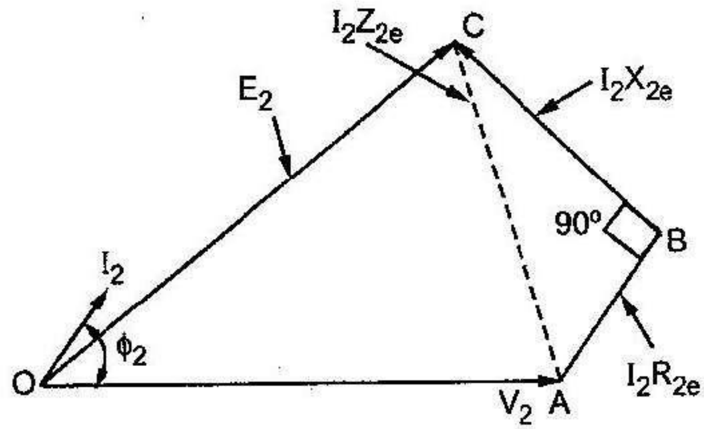
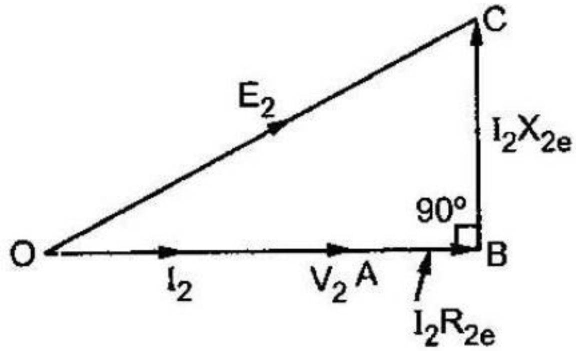


Fig: 2.19

For Unity P.F. Loading

Approximate voltage drop = I_2R_{2e} (referred to secondary) Similarly:

Approximate voltage drop = I_1R_{1e} (referred to primary)



$\text{Cos}\phi = 1$
$\text{Sin}\phi = 0$

Fig: 2.20

Approximate voltage drop = $E_2 – V_2$

= $I_2R_{2e} \cos\phi \pm I_2X_{2e} \sin\phi$ (referred to secondary)

= $I_1R_{1e} \cos\phi \pm I_1X_{1e} \sin\phi$ (referred to primary)

Losses in a Transformer

The power losses in a transformer are of two types, namely;

1. Core or Iron losses

2. Copper losses

These losses appear in the form of heat and produce (i) an increase in Temperature and (ii) a drop in efficiency.

2.7.1 Core or Iron losses (Pi)

These consist of hysteresis and eddy current losses and occur in the transformer core due to the alternating flux. These can be determined by open-circuit test.

Hysteresis loss = $k_h f B_m^{1.6}$ watts /m^3

K_h – hysteresis constant depend on material f -

Frequency

B_m – maximum flux density

Eddy current loss = $K_e f^2 B_m^2 t^2$ watts /m^3 Ke

– eddy current constant

t - Thickness of the core

Both hysteresis and eddy current losses depend upon

(i) Maximum flux density B_m in the core

(ii) Supply frequency f. Since transformers are connected to constant-frequency, constant voltage supply, both f and Bm are constant. Hence, core or iron losses are practically the same at all loads.

Iron or Core losses, Pi = Hysteresis loss + Eddy current loss = Constant losses (Pi)

The hysteresis loss can be minimized by using steel of high silicon content .Whereas eddy current loss can be reduced by using core of thin laminations.

Copper losses (P_{cu})

These losses occur in both the primary and secondary windings due to their ohmic resistance. These can be determined by short-circuit test. The copper loss depends on the magnitude of the current flowing through the windings.

$$\text{Total copper loss} = I_1^2R_1 + I_2^2R_2 = I_1^2(R_1 + R_2') = I_2^2(R_2 + R_1')$$

$$\boxed{\text{Total loss} = \text{iron loss} + \text{copper loss} = Pi + Pcu}$$

Efficiency of a Transformer

Like any other electrical machine, the efficiency of a transformer is defined as the ratio of output power (in watts or kW) to input power (watts or kW) i.e.

Power output = power input – Total losses

Power input = power output + Total losses

$$\text{Efficiency} = \frac{power\ output}{power\ input}$$

$$\text{Efficiency} = \frac{power\ output}{power\ input + Pi + Pcu}$$

Power output = $V_2 I_2 \cos\phi$, $\cos\phi$ = load power factor

Transformer supplies full load of current I_2 and with terminal voltage V_2

Pcu = copper losses on full load = $I_2^2 R_{2e}$

$$\text{Efficiency} = \frac{V2I2\cos\phi}{V2I2\cos\phi + Pi + I2^2 R2e}$$

$V_2 I_2$ = VA rating of a transformer

$$\text{Efficiency} = \frac{(\text{VA rating})\text{X}\cos\phi}{(\text{VA rating})\text{X}\cos\phi + Pi + I2^2 R2e}$$

$$\boxed{\%\ \text{Efficiency} = \frac{(\text{VA rating})\text{X}\cos\phi}{(\text{VA rating})\text{X}\cos\phi + Pi + I2^2 R2e}\ \text{X}\ 100}$$

= power output + Pi + Pcu

This is full load efficiency and I_2 = full load current.

We can now find the full-load efficiency of the transformer at any p.f. without actually loading the transformer.

$$\text{Full load Efficiency} = \frac{(\text{Full load VA rating})\text{X}\cos\phi}{(\text{Full load VA rating})\text{X}\cos\phi + Pi + I2^2 R2e}$$

Also for any load equal to n x full-load,

Corresponding total losses = $P_i + n^2 P_{Cu}$

$$\text{n = fractional by which load is less than full load} = \frac{actual\ load}{full\ load}$$

$$n = \frac{half\ load}{fullload} = \frac{(\frac{1}{2})}{1} = 0.5$$

$$\boxed{\text{Corresponding (n) \% Efficiency} = \frac{n(\text{VA rating})\text{X}\cos\phi}{n(\text{VA rating})\text{X}\cos\phi + Pi + n^2 Pcu}\ \text{X}\ 100}$$

<u>Condition for Maximum Efficiency</u>

Voltage and frequency supply to the transformer is constant the efficiency varies with the load. As load increases, the efficiency increases. At a certain load current, it loaded further the efficiency start decreases as shown in fig. 2.21.

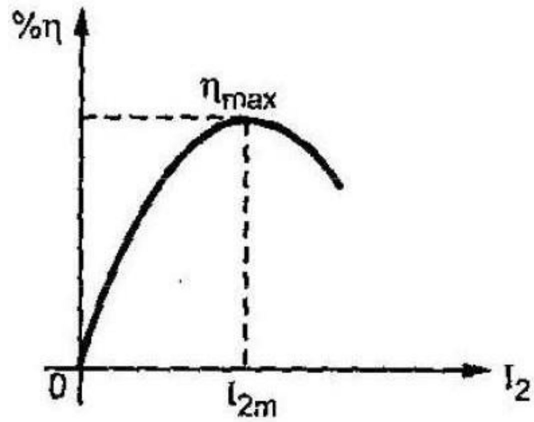


Fig: 2.21

The load current at which the efficiency attains maximum value is denoted as I_{2m} a n d maximum efficiency is denoted as ηmax, now we find -

(a) condition for maximum efficiency

(b) load current at which ηmax occurs

(c) KVA supplied at maximum efficiency

Considering primary side,

Load output = $V_1I_1 \cos\phi 1$

Copper loss = $I_1^2 R_{1e}$ or $I2^2 R2e$ Iron loss = hysteresis + eddy current loss = Pi

$$\text{Efficiency} = \frac{V1I1\ \cos\phi1 - \text{losses}}{V1I1\ \cos\phi1} = \frac{V1I1\ \cos\phi1 - I1^2R1e + Pi}{V1I1\ \cos\phi1}$$

$$= 1 - \frac{I1R1e}{V1I21\cos\phi1} = \frac{Pi}{V1I1\ \cos\phi1}$$

Differentiating both sides with respect to I2, we get

$$\frac{d\eta}{dI2} = 0 - \frac{R1e}{V1\ \cos\phi1} = \frac{Pi}{V1I1^2\ \cos\phi1}$$

For **η** to be maximum, $\frac{d\eta}{dI2} = 0$. Hence, the above equation becomes

$$\frac{R1e}{V1\ \cos\phi1} = \frac{Pi}{V1I1^2\ \cos\phi1} \text{ or } Pi = I_1^2R_{1e}$$

P_{cu} loss = P_i iron loss

The output current which will make P_{cu} loss equal to the iron loss. By proper design, it is possible to make the maximum efficiency occur at any desired load.

