# GURUNANAK INSTITUTE OF TECHNOLOGY

## Department of Electrical Engineering

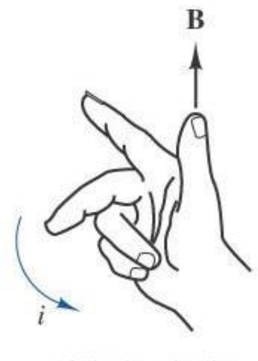
# ELECTRICAL MACHINES-I

# EE401

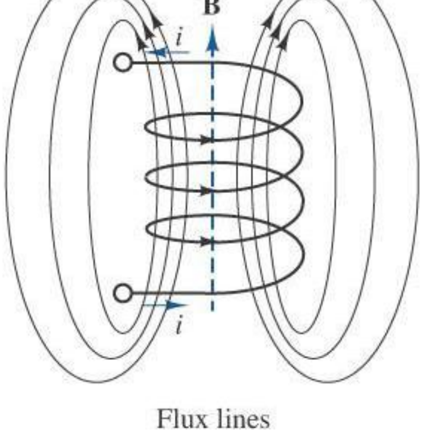
# Gurunanak Institute of Technology

**Department of Electrical Engineering**

# Magnetic Circuits




Right-hand rule




Flux lines

- Magnetomotive Force
  - The “driving force” that causes a magneticfield
  - Symbol, *F*
  - Definition, $F = NI$

  Units, Ampere-turns, (A-t)

- Magnetic Field Intensity
  - mmf gradient, or mmf per unit length
  - Symbol, H
  - Definition, $H = F/l = NI/l$
  - Units, (A-t/m)

- Flux Density
  - he concentration of the lines of force in amagnetic circuit
  - Symbol, B
  - Definition, $B = \Phi/A$
  - Units, (Wb/$m^2$), or T (Tesla)

- Reluctance
  - The measure of “opposition” the magneticcircuit offers to the flux
  - The analog of Resistance in an electricalcircuit
  - Symbol, *R*
  - Definition, $R = F/\Phi$
  - Units, (A-t/Wb)

- Permeability
  - Relates flux density and field intensity
  - Symbol, μ
  - Definition, $\mu = B/H$
  - Units, (Wb/A-t-m)

What Is Ampere’s Law?

According to Ampere’s law, magnetic fields are related to the electric current produced in them. The law specifies the magnetic field that is associated with a given current or vice-versa, provided that the electric field doesn’t change with time.

**Ampere’s Law can be stated as:**

“The magnetic field created by an electric current is proportional to the size of that electric current with a constant of proportionality equal to the permeability of free space.”
The equation explaining Ampere’s law which is the final Maxwell’s equation is given below:

**Maxwell’s Equation**

What Is Ampere’s Circuital Law?

Ampere’s circuital law can be written as the line integral of the magnetic field surrounding closed-loop equals the number of times the algebraic sum of currents passing through the loop.

$$\nabla \times \mathbf{H} = \frac{\partial \mathbf{D}}{\partial t} + \mathbf{J}$$

Maxwell’s Equation

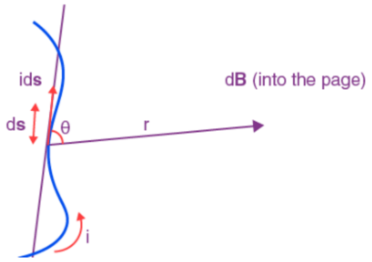
Suppose a conductor carries a current I, then this current flow generates a magnetic field that surrounds the wire.

The equation’s left side describes that if an imaginary path encircles the wire and the magnetic field is added at every point, then it is numerically equal to the current encircled by this route, indicated by $\mathbf{I_{enc}}$.

$$\oint \mathbf{H} \cdot d\mathbf{L} = I_{enc}$$

Biot-Savart Law

Biot-Savart’s law is an equation that gives the magnetic field produced due to a current carrying segment. This segment is taken as a vector quantity known as the current element.



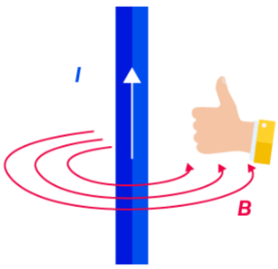

Consider a current carrying wire ‘i’ in a specific direction as shown in the above figure. Take a small element of the wire of length ds. The direction of this element is along that of the current so that it forms a vector id.

To know the magnetic field produced at a point due to this small element, one can apply Biot-Savart’s Law. Let the position vector of the point in question drawn from the current element be **r** and the angle between the two be θ. Then,

$$dB| = \left(\frac{\mu_0}{4\pi}\right)\left(\frac{Ids\ sin\theta}{r^2}\right)$$

Where, $\mu_0$ is the permeability of free space and is equal to $4\pi \times 10^{-7}$ $TmA^{-1}$.

The direction of the magnetic field is always in a plane perpendicular to the line of element and position vector. It is given by the right-hand thumb rule where the thumb points to the direction of conventional current and the other fingers show the magnetic field’s direction.




In the figure shown above, the direction of the magnetic field is pointing into the page.

Applications of Biot-Savart’s Law

Some of Biot-Savart’s Law applications are given below.

- We can use Biot–Savart law to calculate magnetic responses even at the atomic or molecular level.
- It is also used in aerodynamic theory to calculate the velocity induced by vortex lines.

## Importance of Biot-Savart Law

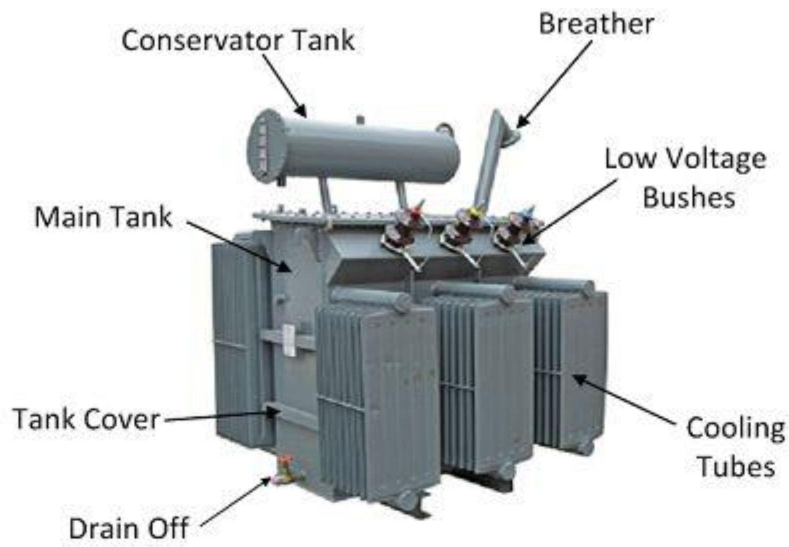
Following are the importance of the Biot-Savart law:

- Biot-Savart law is similar to Coulomb's law in electrostatics.
- The law is applicable for very small conductors too which carry current.
- The law is applicable for symmetrical current distribution.

# Single Phase Transformer 1

A Transformer is a static electrical machine which transfers AC electrical power from one circuit to the other circuit at the constant frequency, but the voltage level can be altered that means voltage can be increased or decreased according to the requirement.

It works on the principle of Faraday's Law of Electromagnetic Induction which states that "the magnitude of voltage is directly proportional to the rate of change of flux."




## Necessity of a Transformer

Usually, electrical power is generated at 11Kv. For economical reasons AC power is transmitted at very high voltages say 220 kV or 440 kV over long distances. Therefore a step-up transformer is applied at the generating stations. Now for safety reasons the voltage is stepped down to different levels by step down transformer at various substations to feed the power to the different locations and thus the utilization of power is done at 400/230 V.


If ($V_2 > V_1$) the voltage is raised on the output side and is known as Step-up transformer

If ($V_2 < V_1$) the voltage level is lowered on the output side and is known as Step down transformer

## Construction of a Transformer

The transformer mainly consists of the Magnetic circuit, electric circuit, dielectric circuit, tanks and accessories. The main elements of the transformer are the primary and secondary windings and the steel core. The core of the transformer is made up of silicon steel in order to provide the continuous magnetic path. Usually, the core of the transformer is laminated for minimizing the eddy current loss.