For η_{max} $I_2^2 R_{2e} = P_i$ but $I_2 = I_{2m}$

$I^2_{2m} R_{2e} = Pi$ $\qquad\qquad I_{2m} = \sqrt{\frac{Pi}{R2e}}$

This is the load current at η_{max}

(I_2)F.L = full load current

$$\frac{I2m}{(I2)F.L} = \frac{1}{(I2)FL}\sqrt{\frac{Pi}{R2e}}$$

$$\frac{I2m}{(I2)F.L} = \sqrt{\frac{Pi}{[(I2)F.L]^2 R2e}} = \sqrt{\frac{Pi}{[Pcu]F.L}}$$

$$\boxed{I_{2m} = (I_2)\ F.L.\ \sqrt{\frac{Pi}{[Pcu]F.L}}}$$

This is the load current at η_{max} in terms of full load current

KVA Supplied at Maximum Efficiency

For constant V_2 the KVA supplied is the function of load current.

$$\text{KVA at } \eta_{max} = I_{2m} V_2 = V_2(I_2)\text{F.L. X } \sqrt{\frac{Pi}{[Pcu]F.L}}$$

$$\boxed{\text{KVA at } \eta_{max} = (\text{KVA rating}) \text{ X } \sqrt{\frac{Pi}{[Pcu]F.L}}}$$

Substituting condition for η_{max} in the expression of efficiency, we can write expression for η_{max} as ,

as Pcu = Pi

$$\%\ \eta_{max} = \frac{V2\ I2m\cos\phi}{V2\ I2m\cos\phi + 2Pi} \text{ X } 100$$

$$\%\ \eta_{max} = \frac{KVA\ for \eta \max \cos\varphi}{KVA\ for \eta \max \cos\varphi + 2Pi}$$

All Day Efficiency (Energy Efficiency)

In electrical power system, we are interested to find out the all-day efficiency of any transformer because the load at transformer is varying in the different time duration of the day. So all day efficiency is defined as the ratio of total energy output of transformer to the total energy input in 24 hours.

$$\text{All day efficiency} = \frac{\text{kWh output during a day}}{\text{kWh input during the day}}$$

Testing of Transforme

The testing of transformer means to determine efficiency and regulation of a transformer at any load and at any power factor condition.

There are two methods

i) Direct loading test

ii) Indirect loading test

a. Open circuit test

b. Short circuit test

i) Load test on transformer

This method is also called as direct loading test on transformer because the load is directly connected to the transformer. We required various meters to measure the input and output reading while change the load from zero to full load. Fig. 2.22 shows the connection of transformer for direct load test. The primary is connected through the variac to change the input voltage as we required. Connect the meters as shown in the figure below.

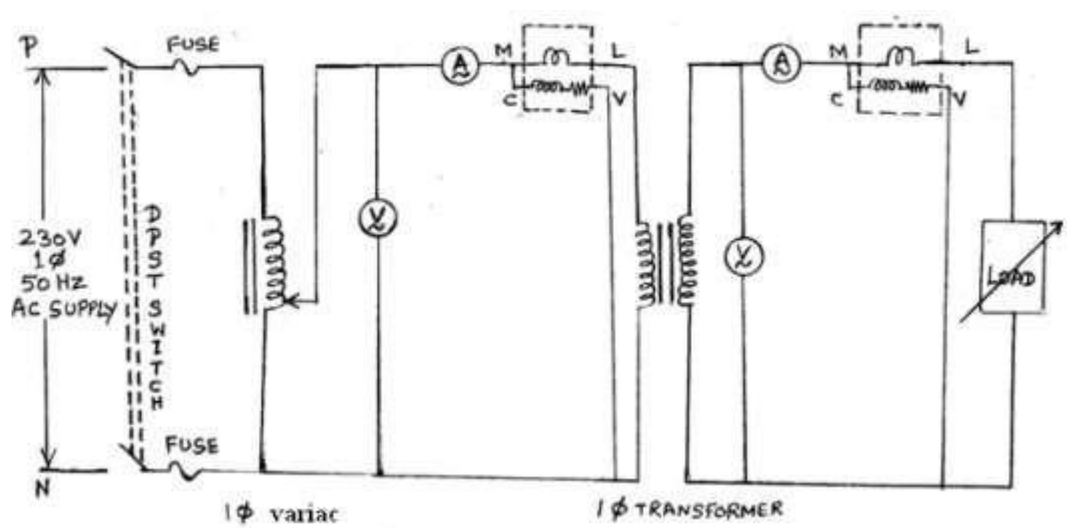


Fig: 2.22

The load is varied from no load to full load in desired steps. All the time, keep primary voltage V_1 constant at its rated value with help of variac and tabulated the reading. The first reading is to be noted on no load for which $I_2 = 0$ A and $W_2 = 0$W.

Calculation

From the observed reading

W_1 = input power to the

transformer

W_2 =output power delivered

to the load

The graph of % η and % R on each load against load current I_L is plotted as shown in fig. 2.23.

$$\boxed{\% \ \eta = \frac{W2}{W1} \text{ X } 100}$$

The first reading is no load so V2 = E_2

The regulation can be obtained as

$$\boxed{\% \ R = \frac{E2 - V2}{V2} \text{ X } 100}$$

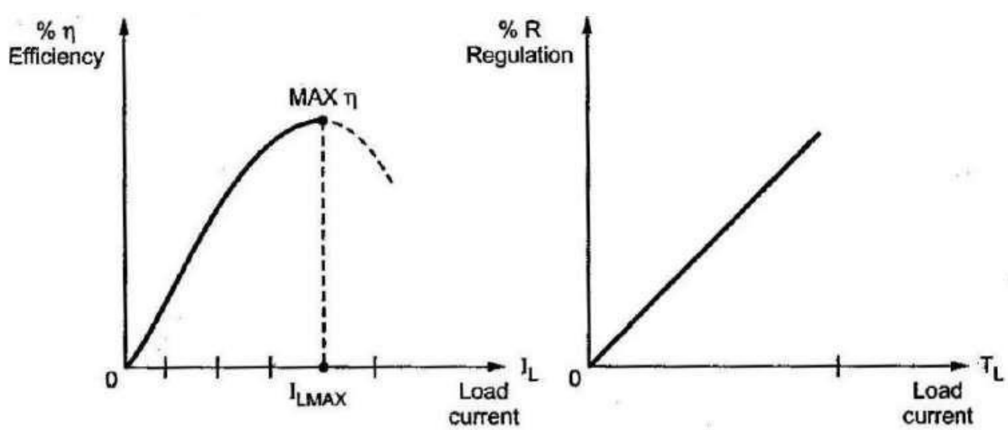


Fig: 2.23

Advantages:

1) This test enables us to determine the efficiency of the transformer accurately at any load.

2) The results are accurate as load is directly used.

Disadvantages:

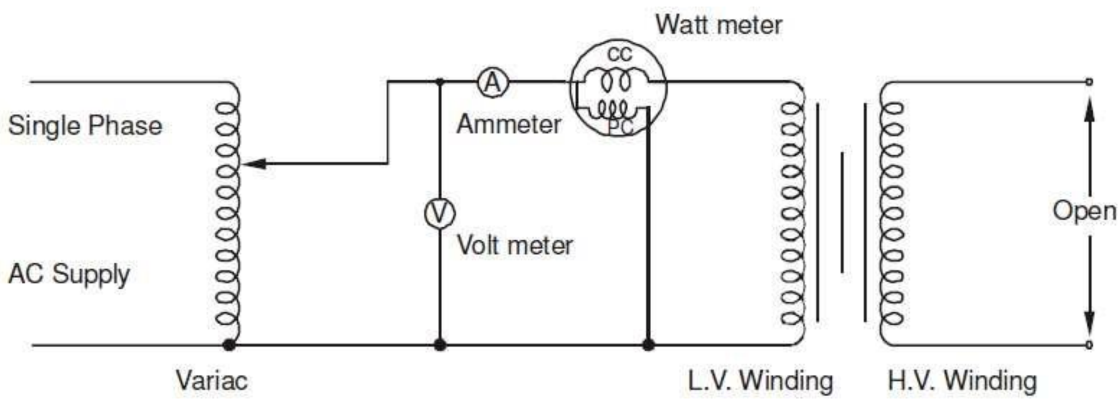
1) There are large power losses during the test.

2) Load not avail in lab while test conduct for large transformer.

Open-Circuit or No-Load Test

This test is conducted to determine the iron losses (or core losses) and parameters R_0 and X_0 of the transformer. In this test, the rated voltage is applied to the primary (usually low-voltage winding) while

the secondary is left open circuited. The applied primary voltage V_1 is measured by the voltmeter, the no load current I_0 by ammeter and no-load input power W_0 by wattmeter as shown in Fig.2.24.a. As the normal rated voltage is applied to the primary, therefore, normal iron losses will occur in the transformer core. Hence wattmeter will record the iron losses and small copper loss in the primary. Since no-load current I_0 is very small (usually 2-10 % of rated current). Cu losses in the primary under no-load condition are negligible as compared with iron losses. Hence, wattmeter reading practically gives the iron losses in the transformer. It is reminded that iron losses are the same at all



loads.

Fig: 2.24.a

Iron losses, P_i = Wattmeter reading = W_0
No load current = Ammeter reading = I_0
Applied voltage = Voltmeter reading = V_1

Input power, $W_0 = V_1 I_0 \cos \phi_0$

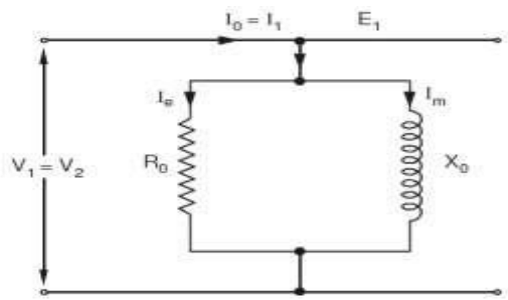
No - load p.f., $\cos\phi = \frac{Wo}{Vo\,Io}$ = no load power factor

$I_m = I_o \sin \phi_o$ = magnetizing component
$I_c = I_o \cos \phi_o$ = Active component

$$R_o = \frac{Vo}{Ic}\ \Omega, \quad X_o = \frac{Vo}{Im}\ \Omega$$

Under no load conditions the PF is very low (near to 0) in lagging region. By using the above data we can draw the equivalent parameter shown in Figure 2.24.b.

Fig: 2.24.b

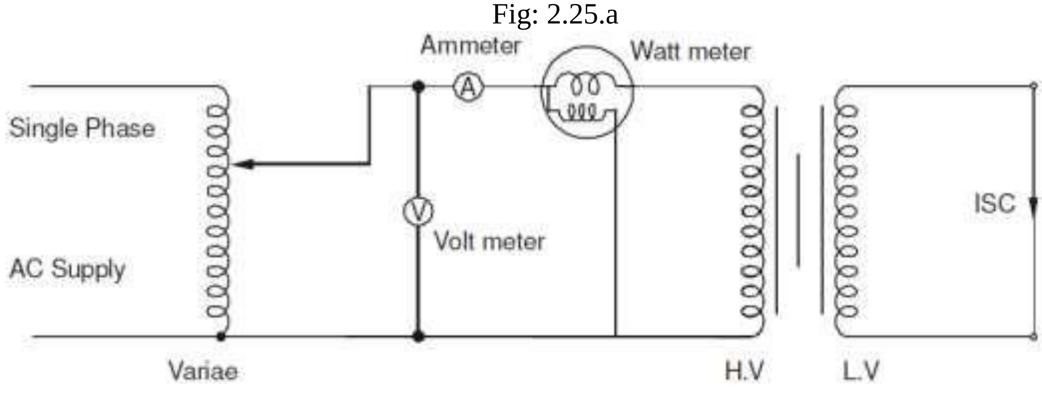


Thus open-circuit test enables us to determine iron losses and parameters R_0 and X_0 of the transformer.

Short-Circuit or Impedance Test

This test is conducted to determine R_{1e} (or R_{2e}), X_{1e} (or X_{2e}) and full-load copper losses of the transformer. In this test, the secondary (usually low-voltage winding) is short-circuited by a thick conductor and variable low voltage is applied to the primary as shown in Fig.2.25. The low input voltage is gradually raised till at voltage V_{SC}, full-load current I_1 flows in the primary. Then I_2 in the secondary also has full-load value since $I_1/I_2 = N_2/N_1$. Under such conditions, the copper loss in the windings is the same as that on full load. There is no output from the transformer under short-circuit conditions. Therefore, input power is all loss and this loss is almost entirely copper loss. It is because iron loss in the core is negligibly small since the voltage V_{SC} is very small. Hence, the wattmeter will practically register the full load copper losses in the transformer windings.

Fig: 2.25.a



Full load Cu loss, PC = Wattmeter reading = W_{sc}
Applied voltage = Voltmeter reading = V_{SC}
F.L. primary current = Ammeter reading = I_1

$Pcu = I_1^2 R_1 + I_1^2 R_2' = I_1^2 R_{1e}$, $R_{1e} = \frac{Pcu}{I1^2}$

Where R_{1e} is the total resistance of transformer referred to primary.

Total impedance referred to primary, $Z1e = \sqrt{Z1e^2 - R1e^2}$,

short – circuit P.F, $\cos \Phi = \frac{Pcu}{Vsc\, I1}$ Thus short-circuit lest gives full-load Cu loss, R1e and X1e.

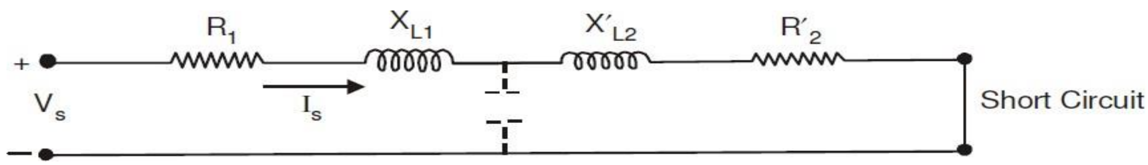


Fig: 2.25.b

From fig: 2.25.b we can calculate,

$$\text{equivalent resistance } R_{eq} = \frac{W_s}{I_s^2} = R_1 + R_2'$$

$$\text{and equivalent impedance } Z_{eq} = \frac{V_s}{I_s}$$

So we calculate equivalent reactance

$$X_{eq} = \sqrt{Z_{eq}^2 - R_{eq}^2} = X_{L1} + X_{L2}'$$

These R_{eq} and X_{eq} are equivalent resistance and reactance of both windings referred in HV side. These are know as equivalent circuit resistance and reactance.

Voltage Regulation of Transformer

Under no load conditions, the voltage at the secondary terminals is E_2 and

$$E_2 \approx V_1 \cdot \frac{N_2}{N_1}$$

(This approximation neglects the drop R_1 and X_{l1} due to small no load current). As load is applied to the transformer, the load current or the secondary current increases. Correspondingly, the primary current.

I_1 also increases. Due to these currents, there is a voltage drop in the primary and secondary leakage reactances, and as a consequence the voltage across the output terminals or the load terminals changes. In quantitative terms this change in terminal voltage is called Voltage

Regulation.

Voltage regulation of a transformer is defined as the drop in the magnitude of load voltage (or secondary terminal voltage) when load current changes from zero to full load value. This is expressed as a fraction of secondary rated voltage.

$$\text{Regulation} = \frac{\text{Secondary terminal voltage at no load} - \text{Secondary terminal voltage at any load}}{\text{Secondary rated voltage}}$$

The secondary rated voltage of a transformer is equal to the secondary terminal voltage at no load (i.e. E_2), this is as per IS.