## Magnetic circuit

The magnetic circuit of a transformer consists of core and yoke. The circuit provides the path to the flow of magnetic flux. The transformer consists of laminated steel core and the two coils. The two coils are insulated from each other and also from the core. The core of the transformer is constructed from laminations of sheet steel or silicon steel assembled to provide a continuous magnetic path. At usual flux densities, the silicon steel material has low hysteresis losses.

The vertical position on which the coil is wound is called the limb while the horizontal position is known as the yoke.

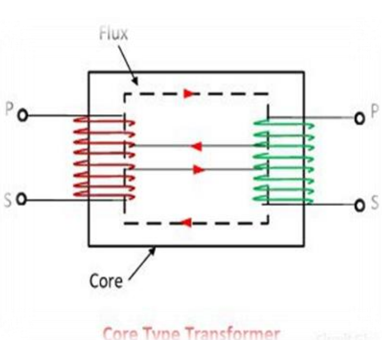
## Electric circuit

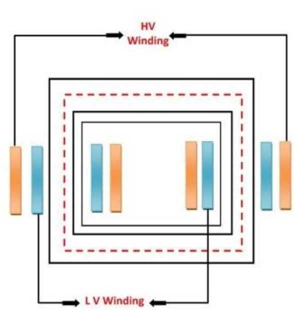
Construction of electric circuit of transformer consists of primary and secondary windings usually made of copper. The Conductors of rectangular cross section are generally used for low voltages winding and also for the high voltage winding for large transformers. Conductors of the circular cross-sectional area are used for high voltage winding in the small transformer.

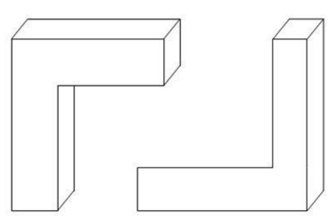
According to the core construction and the manner in which the primary and secondary windings are placed around it, the transformer is named as core type and shell type.

## Core Type Transformer

In a simple core type construction of the transformer, rectangular frame laminations are formed to build the core of the transformer. The laminations are cut in the form of L-shape strips as shown in the figure below. In order to avoid high reluctance at the joints where laminations are butted against each other, the alternate layers are placed differently to eliminate the continuous joints.



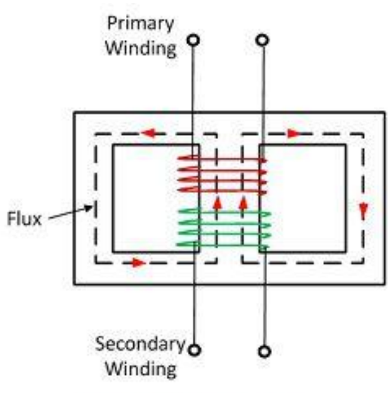



The primary and the secondary windings are interleaved to reduce the leakage flux. Half of the each winding are placed side by side or concentrically on either limb of the core.

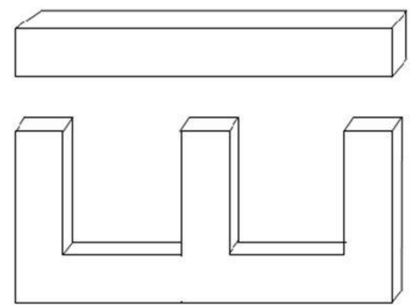
While placing these windings an insulation of Bakelite former is provided between the core and low voltage winding (LV), between the two windings that is between LV and high voltage (HV) windings and also in between coils and yoke an also in between HV limb and yoke as shown in the figure below. To reduce the insulation, the low voltage winding is always placed nearer to the core.

## Shell Type Transformer

In shell type transformer the individual laminations are cut in the form of long strips of E and I shape as shown in the figure below. It has two magnetic circuits, and the core has three limbs. The central limb carries whole of the flux where as the side limbs carry half of the flux. Therefore, the width of the central is double to that of the outer limbs.



Shell Type Transformer



The leakage flux is reduced by the subdivision of the windings which in return have lesser reactance's. Both the primary and the secondary windings are placed on the central limb side by side. The low voltage winding is placed nearer to the core and the high voltage winding is placed outside the low voltage winding. To reduce the cost of lamination between the core and the low voltage winding. The windings are formed and is wound to the cylindrical shape and then the core laminations are inserted later.

## Dielectric Circuit

The dielectric circuit consists of insulations used in different places in the transformer to insulate the conducting parts. The core is laminated to minimize the eddy current losses. The laminations are insulated from each other by a light coating of varnish or by an oxide layer. The thickness of laminations varies from 0.35mm to 0.5mm for a frequency of 50 Hz.

## Tanks and Accessories

Other different parts and accessories are also fitted on the transformer for its efficient work as well as for longer life and better services of the transformer. They are as follows

## Conservator

The Conservator is a cylindrical tank placed on the top or on the roof of the transformer main tank. A large cover is provided which can be opened from time to time for the proper maintenance and cleaning of the transformer. It acts as a reservoir for the transformer insulating oil.

When the transformer is fully loaded and the temperature of the transformer rises high, an increase in the volume of the air inside the transformer takes place. As the level of the oil increases and decreases simultaneously, thus, a conservator provides adequate space for this expanded oil inside the transformer.

## Breather

As in the human body, there is a heart similarly a breather acts as a heart for the transformer. When the temperature of the transformer rises, the insulating oil in the transformer gets heated up. This oil expands and contracts. When the oil heats up and expands the transformer breaths air in and thus the oil gets cooled and the level of oil goes down and the air is absorbed in it. This process of taking air in and out is called breathing of the transformer.

The level of oil in the chamber increases and decreases when the breather takes the air in and out for cooling of the oil. This air carries moisture, which contaminates the oil and thus the quality of oil gets deteriorate. For eliminating this moisture content , the breather is filled with Silica Gel. The main function of the silica gel is to separate moisture from the oil, maintaining the quality of the insulating oil. Initially, the colour of the silica gel is blue and as it absorbs the moisture from the oil its turns into pink colour.

Fresh Silica gels dry down the air to a dew point below -40 degrees Celsius.

## Explosion Vent

The explosion vent is a thin aluminum pipe placed at both the ends of the transformer to prevent the transformer from the damage. When the temperature increases in the transformer drastically and the excessive pressure is created inside the transformer, the explosive vent helps in releasing the pressure.

## Radiator

The main function of the radiator is to cool the oil in the transformer. Radiator is the detachable device whose upper and lower portion is connected by a valve to the transformer tank. When the transformer cleaning and maintenance is done the valve prevent the draining of the oil when the radiator is detached from the transformer.

When the transformer is in the working conditions, the oil of the transformer gets heated and moves up in the main tank and enters into the radiator through the upper valve, where it gets cooled and from the lower valve of the radiating unit the oil again enters the transformer tank and this process continues.

## Bushings

The Bushings in the transformer are the insulting device which allows an electric conductor to pass electrical energy safely through it. It provides electrical field strength to the insulation of the conductors to withstand if a large amount of electric energy passes through it. Solid porcelain type bushing is used in smaller transformer and oil filled condenser type bushing is used in large transformer.

The most common cause of the failure of the bushing resulting in damage of the transformer is the entrance of the moisture. The power factor of the bushing will always be in stable condition, but if the variation is seen in the power factor that means there is deterioration in the insulation. This can be identified by the tests known as acceptance or routine test and Double Power Factor Test.

## Types of Transformer

The various types are described below

1. **Position of the windings concerning the core**

- Core type
- Shell type

2. **According to the transformation ratio or number of turns in the windings**

- Step up
- Step down

3. **Types of services**

- Power transformer
- Distribution transformer
- Instrument transformer
  - Current transformer
  - Potential transformer
  - Auto-transformer

4. **On the basis of the supply**

- Single phase
- Three phase

5. **On the basis of cooling**

- Air Natural (AN) or Self air cooled or dry type
- Air Forced (AF) or Air Blast type
- Oil Natural Air Natural (ONAN)
- Oil Natural Air Forced (ONAF)

- Oil Forced Air Forced (OFAF)
- Oil Natural Water Forced (ONWF)
- Oil Forced Water Forced (OFWF)

## Difference between Core Type and Shell Type Transformer

One of the major differences between the core type and the shell type transformers is that in core type transformer the winding encircles the core, whereas, in shell type transformer, the core encircles the winding of the transformer. Some other differences between them are explained below in the form of the comparison chart.