Voltage regulation is generally expressed as a percentage.

$$\text{Percent voltage regulation (\% VR)} = \frac{E_2 - V_2}{E_2} \times 100.$$

Note that E_2, V_2 are magnitudes, and not phasor or complex quantities. Also note that voltage regulation depends not only on load current, but also on its power factor. Using approximate equivalent circuit referred to primary or secondary, we can obtain the voltage regulation. From approximate equivalent circuit referred to the secondary side and phasor diagram for the circuit.

$$E_2 = V_2 + I_2\ r_{eq}\ \cos\phi_2 \pm I_2\ x_{eq}\ \sin\phi_2$$

where $r_{eq} = r_2 + r_1^1$ (referred to secondary) $x_e = x_2 + x_1^1$ (+ sign applies lagging power factor load and – sign applies to leading pf load).

So
$$\frac{E_2 - V_2}{E_2} = \frac{I_2\ r_{eq}\ \cos\phi_2 \pm I_2\ x_{eq}\ \sin\phi_2}{E_2}$$

$$\frac{E_2 - V_2}{E_2} = \frac{I_2\ r_{eq}}{E_2}\cos\phi_2 \pm \frac{I_2\ x_{eq}}{E_2}\sin\phi_2$$

% Voltage regulation = (% resistive drop) $\cos\phi_2$ ± (% reactive drop) $\sin\phi_2$.

Ideally voltage regulation should be zero.

Parallel Operation of Transformers

It is economical to install numbers of smaller rated transformers in parallel than installing a bigger rated electrical power transformers. This has mainly the following advantages,

To maximize electrical power system efficiency: Generally electrical power transformer gives the maximum efficiency at full load. If we run numbers of transformers in parallel, we can switch on only those transformers which will give the total demand by running nearer to its full load rating for that time. When load increases, we can switch none by one other transformer connected in parallel to fulfil the total demand. In this way we can run the system with maximum efficiency.

To maximize electrical power system availability: If numbers of transformers run in parallel, we can shut down any one of them for maintenance purpose. Other parallel transformers in system will serve the load without total interruption of power.

To maximize power system reliability: if any one of the transformers run in parallel, is tripped due to fault of other parallel transformers is the system will share the load, hence power supply may not be interrupted if the shared loads do not make other transformers over loaded.

To maximize electrical power system flexibility: There is always a chance of increasing or decreasing future demand of power system. If it is predicted that power demand will be increased in future, there must be a provision of connecting transformers in system in parallel to fulfil the extra demand because, it is not economical from business point of view to install a bigger rated single transformer by forecasting the increased future demand as it is unnecessary investment of money. Again if future demand is decreased, transformers running in parallel can be removed from system to balance the capital investment and its return.

Conditions for Parallel Operation of Transformers

When two or more transformers run in parallel, they must satisfy the following conditions for satisfactory performance. These are the conditions for parallel operation of transformers.

- ***Same voltage ratio of transformer.***
- ***Same percentage impedance.***
- ***Same polarity.***
- ***Same phase sequence.***
- ***Same Voltage Ratio***

Same voltage ratio of transformer.

If two transformers of different voltage ratio are connected in parallel with same primary supply voltage, there will be a difference in secondary voltages. Now say the secondary of these transformers are connected to same bus, there will be a circulating current between secondaries and therefore between primaries also. As the internal impedance of transformer is small, a small voltage difference may cause sufficiently high circulating current causing unnecessary extra I2R loss.

Same Percentage Impedance

The current shared by two transformers running in parallel should be proportional to their MVA ratings. Again, current carried by these transformers are inversely proportional to their internal impedance. From these two statements it can be said that, impedance of transformers running in parallel are inversely proportional to their MVA ratings. In other words, percentage impedance or per unit values of impedance should be identical for all the transformers that run in parallel.

Same Polarity

Polarity of all transformers that run in parallel, should be the same otherwise huge circulating current that flows in the transformer but no load will be fed from these transformers. Polarity of transformer means the instantaneous direction of induced emf in secondary. If the instantaneous directions of induced secondary emf in two transformers are opposite to each other when same input power is fed to both of the transformers, the transformers are said to be in opposite polarity. If the instantaneous directions of induced secondary e.m.f in two transformers are same when same input power is fed to the both of the transformers, the transformers are said to be in same polarity.

Same Phase Sequence

The phase sequence or the order in which the phases reach their maximum positive voltage, must be identical for two parallel transformers. Otherwise, during the cycle, each pair of phases will be short circuited.

The above said conditions must be strictly followed for parallel operation of transformers but totally identical percentage impedance of two different transformers is difficult to achieve practically, that is why the transformers run in parallel may not have exactly same percentage impedance but the values would be as nearer as possible.

Why Transformer Rating in kVA?

An important factor in the design and operation of electrical machines is the relation between the life of the insulation and operating temperature of the machine. Therefore, temperature rise resulting from the losses is a determining factor in the rating of a machine. We know that copper loss in a transformer depends on current and iron loss depends on voltage. Therefore, the total loss in a transformer depends on the volt-ampere product only and not on the phase angle between voltage and current i.e., it is independent of load power factor. For this reason, the rating of a transformer is in kVA and not kW.

Three Phase Transformer

In general, for transformation, transmission and utilization of electric energy, it is economical to use the three phase system rather than the single phase. For three phase transformation, two arrangements are possible. First is to use a bank of three single phase transformer and the second, a single three phase transformer with the primary and secondary of each phase wound on three lags of a common core. The advantages of a single unit of 3-phase transformer as compared to a bank of three single phase transformer are the cost is much less, occupies less floor space for equal rating and weighs less.

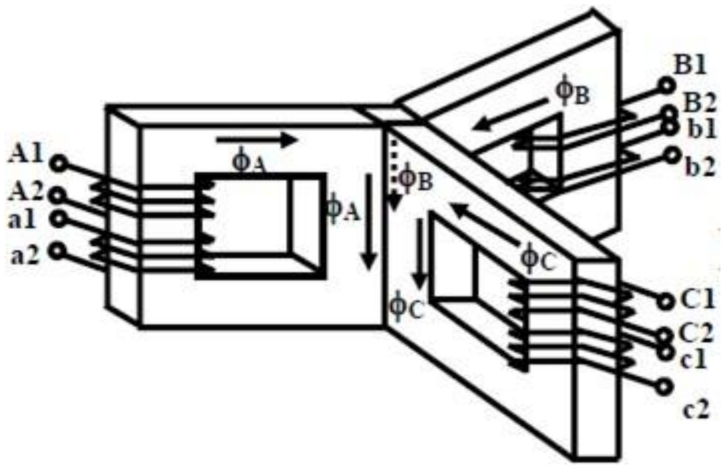


Fig.4.1 A conceptual three phase transformer

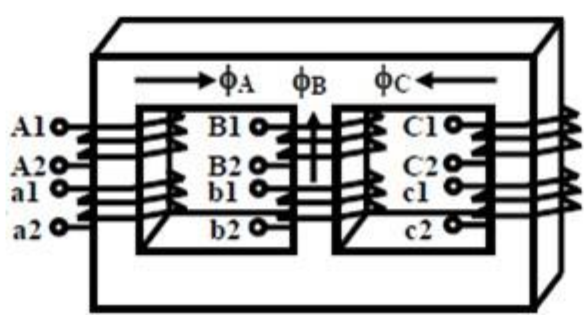


Fig.4.2 A practical three phase core type three phase transformers

4.1 Three phase transformer connections

A variety of connections are possible on each side of a 3-phase transformer. The three phases could be connected in star, delta, open delta or zig-zag star. Each of the three phases could have two windings or may have auto connection. Further, certain types of connections require a third winding known as tertiary.