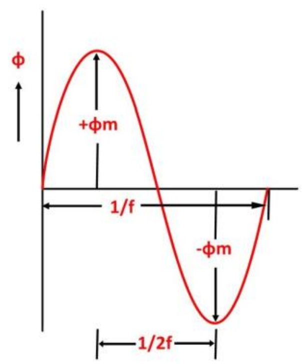
| Basis for Comparison | Core Type Transformer | Shell Type Transformer |
|---|---|---|
| Definition | The winding surround the core. | The cores surround the winding. |
| Lamination Shape | The lamination is cut in the form of the L strips. | Lamination are cut in the form of the long strips of E and L. |
| Cross Section | Cross-section may be square, cruciform and three stepped | The cross section is rectangular in shape. |
| Copper Require | More | Less |
| Other Name | Concentric Winding or Cylindrical Winding. | Sandwich or Disc Winding |
| Limb | Two | Three |
| Insulation | More | Less |
| Flux | The flux is equally distributed on the side limbs of the core. | Central limb carry the whole flux and side limbs carries the half of the flux. |
| Winding | The primary and secondary winding are placed on the side limbs. | Primary and secondary windings are placed on the central limb |
| Magnetic Circuit | Two | One |
| Losses | More | Less |

| | | |
|---|---|---|
| Maintenance | Easy | Difficult |
| Mechanical Strength | Low | High |
| Output | Less | High |
| Natural Cooling | Does not Exist | Exist |

## EMF Equation of a Transformer

When a sinusoidal voltage is applied to the primary winding of a transformer, alternating flux $\phi_m$ sets up in the iron core of the transformer. This sinusoidal flux links with both primary and secondary winding. The function of flux is a sine function. The rate of change of flux with respect to time is derived mathematically.

The derivation of EMF Equation of the transformer is shown below. Let




- $\phi_m$ be the maximum value of flux in Weber
- f be the supply frequency in Hz
- $N_1$ is the number of turns in the primary winding
- $N_2$ is the number of turns in the secondary winding

$\Phi$ is the flux per turn in Weber
As shown in the above figure that the flux changes from + $\phi_m$ to – $\phi_m$ in half a cycle of 1/2f seconds.

By Faraday's Law

Let $E_1$ is the emf induced in the primary winding

$$E_1 = -\frac{d\psi}{dt} \ldots\ldots\ldots (1)$$

Where $\Psi = N_1\phi$

Therefore, $E_1 = -N_1 \frac{d\varphi}{dt}$ ………(2)

Since $\phi$ is due to AC supply $\phi = \phi_m$ Sinwt

$$E_1 = -N_1 \frac{d}{dt} (\varphi_m \text{ Sinwt})$$

$$E_1 = -N_1 w\varphi_m \text{ Coswt}$$

$$E_1 = N_1 w\varphi_m \text{ Sin}(wt - \pi/2) \ldots\ldots\ldots (3)$$

So the induced emf lags flux by 90 degrees.

Maximum valve of emf

$$E_1 max = N_1 w\varphi_m \ldots\ldots\ldots (4)$$

But w = 2πf

$$E_1 max = 2\pi f N_1 \varphi_m \ldots\ldots\ldots (5)$$

Root mean square RMS value is

$$E_1 = \frac{E_{1max}}{\sqrt{2}} \ldots\ldots\ldots.. (6)$$

Putting the value of $E_1$max in equation (6) we get

$$E_1 = \sqrt{2}\pi f N_1 \varphi_m \ldots\ldots(7)$$

Putting the value of π = 3.14 in the equation (7) we will get the value of $E_1$ as

$$E_1 = 4.44 f N_1 \varphi_m \ldots\ldots\ldots (8)$$

Similarly

$$E_2 = \sqrt{2}\pi f N_2 \varphi_m$$

Or

$$E_2 = 4.44 f N_2 \varphi_m \ldots\ldots\ldots (9)$$

Now, equating the equation (8) and (9) we get

$$\frac{E_2}{E_1} = \frac{4.44 f N_2 \varphi_m}{4.44 f N_1 \varphi_m}$$

Or

$$\frac{E_2}{E_1} = \frac{N_2}{N_1} = K$$

The above equation is called the turn ratio where K is known as transformation ratio.

The equation (8) and (9) can also be written as shown below using the relation

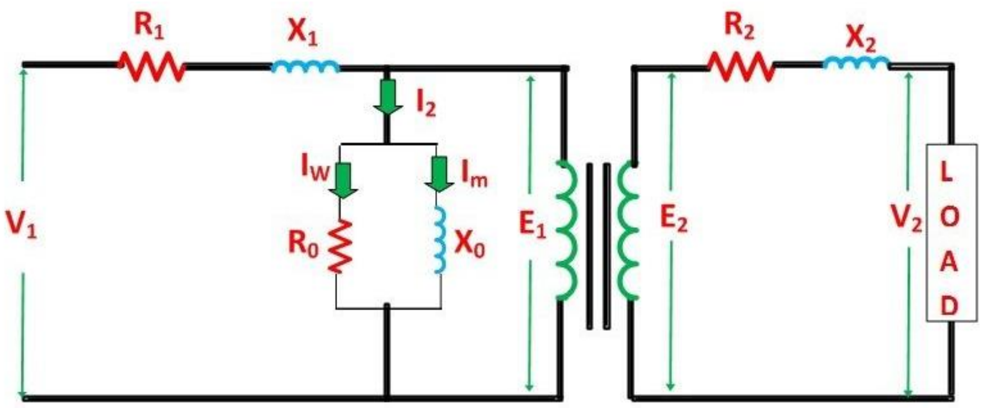
($\phi m = B_m \times A_i$) where $A_i$ is the iron area and $B_m$ is the maximum value of flux density.

$$E_1 = 4.44 N_1 f B_m A_i \text{ Volts} \quad \text{and} \quad E_2 = 4.44 N_2 f B_m A_i \text{ Volts}$$

## Equivalent Circuit of a Transformer

The equivalent circuit diagram of any device can be quite helpful in predetermination of the behavior of the device under the various condition of operation. It is simply the circuit representation of the equation describing the performance of the device.

The simplified equivalent circuit of a transformer is drawn by representing all the parameters of the transformer either on the secondary side or on the primary side. The equivalent circuit diagram of the transformer is shown below




*EQUIVALENT CIRCUIT DIAGRAM OF A TRANSFORMER*

- Equivalent Circuit When all the Quantities are Referred to Primary side
- Equivalent Circuit When all the Quantities are Referred to Secondary side

Let the equivalent circuit of a transformer having the transformation ratio $K = E_2/E_1$

The induced emf $E_1$ is equal to the primary applied voltage $V_1$ less primary voltage drop. This voltage causes current $I_0$ no load current in the primary winding of the transformer. The value of no-load current is very small, and thus, it is neglected. Hence, $I_1 = I_1'$. The no load current is further divided into two components called magnetizing current ($I_m$) and working current ($I_w$).

These two components of no-load current are due to the current drawn by a no inductive resistance $R_0$ and pure reactance $X_0$ having voltage $E_1$ or ($V_1$ – primary voltage drop).

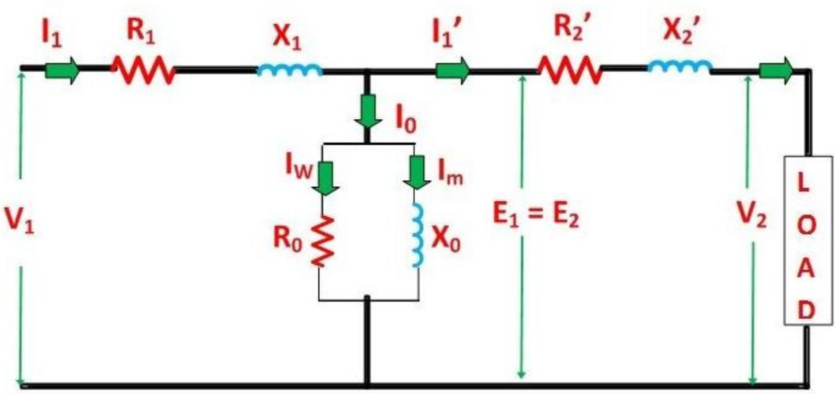
The secondary current $I_2$ is

$$I_2 = \frac{I_1'}{K} = \frac{I_1 - I_0}{K}$$

The terminal voltage $V_2$ across the load is equal to the induced emf $E_2$ in the secondary winding less voltage drop in the secondary winding.

### Equivalent Circuit when all the Quantities are referred to Primary side

In this case to draw the equivalent circuit of the transformer all the quantities are to be referred to the primary as shown in the figure below




*Circuit Diagram of Transformer when all the Secondary Quantities are Referred to Primary Side*

The following are the values of resistance and reactance given below

Secondary resistance referred to primary side is given as

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

The equivalent resistance referred to primary side is given as

$$R_{ep} = R_1 + R_2'$$

Secondary reactance referred to primary side is given as

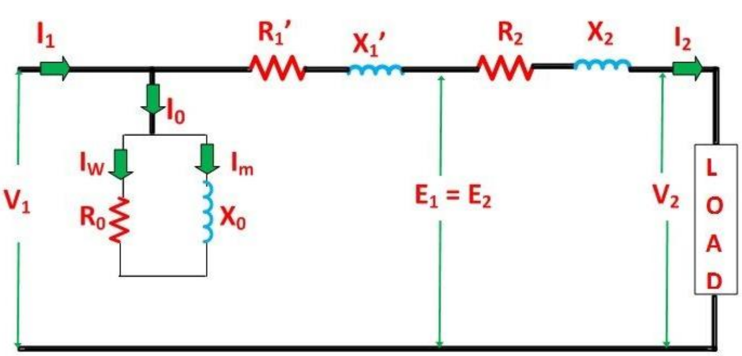
$$X_2' = \frac{X_2}{K^2}$$

The equivalent reactance referred to primary side is given as

$$X_{ep} = X_1 + X_2'$$

## Equivalent Circuit when all the Quantities are referred to Secondary side

The equivalent circuit diagram of the transformer is shown below when all the quantities are referred to the secondary side.




*Circuit Diagram of Transformer When All the Primary Quantities are Referred to Secondary Side*

The following are the values of resistance and reactance given below
Primary resistance referred to secondary side is given as

$$R_1' = K^2 R_1$$

The equivalent resistance referred to secondary side is given as

$$R_{es} = R_2 + R_1'$$

Primary reactance referred to secondary side is given as

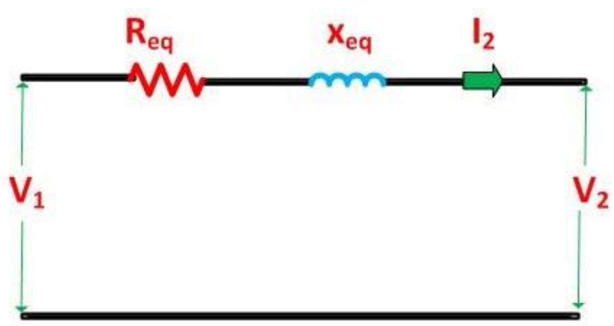
$$X_1' = K^2 X_1$$

The equivalent reactance referred to secondary side is given as

$$X_{eq} = X_2 + X_I'$$

No load current $I_0$ is hardly 3 to 5% of full load rated current, the parallel branch consisting of resistance $R_0$ and reactance $X_0$ can be omitted without introducing any appreciable error in the behavior of the transformer under the loaded condition.

Further simplification of the equivalent circuit of the transformer can be done by neglecting the parallel branch consisting $R_0$ and $X_0$. The simplified circuit diagram of the transformer is shown below



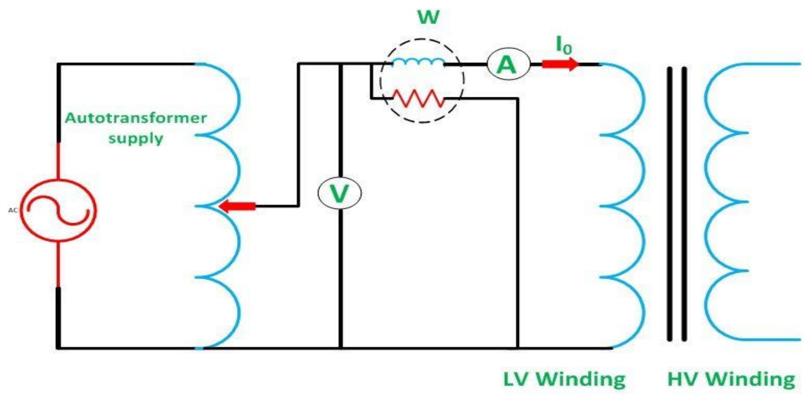

*Simplified Equivalent Circuit Diagram of a Transformer*

## Open Circuit and Short Circuit Test on Transformer

The open circuit and short circuit test are performed for determining the parameter of the transformer like their efficiency, voltage regulation, circuit constant etc. These tests are performed without the actual loading and because of this reason the very less power is required for the test. The open circuit and the short circuit test gives the very accurate result as compared to the full load test.

## Open Circuit Test

The purpose of the open circuit test is to determine the no-load current and losses of the transformer because of which their no-load parameter are determined. This test is performed on the primary winding of the transformer. The wattmeter, ammeter and the voltage are connected to their primary winding. The nominal rated voltage is supplied to their primary winding with the help of the ac source.




*Circuit Diagram of Open Circuit Test on Transformer*

The secondary winding of the transformer is kept open and the voltmeter is connected to their terminal. This voltmeter measures the secondary induced voltage. As the secondary of the transformer is open the no-load current flows through the primary winding.

The value of no-load current is very small as compared to the full rated current. The copper loss occurs only on the primary winding of the transformer because the secondary winding is open. The reading of the wattmeter only represents the core and iron losses. The core loss of the transformer is same for all types of loads.

**Calculation of open circuit test**

Let,

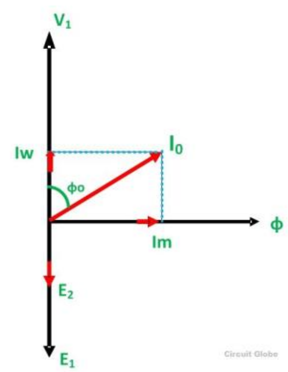
- $W_0$ – wattmeter reading
- $V_1$ – voltmeter reading
- $I_0$ – ammeter reading

Then the iron loss of the transformer $P_i = W_0$ and

$$W_0 = V_1 I_0 \cos\varphi_0 \qquad \ldots\ldots\ldots\ldots.(1)$$

The no-load power factor is

$$\cos\varphi_0 = \frac{W_0}{V_1 I_0}$$




*Phasor Diagram of Open Circuit Test*

Working component $I_w$ is

$$I_w = \frac{W_0}{V_1} \ldots\ldots\ldots\ldots.(2)$$

Putting the value of $W_0$ from the equation (1) in equation (2) you will get the value of working component as

$$I_w = I_0 \cos\varphi_0$$

Magnetizing component is

$$I_m = \sqrt{I_0^2 - I_w^2}$$

No load parameters are given below
Equivalent exciting resistance is

$$R_0 = \frac{V_1}{I_w}$$

Equivalent exciting reactance is

$$X_0 = \frac{V_1}{I_m}$$

The phasor diagram of transformer at no load or when an open circuit test is performed is shown below

The iron losses measured by the open circuit test are used for calculating the efficiency of the transformer.

## Short Circuit Test

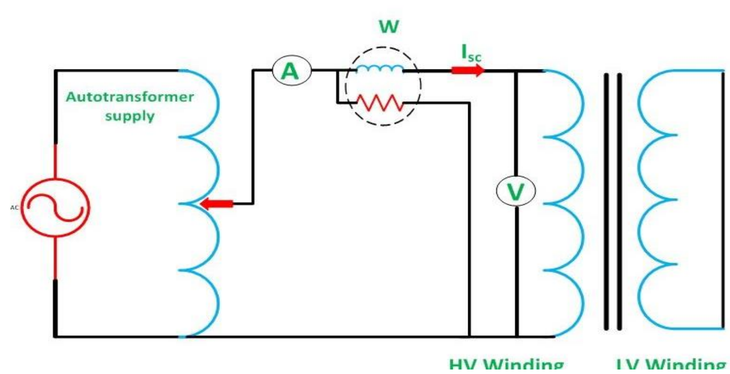
The short circuit test is performed for determining the below mention parameter of the transformer.