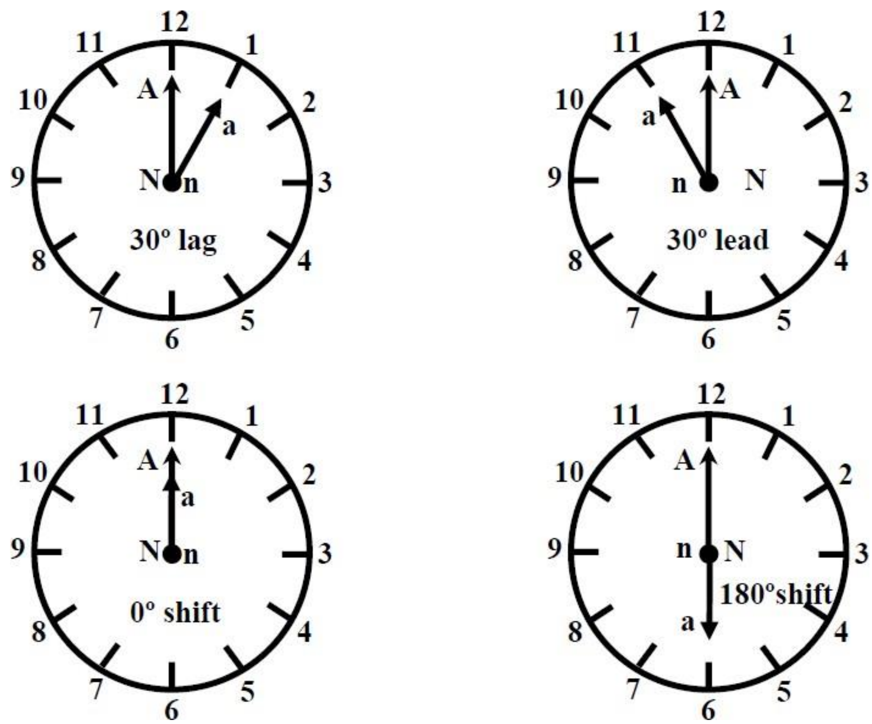


Fig.4.3 Clock convention representing vector groups

The identical single phase transformers can be suitably inter-connected and used instead of a single unit 3—phase transformer. The single unit 3 phase transformer is housed in a single tank. But the transformer bank is made up of three separate single phase transformers each with its own, tanks and bushings. This method is preferred in mines and high altitude power stations because transportation becomes easier. Bank method is adopted also when the voltage involved is high because it is easier to provide proper insulation in each single phase transformer.

As compared to a bank of single phase transformers, the main advantages of a single unit 3-phase transformer are that it occupies less floor space for equal rating, less weight costs about 20% less and further that only one unit is to be handled and connected.

There are various methods available for transforming 3 phase voltages to higher or lower 3 phase voltages.

The most common connections are

(i) star — star (ii) Delta—Delta (iii) Star —Delta (iv) Delta — Star.

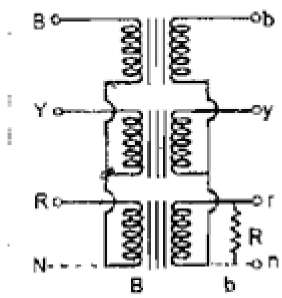


Fig 4.5 Star-star connection

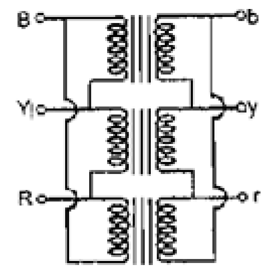


Fig. 4.6 Delta-delta connection

The star-star connection is most economical for small, high voltage transformers because the number of turns per phase and the amount of insulation required is minimum (as phase voltage is only 1/3 of line voltage. In fig. 4.5 a bank of three transformers connected in star on both the primary and the secondary sides is shown. The ratio of line voltages on the primary to the secondary sides is the same as a transformation ratio of single phase transformer.

The delta— delta connection is economical for large capacity, low voltage transformers in which insulation problem is not a serious one. The transformer connection are as shown in fig. 4.6.

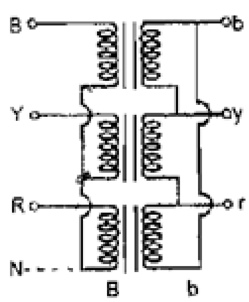


Fig. 4.7 Star-delta connection

The main use of star-delta connection is at the substation end of the transmission line where the voltage is to be stepped down. The primary winding is star connected with grounded neutral as shown in Fig. 4.7. The ratio between the secondary and primary line voltage is 1/3 times the transformation ratio of each single phase transformer. There is a 30° shift between the primary and secondary line voltages which means that a star-delta transformer bank cannot be paralleled with either a star-star or a delta-delta bank.

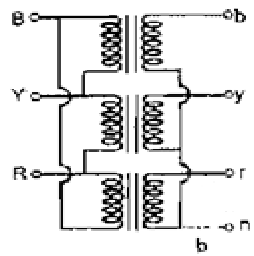


Fig. 4.8 Delta-star connection

Delta-Star connection is generally employed where it is necessary to step up the voltage. The connection is shown in fig. 4.8. The neutral of the secondary is grounded for providing 3-phase, 4-wire service. The connection is very popular because it can be used to serve both the 3-phase power equipment and single phase lighting circuits.

<u>Delta/delta (Dd0, Dd6) connection</u> :

The connection of Dd0 is shown in fig. 4.10 and the voltages on primary and secondary sides is also shown on the phasor diagram. The phase angle difference between the phase voltage of high voltage side and low voltage side is zero degree (0°).

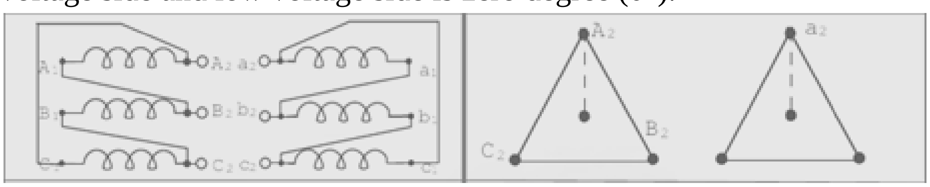


Fig 4.10 Dd0 connection and phasor diagram

The connection of Dd6 is shown in fig. 4.11 and the voltages on primary and secondary sides is also shown on the phasor diagram. The phase angle difference between the phase voltage of high voltage side and low voltage side is 180°.

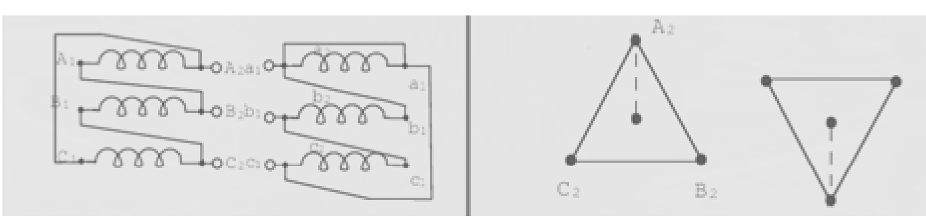


Fig 4.11 Dd6 connection and phasor diagram

This connection proves to be economical for large low voltage transformers as it increases number of turns per phase. Primary side line voltage is equal to secondary side line voltage. Primary side phase voltage is equal to secondary side phase voltage. There is no phase shift between primary and secondary voltages for Dd0 connection. There is 180° phase shift between primary and secondary voltages for Dd6 connection.

Star/star (YyO, Yy6) connection

This is the most economical one for small high voltage transformers. Insulation cost is highly reduced. Neutral wire can permit mixed loading. Triplen harmonics are absent in the lines. These triplen harmonic currents cannot flow, unless there is a neutral wire. This connection produces oscillating neutral. Three phase shell type units have large triplen harmonic phase voltage. However three phase core type transformers work satisfactorily. A tertiary mesh connected winding may be required to stabilize the oscillating neutral due to third harmonics in three phase banks.
The connection of Yy0 is shown in fig. 4.12 and the voltages on primary and secondary sides is also shown on the phasor diagram. The phase angle difference between the phase voltage of high voltage side and low voltage side is zero degree (0°).

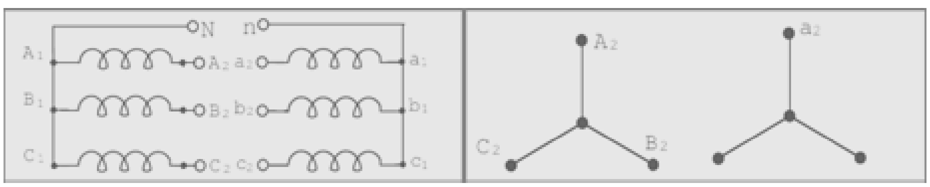


Fig .4.12 Yy0 connection and phasor diagram

The connection of Yy6 is shown in fig. 4.13 and the voltages on primary and secondary sides is also shown on the phasor diagram. The phase angle difference between the phase voltage of high voltage side and low voltage side is 180°.

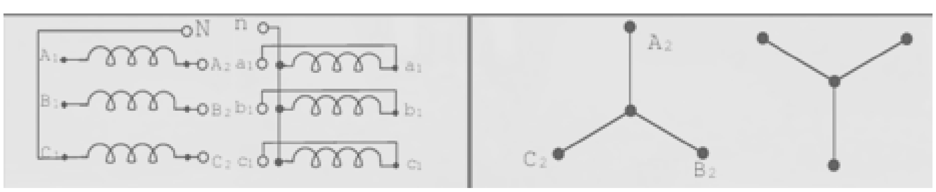


Fig 4.13. Yy6 connection and phasor diagram

Star/Delta connection(Yd1/Yd11)

There is a +30 Degree or -30 Degree Phase Shift between Secondary Phase Voltage to Primary Phase Voltage. The connection of Yd1 is shown in fig. 4.14 and the voltages on primary and secondary sides is also shown on the phasor diagram. The phase angle difference between the phase voltage of high voltage side and low voltage side is -30°.

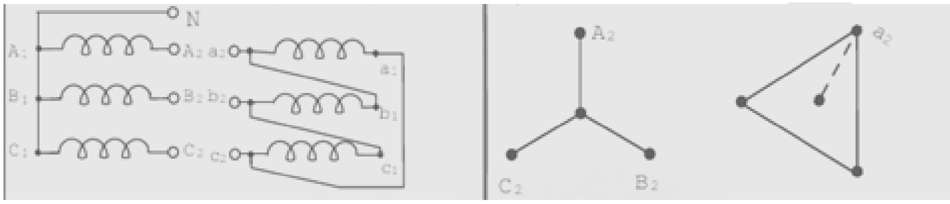


Fig 4.14. Yd1 connection and phasor diagram

The connection of Yd11 is shown in fig. 4.15 and the voltages on primary and secondary sides is also shown on the phasor diagram. The phase angle difference between the phase voltage of high voltage side and low voltage side is 30°.

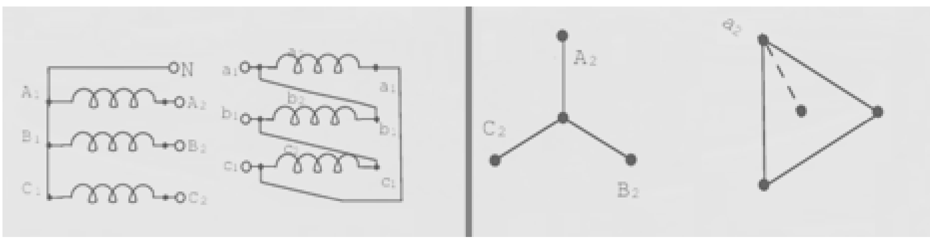


Fig 4.15. Yd11 connection and phasor diagram

<u>Delta-star connection (Dy1/Dy11)</u>

In this type of connection, the primary connected in delta fashion while the secondary current is connected in star. There is s +30 Degree or -30 Degree Phase Shift between Secondary Phase Voltage to Primary Phase Voltage.

The connection of Dy1 is shown in fig. 4.16 and the voltages on primary and secondary sides is also shown on the phasor diagram. The phase angle difference between the phase voltage of high voltage side and low voltage side is -30°.

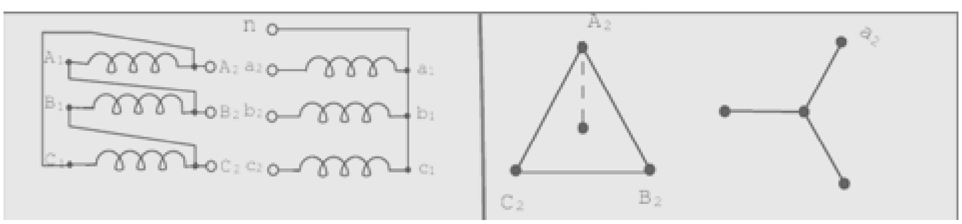


Fig 4.16. Dy1 connection and phasor diagram

The connection of Dy11 is shown in fig. 4.17 and the voltages on primary and secondary sides is also shown on the phasor diagram. The phase angle difference between the phase voltage of high voltage side and low voltage side is 30°.

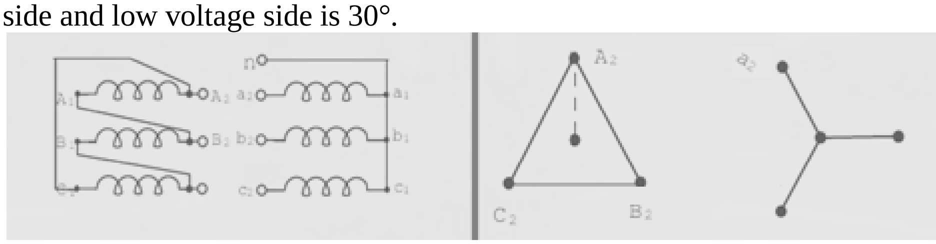


Fig 4.17. Dy11 connection and phasor diagram

Delta-zigzag and Star zigzag connections (Dz0/Dz6 & Yz1/Yz6) –

The connection of Dz0 is shown in fig. 4.18 and the voltages on primary and secondary sides is also shown on the phasor diagram. The phase angle difference between the phase voltage of high voltage side and low voltage side is 0°.

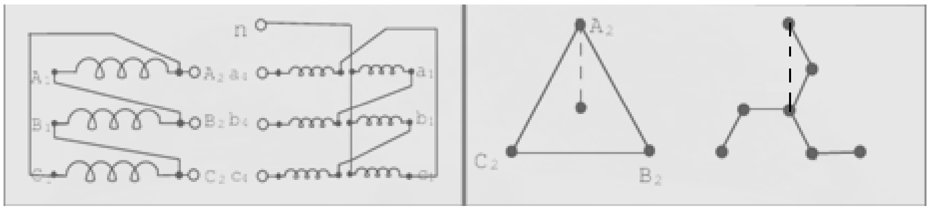


Fig 4.18. Dz0 connection and phasor diagram

The connection of Dz6 is shown in fig. 4.19 and the voltages on primary and secondary sides is also shown on the phasor diagram. The phase angle difference between the phase voltage of high voltage side and low voltage side is 180°.

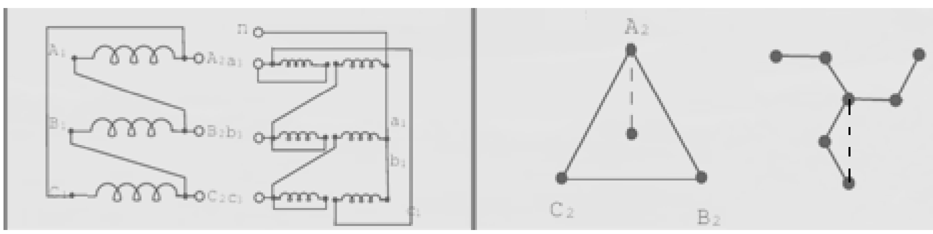


Fig 4.19. Dz6 connection and phasor diagram

The connection of Yz1 is shown in fig. 4.20 and the voltages on primary and secondary sides is also shown on the phasor diagram. The phase angle difference between the phase voltage of high voltage side and low voltage side is -30°.

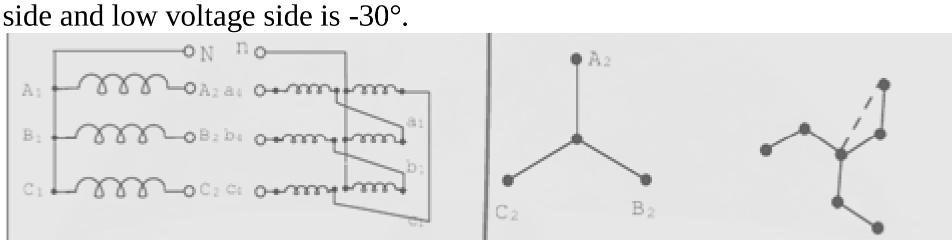


Fig 4.20. Yz1 connection and phasor diagram

The connection of Yz11 is shown in fig. 4.21 and the voltages on primary and secondary sides is also shown on the phasor diagram. The phase angle difference between the phase voltage of high voltage side and low voltage side is 30°.