- It determines the copper loss occur on the full load. The copper loss is used for finding the efficiency of the transformer.
- The equivalent resistance, impedance, and leakage reactance are known by the short circuit test.

The short circuit test is performed on the secondary or high voltage winding of the transformer. The measuring instrument like wattmeter, voltmeter and ammeter are connected to the High voltage winding of the transformer. Their primary winding is short-circuited by the help of thick strip or ammeter which is connected to their terminal.

The low voltage source is connected across the secondary winding because of which the full load current flows from both the secondary and the primary winding of the transformer. The full load current is measured by the ammeter connected across their secondary winding.

The circuit diagram of the short circuit test is shown below




*Circuit Diagram of Short Circuit Test on Transformer*

The low voltage source is applied across the secondary winding which is approximately 5 to 10% of the normal rated voltage. The flux is set up in the core of the transformer. The magnitude of the flux is small as compared to the normal flux.

The iron loss of the transformer depends on the flux. It is less occur in the short circuit test because of the low value of flux. The reading of the wattmeter only determines the copper loss occur on their windings. The voltmeter measures the voltage applied to their high voltage winding. The secondary current induces in the transformer because of the applied voltage.

**Calculation of Short Circuit Test**

Let,

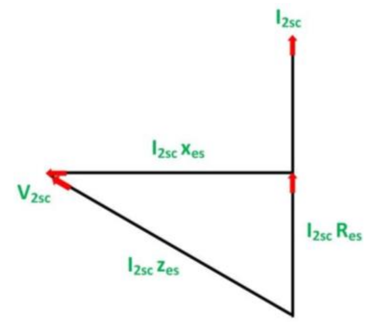
- $W_c$ – Wattmeter reading
- $V_{2sc}$ – voltmeter reading
- $I_{2sc}$ – ammeter reading

Then the full load copper loss of the transformer is given by

$$P_c = \left(\frac{I_{2fl}}{I_{2sc}}\right)^2 W_c \quad \text{And} \quad I_{2sc}^2 R_{es} = W_c$$

Equivalent resistance referred to secondary side is

$$R_{es} = \frac{W_c}{I_{2sc}^2}$$




*Phasor Diagram of Short Circuit Test*

The phasor diagram of the short circuit test of the transformer is shown below

From the phasor diagram

$$I_{2sc}Z_{es} = V_{2sc}$$

Equivalent impedance referred to the secondary side is given by

$$Z_{es} = \frac{V_{2sc}}{I_{2sc}}$$

The Equivalent reactance referred to the secondary side is given by

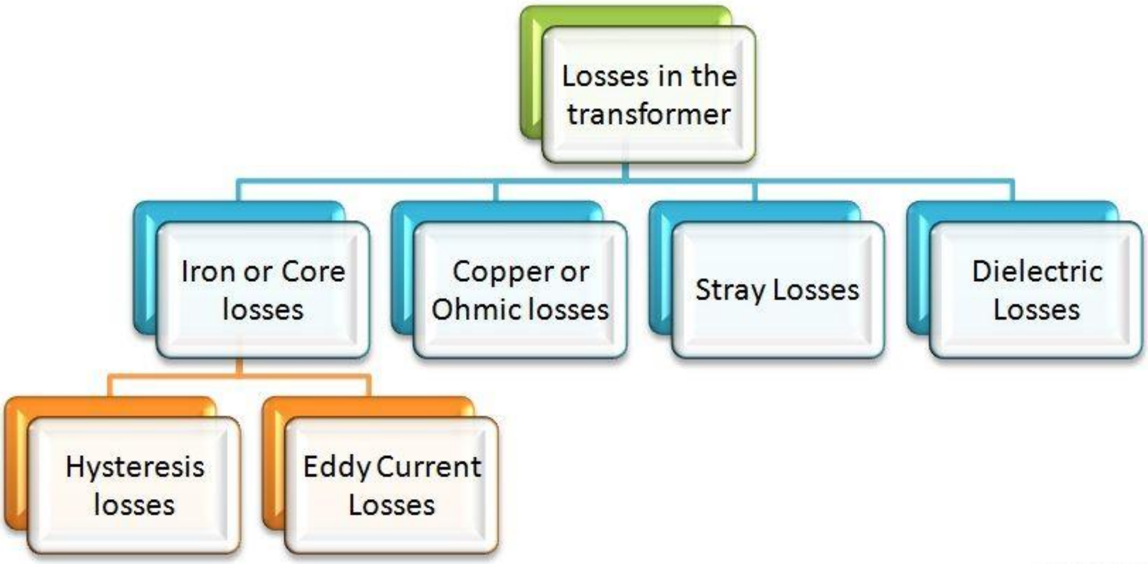
$$X_{es} = \sqrt{(Z_{es})^2 - (R_{es})^2}$$

The voltage regulation of the transformer can be determined at any load and power factor after knowing the values of $Z_{es}$ and $R_{es}$.

In the short circuit test the wattmeter record, the total losses including core loss but the value of core loss are very small as compared to copper loss so, the core loss can be neglected.

## Types of Losses in a Transformer

There are various types of losses in the transformer such as iron losses, copper losses, hysteresis losses, eddy current losses, stray loss, and dielectric losses. The hysteresis losses occur because of the variation of the magnetization in the core of the transformer and the copper loss occur because of the transformer winding resistance. The various types of losses are explained below in detail.




### Iron Losses

Iron losses are caused by the alternating flux in the core of the transformer as this loss occurs in the core it is also known as Core loss. Iron loss is further divided into hysteresis and eddy current loss.

### Hysteresis Loss

The core of the transformer is subjected to an alternating magnetizing force, and for each cycle of emf, a hysteresis loop is traced out. Power is dissipated in the form of heat known as hysteresis loss and given by the equation shown below

$$P_h = K\eta B_{max}^{1.6} f V \quad \text{watts}$$

Where

- Kɳ is a proportionality constant which depends upon the volume and quality of the material of the core used in the transformer.
- f is the supply frequency
- Bmax is the maximum or peak value of the flux density

The iron or core losses can be minimized by using silicon steel material for the construction of the core of the transformer.

### Eddy Current Loss

When the flux links with a closed circuit, an emf is induced in the circuit and the current flows, the value of the current depends upon the amount of emf around the circuit and the resistance of the circuit. Since the core is made of conducting material, these EMFs circulates currents within the body of the material. These circulating currents are called Eddy Currents. They will occur when the conductor experiences a changing magnetic field. As these currents are not responsible for doing any useful work, and it produces a loss ($I^2R$ loss) in the magnetic material known as an Eddy Current Loss.
The eddy current loss is minimized by making the core with thin laminations.

The equation of the eddy current loss is given as

$$P_e = K_e B_m^2 t^2 f^2 V \qquad \text{watts}$$

Where,

- $K_e$ – co-efficient of eddy current. Its value depends upon the nature of magnetic material like volume and resistivity of core material, thickness of laminations
- $B_m$ – maximum value of flux density in wb/$m^2$
- T – thickness of lamination in meters
- F – frequency of reversal of magnetic field in Hz
- V – volume of magnetic material in $m^3$

### Copper Loss Or Ohmic Loss

These losses occur due to ohmic resistance of the transformer windings. If $I_1$and $I_2$ are the primary and the secondary current. $R_1$ and $R_2$ are the resistance of primary and secondary winding then the copper losses occurring in the primary and secondary winding will be $I_1^2R_1$ and $I_2^2R_2$ respectively.

Therefore, the total copper losses will be

$$P_c = I_1^2R_1 + I_2^2R_2$$

These losses varied according to the load and known hence it is also known as variable losses. Copper losses vary as the square of the load current.

### Stray Loss

The occurrence of these stray losses is due to the presence of leakage field. The percentages of these losses are very small as compared to the iron and copper losses so they can be neglected.

### Dielectric Loss

Dielectric loss occurs in the insulating material of the transformer that is in the oil of the transformer, or in the solid insulations. When the oil gets deteriorated or the solid insulation get damaged, or its quality decreases, and because of this, the efficiency of transformer is effected

## Transformer Efficiency

The Efficiency of the transformer is defined as the ratio of useful power output to the input power. The input and the output power are measured in the same unit. Its unit is either in Watts (W) or KW. Transformer efficiency is denoted by η.

$$\eta = \frac{\text{output power}}{\text{input power}} = \frac{\text{output power}}{\text{output power} + \text{losses}}$$

$$\eta = \frac{\text{output power}}{\text{output power} + \text{iron losses} + \text{copper losses}}$$

$$\eta = \frac{V_2 I_2 \mathrm{Cos}\varphi_2}{V_2 I_2 \mathrm{Cos}\varphi_2 + P_i + P_c}$$

Where,

- $V_2$ – Secondary terminal voltage
- $I_2$ – Full load secondary current
- $\mathrm{Cos}\phi_2$ – power factor of the load
- $P_i$ – Iron losses = hysteresis losses + eddy current losses
- Pc – Full load copper losses = $I_2^2 R_{es}$

Consider, the x is the fraction of the full load. The efficiency of the transformer regarding x is expressed as

$$\eta_x = \frac{x\ \mathrm{X\ output}}{x\ \mathrm{X\ output} + P_i + x^2 P_c} = \frac{x\ V_2 I_2 \mathrm{Cos}\varphi_2}{x\ V_2 I_2 \mathrm{Cos}\varphi_2 + P_i + x^2 I_2^2 R_{es}}$$

The copper losses vary according to the fraction of the load.

### Maximum Efficiency Condition of a Transformer

The efficiency of the transformer along with the load and the power factor is expressed by the given relation.

$$\eta = \frac{V_2 I_2 \mathrm{Cos}\varphi_2}{V_2 I_2 \mathrm{Cos}\varphi_2 + P_i + I_2^2 R_{es}} = \frac{V_2 \mathrm{Cos}\varphi_2}{V_2 \mathrm{Cos}\varphi_2 + P_i/I_2 + I_2 R_{es}} \ldots\ldots\ldots (1)$$

The value of the terminal voltage $V_2$ is approximately constant. Thus, for a given power factor the Transformer efficiency depends upon the load current $I_2$. In the equation (1) shown above the numerator is constant and the transformer efficiency will be maximum if the denominator with respect to the variable $I_2$ is equated to zero.

$$\frac{d}{dI_2} = \left( V_2 \ Cos\varphi_2 + \frac{P_i}{I_2} + I_2 R_{es} \right) = 0 \qquad or \qquad 0 - \frac{P_i}{I_2^2} + R_{es} = 0$$

Or

$$I_2^2 R_{es} = P_i \ \ldots\ldots\ldots..(2)$$

i.e Copper losses = Iron losses

Thus, the transformer will give the maximum efficiency when their copper loss is equal to the iron loss.

$$\eta_{max} = \frac{V_2 I_2 Cos\varphi_2}{V_2 I_2 Cos\varphi_2 + 2P_i} \qquad as\ (P_c = P_i)$$

From equation (2) the value of output current $I_2$ at which the transformer efficiency will be maximum is given as

$$I_2 = \sqrt{\frac{P_i}{R_{es}}}$$

If x is the fraction of full load KVA at which the efficiency of the transformer is maximum

Then, copper losses = $x^2 P_c$ (where $P_c$ is the full load copper losses)

Iron losses = $P_i$

For maximum efficiency $x^2 P_c = P_i$

$$x = \sqrt{\frac{P_i}{P_c}} \ldots\ldots\ldots\ldots..(3)$$

Therefore, Output KVA corresponding to maximum efficiency

$$\eta_{max} = x \ X\ full\ load\ KVA \ldots\ldots\ldots\ldots(4)$$

Putting the value of x from the above equation (3) in equation (4) we will get

$$\eta_{max} = \sqrt{\frac{P_i}{P_c}}\ X\ full\ load\ KVA$$

$$\eta_{max} = Full\ load\ KVA\ X \sqrt{\frac{iron\ losses}{copper\ losses\ at\ full\ load}} \ldots\ldots\ldots\ldots.(5)$$

The above equation (5) is the maximum efficiency condition of a transformer.

## All Day Efficiency of a Transformer

All day efficiency means the power consumed by the transformer throughout the day. It is defined as the ratio of output power to the input power in kWh or Wh of the transformer over 24 hours. Mathematically, it is represented as

$$\text{All day efficiency, } \eta_{\text{all day}} = \frac{\text{output in kWh}}{\text{input in kWh}} \quad (\text{for 24 hours})$$

All day efficiency of the transformer depends on their load cycle. The load cycle of the transformer means the repetitions of load on it for a specific period.

The ordinary or commercial efficiency of a transformer define as the ratio of the output power to the input power.

$$\eta = \frac{\text{output power}}{\text{input power}} = \frac{\text{output power}}{\text{output power} + \text{losses}}$$

**What is the need of All Day Efficiency?**

Some transformer efficiency cannot be judged by simple commercial efficiency as the loads on certain transformer fluctuate throughout the day. For example, the distribution transformers are energized for 24 hours, but they deliver very light loads for the major portion of the day, and they do not supply rated or full load, and most of the time the distribution transformer has 50 to 75% load on it.

As we know, there are various losses in the transformer such as iron and copper loss. The iron loss takes place in the core of the transformer. Thus, the iron or core loss occurs for the whole day in the distribution transformer. The second type of loss known as copper loss takes place in the windings of the transformer also known as the variable loss. It occurs only when the transformers are in the loaded condition.

Hence, the performance of such transformers cannot be judged by the commercial or ordinary efficiency, but the efficiency is calculated or judged by All Day Efficiency also known as operational efficiency or energy efficiency which is computed by energy consumed during 24 hours.

## Voltage Regulation of a Transformer

The voltage regulation is defined as the change in the magnitude of receiving and sending the voltage of the transformer. The voltage regulation determines the ability of the transformer to provide the constant voltage for variable loads.

When the transformer is loaded with continuous supply voltage, the terminal voltage of the transformer varies. The variation of voltage depends on the load and its power factor.

Mathematically, the voltage regulation is represented as

$$\text{Voltage Regulation} = \frac{E_2 - V_2}{E_2}$$

$$\%\ \text{Voltage Regulation} = \frac{E_2 - V_2}{E_2} \times 100$$

Where,
$E_2$ – secondary terminal voltage at no load
$V_2$ – secondary terminal voltage at full load

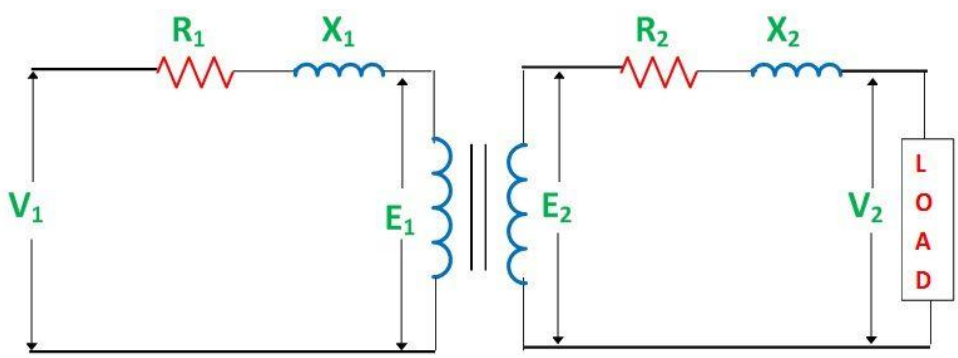
The voltage regulation by considering the primary terminal voltage of the transformer is expressed as,

$$\%\ \text{Voltage Regulation} = \frac{V_1 - E_1}{V_1} \times 100$$

Let us understand the voltage regulation by taking an example explained below

If the secondary terminals of the transformer are open circuited or no load is connected to the secondary terminals, the no-load current flows through it. If the no current flows through the secondary terminals of the transformer, the voltage drops across their resistive and reactive load become zero. The voltage drop across the primary side of the transformer is negligible.

If the transformer is fully loaded, i.e., the load is connected to their secondary terminal, the voltage drops appear across it. The value of the voltage regulation should always be less for the better performance of transformer.