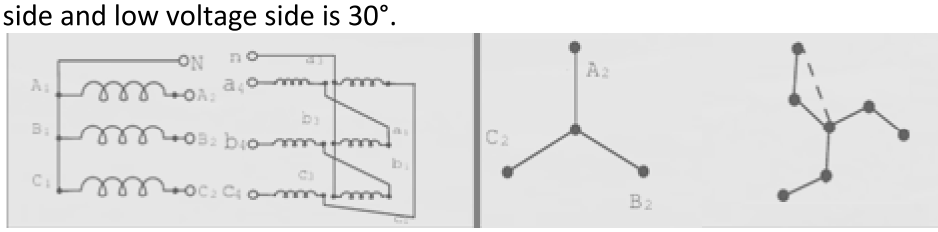


Fig 4.22 Yz11 connection and phasor diagram

Scott connection

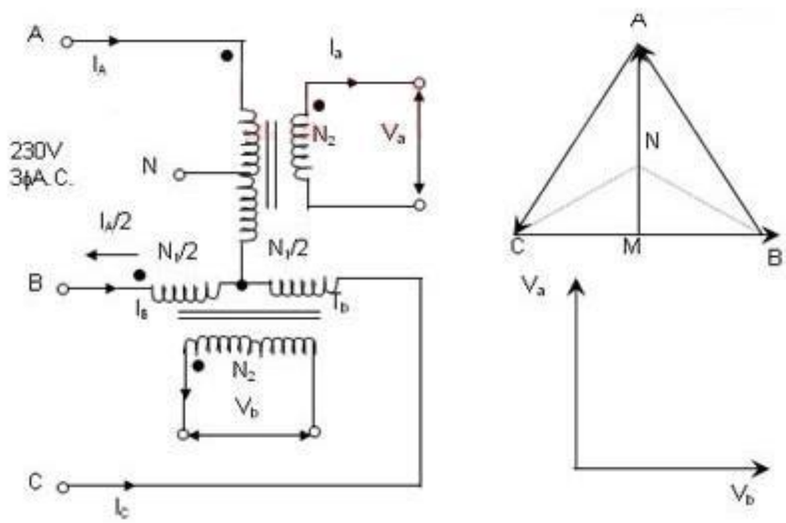
There are two main reasons for the need to transform from three phases to two phases,

1. To give a supply to an existing two phase system from a three phase supply.
2. To supply two phase furnace transformers from a three phase source.

Two-phase systems can have 3-wire, 4-wire, or 5-wire circuits. It is needed to be considering that a two-phase system is not 2/3 of a three-phase system. Balanced three-wire, two-phase circuits have two phase wires, both carrying approximately the same amount of current, with a neutral wire carrying 1.414 times the currents in the phase wires. The phase-to-neutral voltages are 90° out of phase with each other.

Two phase 4-wire circuits are essentially just two ungrounded single-phase circuits that are electrically 90° out of phase with each other. Two phase 5-wire circuits have four phase wires plus a neutral; the four phase wires are 90° out of phase with each other.

A Scott-T transformer (also called a Scott connection) is a type of circuit used to derive two-phase power from a three-phase source or vice-versa. The Scott connection evenly distributes a balanced load between the phases of the source. Scott T Transformers require a three phase power input and provide two equal single phase outputs called Main and Teaser. The MAIN and Teaser outputs are 90 degrees out of phase. The MAIN and the Teaser outputs must not be connected in parallel or in series as it creates a vector current imbalance on the primary side. MAIN and Teaser outputs are on separate cores. An external jumper is also required to connect the primary side of the MAIN and Teaser sections. The schematic of a typical Scott T Transformer is shown below:



4.23 Connection diagram of Scott-connected transformer and vector relation of input and output

From the phasor diagram it is clear that the secondary voltages are of two phases with equal magnitude and 90° phase displacement.

Scott T Transformer is built with two single phase transformers of equal power rating. Assuming the desired voltage is the same on the two and three phase sides, the Scott-T transformer connection consists of a center-tapped 1:1 ratio main transformer, T1, and an 86.6% (0.5√3) ratio teaser transformer, T2. The center-tapped side of T1 is connected between two of the phases on the three-phase side. Its center tap then connects to one end of the lower turn count side of T2, the other end connects to the remaining phase. The other side of the transformers then connects directly to the two pairs of a two-phase four-wire system.

If the main transformer has a turn's ratio of 1: 1, then the teaser transformer requires a turn's ratio of 0.866: 1 for balanced operation. The principle of operation of the Scott connection can be most easily seen by first applying a current to the teaser secondary windings, and then applying a current to the main secondary winding, calculating the primary currents separately and superimposing the results. The primary three-phase currents are balanced; i.e., the phase currents have the same magnitude and their phase angles are 120° apart. The apparent power supplied by the main transformer is greater than the apparent power supplied by the teaser transformer. This is easily verified by observing that the primary currents in both transformers have the same magnitude; however, the primary voltage of the teaser transformer is only 86.6% as great as the primary voltage of the main transformer. Therefore, the teaser transforms only 86.6% of the apparent power transformed by the main.
 The total real power delivered to the two phase load is equal to the total real power supplied from the three-phase system, the total apparent power transformed by both transformers is greater than the total apparent power delivered to the two-phase load.

 The apparent power transformed by the teaser is 0.866 X IH1= 1.0 and the apparent power transformed by the main is 1.0X IH2 =1.1547 for a total of 2.1547 of apparent power transformed.

 The additional 0.1547 per unit of apparent power is due to parasitic reactive power owing between the two halves of the primary winding in the main transformer.

 Single-phase transformers used in the Scott connection are specialty items that are virtually impossible to buy ''off the shelf '' nowadays. In an emergency, standard distribution transformers can be used.

If desired, a three phase, two phase, or single phase load may be supplied simultaneously using scott-connection. The neutral points can be available for grounding or loading purposes. The Scott T connection in theory would be suitable for supplying a three, two and single phase load simultaneously, but such loads are not found together in modern practice.

The Scott T would not be recommended as a connection for 3 phase to 3 phase applications for the following reasons:

The loads of modern buildings and office buildings are inherently unbalanced and contain equipment that can be sensitive to potential voltage fluctuations that may be caused by the Scott T design.
A properly sized Scott T transformer will have to be a minimum of 7.75% larger than the equivalent Delta-Wye transformer. Properly sized, it would be a bulkier and heavier option and should not be considered a less expensive solution.

Open Delta or V-Connection

As seen previously in connection of three single phase transformers that if one of the transformers is unable to operate then the supply to the load can be continued with the remaining two transformers at the cost of reduced efficiency. The connection that obtained is called V-V connection or open delta connection.

Consider the Fig. 4.24 in which 3 phase supply is connected to the primaries. At the secondary side three equal three phase voltages will be available on no load.
The voltages are shown on phasor diagram. The connection is used when the three phase load is very very small to warrant the installation of full three phase transformer.

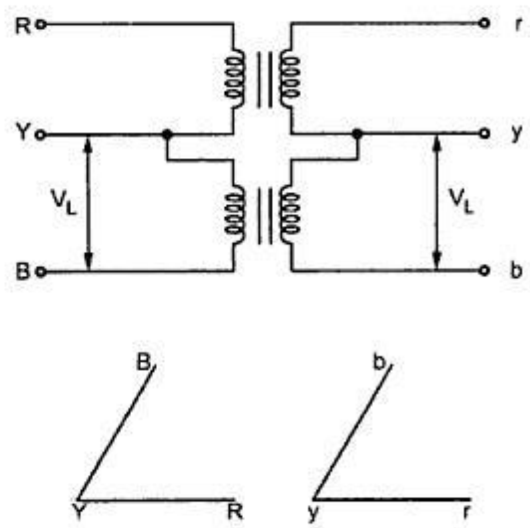


Fig. 4.24 Open delta connection of transformer at noload

If one of the transformers fails in Δ - Δ bank and if it is required to continue the supply even though at reduced capacity until the transformer which is removed from the bank is repaired or a new one is installed then this type of connection is most suitable.
When it is anticipated that in future the load increase, then it requires closing of open delta. In such cases open delta connection is preferred. It can be noted here that the removal of one of the transformers will not give the total load carried by V - V bank as two third of the capacity of Δ - Δ bank.
The load that can be carried by V - V bank is only 57.7% of it.