From the circuit diagram shown above, the following conclusions are made

- The primary voltage of the transformer is always greater than the emf induces on the primary side. $V_1 > E_1$
- The secondary terminal voltage at no load is always greater than the voltage at full load condition. $E_2 > V_2$
- By considering the above circuit diagram, the following equations are drawn

$$V_1 = I_1R_1\text{Cos}\varphi_1 + I_1X_1\text{Sin}\varphi_1 + E_1$$

$$E_2 = I_2R_2\text{Cos}\varphi_2 + I_2X_2\text{Sin}\varphi_2 + V_2$$

The approximate expression for the no-load secondary voltage for the different types of load is

1. For Inductive Load:

$$E_2 = I_2R_{02}Cos\varphi_2 + I_2X_{02}Sin\varphi_2 + V_2$$

OR

$$E_2 - V_2 = I_2R_{02}Cos\varphi_2 + I_2X_{02}Sin\varphi_2$$

OR

$$\frac{E_2 - V_2}{E_2} \text{ x } 100 = \frac{I_2R_{02}}{E_2} \text{ x } 100 \text{ } Cos\varphi_2 + \frac{I_2X_{02}}{E_2} \text{ x } 100 \text{ } Sin\varphi_2$$

Where,

$\frac{I_2R_{02}}{E_2}$ x 100 is a percentage resistance drop

$\frac{I_2X_{02}}{E_2}$ x 100 is a percentage reactance drop

2. For Capacitive load

$$E_2 = I_2R_{02}Cos\varphi_2 - I_2X_{02}Sin\varphi_2 + V_2$$

OR

$$E_2 - V_2 = I_2R_{02}Cos\varphi_2 - I_2X_{02}Sin\varphi_2$$

OR

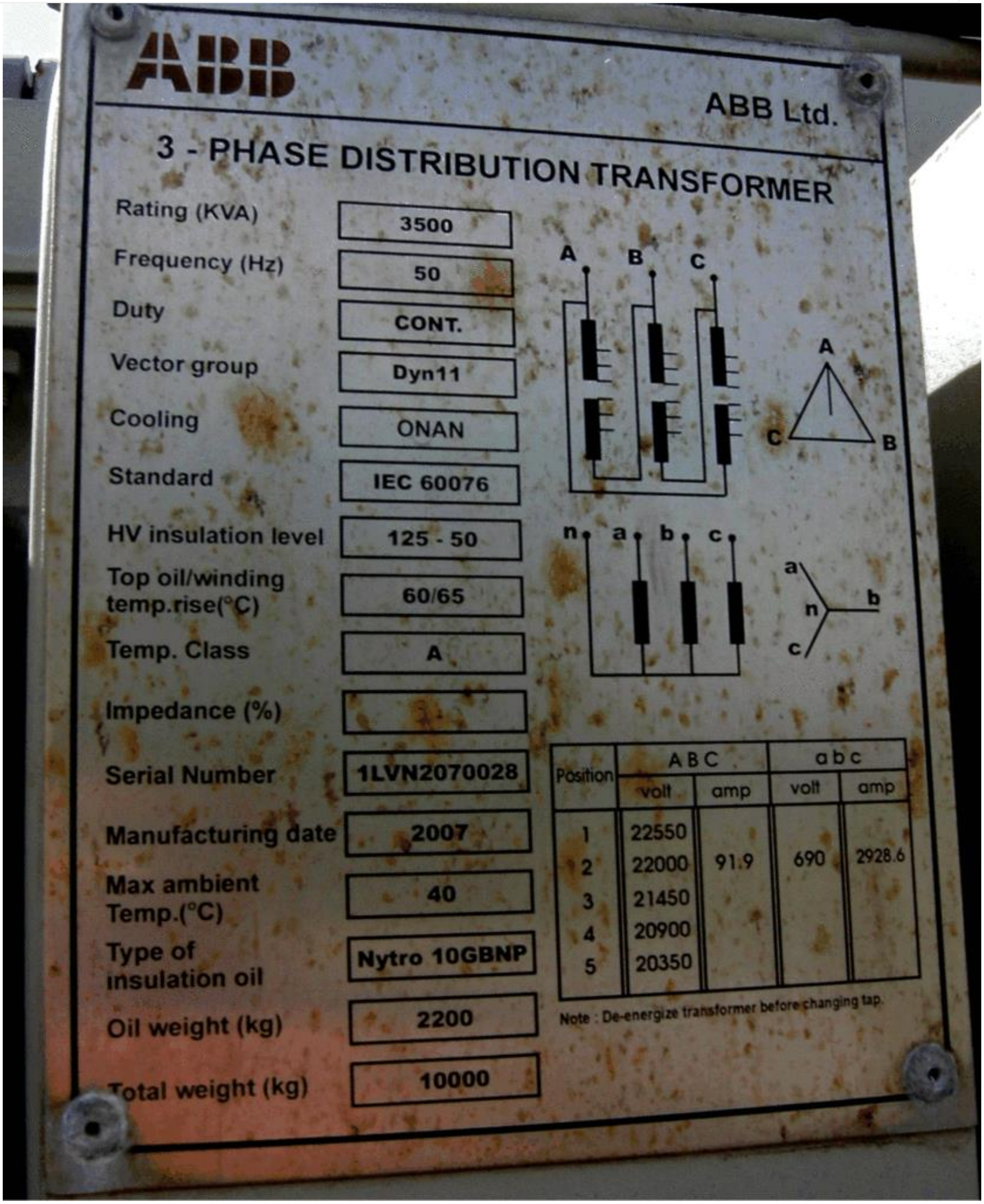
$$\frac{E_2 - V_2}{E_2} \text{ x } 100 = \frac{I_2R_{02}}{E_2} \text{ x } 100 \text{ } Cos\varphi_2 - \frac{I_2X_{02}}{E_2} \text{ x } 100 \text{ } Sin\varphi_2$$

## Transformer Nameplate Details

Following are the key information which are provided on the transformer nameplate from the manufacturer.

| | |
|---|---|
| Serial number | Number of phases |
| Frequency | Voltage rating |
| kVA Rating | Temperature Rise |
| Polarity | Percentage Impedance |
| Connection Diagram | Name of Manufacturer |
| Type of insulating liquid | Conductor Material for each Winding |

| | |
|---|---|
| Basic Insulation Level (BIL) | Total Weight (kg) |




## Ideal Transformer

The transformer which is free from all types of losses is known as an ideal transformer**.** It is an imaginary transformer which has no core loss, no ohmic resistance and no leakage flux. The ideal transformer has the following important characteristic.

1. The resistance of their primary and secondary winding becomes zero.
2. The core of the ideal transformer has infinite permeability. The infinite permeable means less magnetizing current requires for magnetizing their core.
3. The leakage flux of the transformer becomes zero, i.e. the whole of the flux induces in the core of the transformer links with their primary and secondary winding.
4. The ideal transformer has 100 percent efficiency, i.e., the transformer is free from hysteresis and eddy current loss.

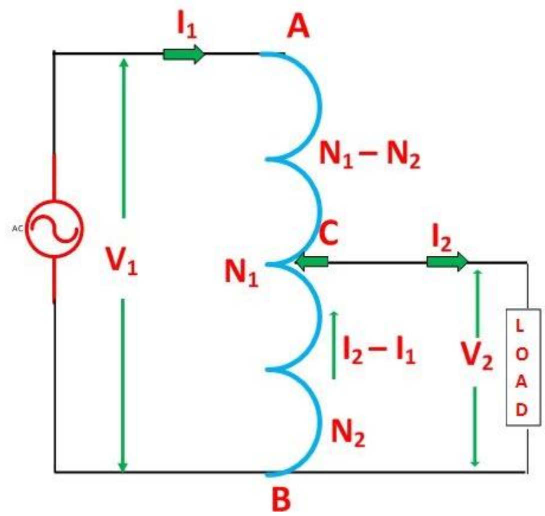
The above mention properties are not possible in the practical transformer. In an ideal transformer, there is no power loss. Therefore, the output power is equal to the input power.

## Auto Transformer

An **A**uto Transformer is a transformer with only one winding wound on a laminated core. An auto transformer is similar to a two winding transformer but differ in the way the primary and secondary winding are interrelated. A part of the winding is common to both primary and secondary sides. On load condition, a part of the load current is obtained directly from the supply and the remaining part is obtained by transformer action. An Auto transformer works as a voltage regulator**.**

There are two types of auto transformer based on the construction. In one type of transformer, there is continuous winding with the taps brought out at convenient points determined by desired secondary voltage and in another type of auto transformer, there are two or more distinct coils which are electrically connected to form a continuous winding. The construction of Auto transformer is shown in the figure below.