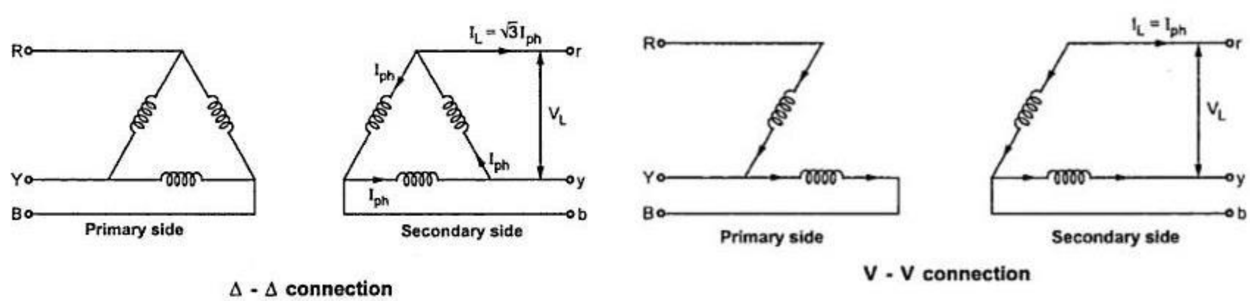


Fig. 4.25 Delta-delta and V-V connection

Parallel operation of three phase transformer

Advantages of using transformers in parallel

1.To maximize electrical power system efficiency: Generally electrical power transformer gives the maximum efficiency at full load. If we run numbers of transformers in parallel, we can switch on

only those transformers which will give the total demand by running nearer to its full load rating for that time. When load increases, we can switch none by one other transformer connected in parallel to fulfill the total demand. In this way we can run the system
with maximum efficiency.

2. To maximize electrical power system availability: If numbers of transformers run in parallel, we can shut down any one of them for maintenance purpose. Other parallel transformers in system will serve the load without total interruption of power.

3. To maximize power system reliability: If any one of the transformers run in parallel, is tripped due to fault of other parallel transformers is the system will share the load, hence power supply may not be interrupted if the shared loads do not make other transformers over loaded.

4. To maximize electrical power system flexibility: There is always a chance of increasing or decreasing future demand of power system. If it is predicted that power demand will be increased in future, there must be a provision of connecting transformers in system in parallel to fulfill the extra demand because, it is not economical from business point of view to install a bigger rated single transformer by forecasting the increased future demand as it is unnecessary investment of money. Again if future demand is decreased, transformers running in parallel can be removed from system to balance the capital investment and its return.

4.10.2 Conditions for parallel operation

Certain conditions have to be met before two or more transformers are connected in parallel and share a common load satisfactorily. They are,

1. The voltage ratio must be the same.

2. The per unit impedance of each machine on its own base must be the same.

3. The polarity must be the same, so that there is no circulating current between the transformers.

4. The phase sequence must be the same and no phase difference must exist between the voltages of the two transformers.

Autotransformer

It is a transformer with one winding only, part of this being common to both primary and secondary. In this transformer the primary and secondary are not electrically isolated from each other as is the case with a two winding transformer. But its theory and operation are similar to those of a two winding transformer. Because of one winding, it uses less copper and hence is cheaper. It is used where transformation ratio offers little from unity.

Weight of copper in autotransformer

$(W_a) = (1 - K) \times (Weight\ of\ copper\ in\ ordinary\ transormer(W_o))$

Hence, saving $= W_0 - W_a$

$= W_0 - (1 - K)W_o = KW_o$

Hence, saving will increase as K approaches unity.

Power conducted inductively $= Inputpower \times (1 - K)$

Power conducted directly $= K \times Inputpower$

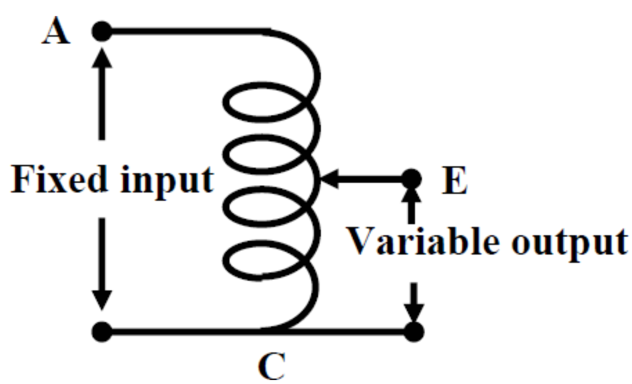


Fig.5.1 Schematic representation of autotransformer

Conventional transformer connected as Autotransformer

Any two winding transformer can be converted into an autotransformer either step-down or step- up. If we employ additive polarity between the high voltage and low voltage sides, we get a step-up transformer. If, however, we use the subtractive polarity, we get a step-down autotransformer. The connections are given in fig.2.

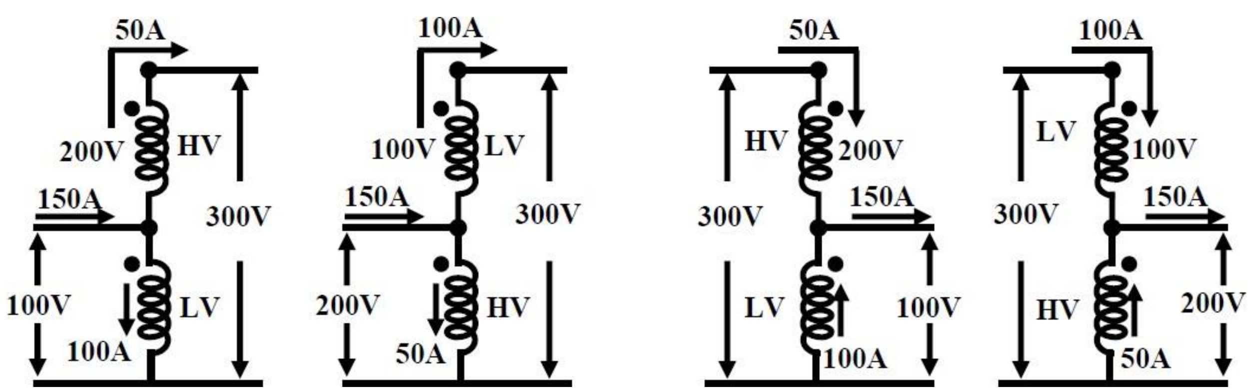


Fig.5.2 A two winding transformer connected as an autotransformer in various ways

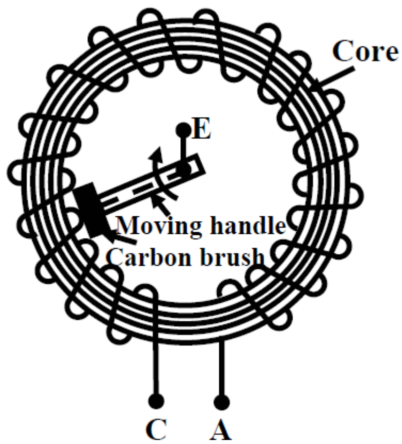


Fig.5.3 Autotransformer or Variac

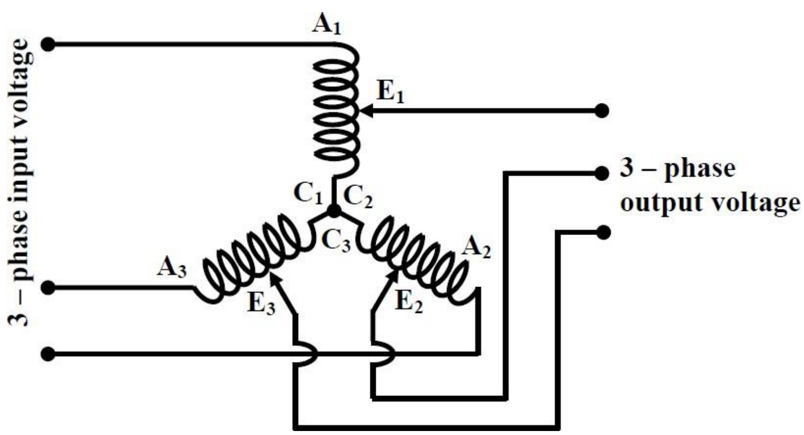


Fig.5.4 3 – Phase autotransformer connection

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