The primary winding AB from which a tapping at C is taken, such that CB acts as a secondary winding. The supply voltage is applied across AB, and the load is connected across CB. The tapping may be fixed or variable. When an AC voltage $V_1$ is applied across AB, an alternating flux is set up in the core, as a result, an emf $E_1$ is induced in the winding AB. A part of this induced emf is taken in the secondary circuit.




*Auto – Transformer*

Let,

- $V_1$ – primary applied voltage
- $V_2$ – secondary voltage across the load
- $I_1$ – primary current

- $I_2$ – load current
- $N_1$ – number of turns between A and B
- $N_2$ – number of turns between C and B

Neglecting no load current, leakage reactance and losses,

$V_1 = E_1$ and $V_2 = E_2$

Therefore the transformation ratio

$$K = \frac{V_2}{V_1} = \frac{N_2}{N_1} = \frac{I_1}{I_2}$$

As the secondary ampere-turns are opposite to primary ampere turns, so the current $I_2$ is in phase opposition to $I_1$. The secondary voltage is less than the primary. Therefore current $I_2$ is more than the current $I_1$. Therefore, the resulting current flowing through section BC is $(I_2 – I_1)$

The ampere-turns due to section BC = current x turns

$$\text{Ampere turns due to section BC} = (I_2 - I_1)N_2 = \left(\frac{I_1}{K} - I_1\right) x\, N_1 K = I_1 N_1\,(1 - K) \ldots\ldots\ldots (1)$$

$$\text{Ampere turns due to section AC} = I_1(N_1 - N_2) = I_1 N_1\left(1 - \frac{N_2}{N_1}\right) = I_1 N_1 (1 - K) \ldots\ldots. (2)$$

Equation (1) and (2) shows that the ampere turns due to section BC and AC balance each other which is characteristic of the transformer action.

**Advantages of Auto transformer**

- Less costly
- Better regulation
- Low losses as compared to ordinary two winding transformer of the same rating.

**Disadvantages of Auto transformer**

There are various advantages of the auto transformer, but then also one major disadvantage, why auto transformer is not widely used, is that

- The secondary winding is not insulated from the primary winding.
  If an auto transformer is used to supply low voltage from a high voltage and there is a break in the secondary winding, the full primary voltage comes across the secondary terminal which is dangerous to the operator and the equipment. So the auto transformer should not be used to for interconnecting high voltage and low voltage system.

- Used only in the limited places where a slight variation of the output voltage from input voltage is required.

**Applications of Auto transformer**

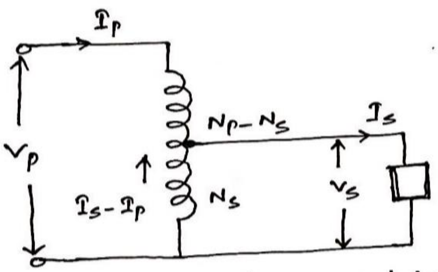
- It is used as a starter to give up to 50 to 60% of full voltage to the stator of a squirrel cage induction motor during starting.
- It is used to give a small boost to a distribution cable, to correct the voltage drop.

- It is also used as a voltage regulator
- Used in power transmission and distribution system and also in the audio system and railways.

## Saving of Copper in Auto Transformer as Compared to Ordinary Two Winding Transformer

It is known that the length of copper in a winding is proportional to the number of turns and the area of cross section of the winding wire is proportional to the current rating. Thus the weight of copper required in a conventional two winding transformer is proportional to $\boxed{I_p \times N_p + I_s N_s}$, where, $N_p$ & $N_s$ are primary & secondary turns respectively.

For an autotransformer, the weight of copper required is proportional to $\boxed{I_p (N_p - N_s) + (I_s - I_p) N_s}$.




Connection diagram of an autotransformer.

Thus,

$$\frac{\text{Weight of copper required in an autotransformer}}{\text{Weight of copper required in a two-winding transformer}} = \frac{I_p (N_p - N_s) + (I_s - I_p) N_s}{I_p N_p + I_s N_s}$$

$$= \frac{I_p N_p + I_s N_s - 2 I_p N_s}{I_p N_p + I_s N_s}$$

$$= 1 - \frac{2 I_p N_s}{2 I_p N_p} \quad (\text{as } I_p N_p = I_s N_s)$$

$$= 1 - \frac{N_s}{N_p} = 1 - \frac{1}{n} \quad \left[\left(n = \frac{N_p}{N_s}\right)\right]$$

$$= \frac{n-1}{n}$$

If for example, the ratio of the primary to secondary voltage of an autotransformer is 100 : 50, then the above ratio would be $(2-1)/2$ $= 1/2$. Thus the saving in copper by using an autotransformer would be 50%.

## Sumpner's Test or Back-To-Back Test on Transformer

Sumpner's test or back to back test on transformer is another method for determining transformer efficiency, voltage regulation and heating under loaded conditions. Short circuit and open circuit tests on transformer can give us parameters of equivalent circuit of transformer, but they cannot help us in finding the heating information. Unlike O.C. and S.C. tests, actual loading is simulated in Sumpner's test. Thus the Sumpner's test gives more accurate results of regulation and efficiency than O.C. and S.C. tests.

Sumpner's test or back to back test can be employed only when two identical transformers are available. Both transformers are connected to supply such that one transformer is loaded on another. Primaries of the two identical transformers are connected in parallel across a supply. Secondary's are connected in series such that emf's of them are opposite to each other.

The full load test on a small transformer is very convenient, but on the large transformer, it is very difficult. The maximum temperature rise in a large transformer is determined by the full load test. This test is called, back-to-back test, regenerative test or Sumpner's test.

The suitable load which absorbs the full load power of a large transformer will not easily be available. Hence a large amount of energy will be wasted. The back-to-back test determines the maximum temperature rise in a transformer, and hence the load is chosen according to the capability of the transformer.

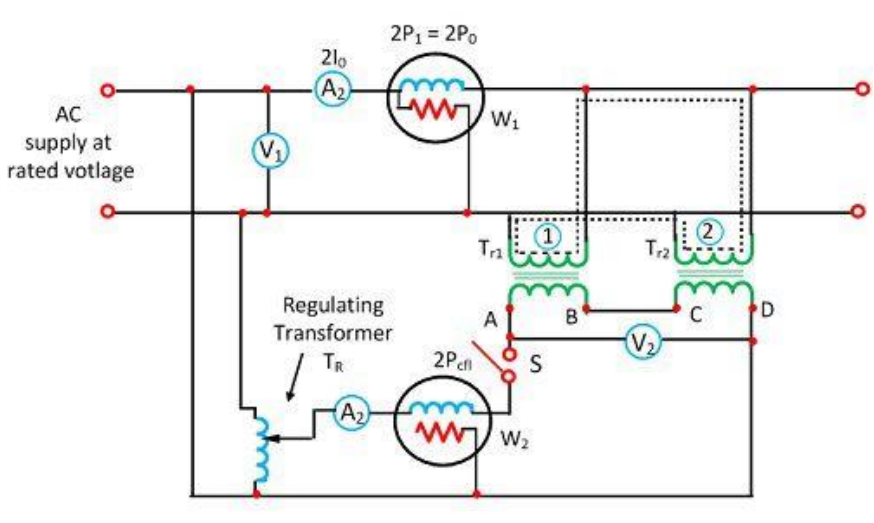
The two identical transformers is used for the back to back test. Consider the $T_{r1}$ and $T_{r2}$ are the primary windings of the transformer connect parallel to each other. The nominal rated voltage and frequency is supplied to their primary winding. The voltmeter and ammeter are connected on their primary side for the measurement of the input voltage and current.

The secondary winding of the transformer is connected in series with the each other but with opposite polarity. The voltmeter $V_2$ is connected to the terminal of the secondary winding for the measurement of the voltage.

The series opposition of the secondary winding is determined by connecting there any two terminals; the voltmeter is connected across their remaining terminals. If it is connected in series opposition, the voltmeter gives the zero reading. The open terminal is used for measuring the parameter of the transformer.

**Determination of Temperature Rise**

The temperature rise of the transformer is determined by measuring the temperature of their oil after every particular interval of time. The transformer is operating back to back for the long time which increases their oil temperature. By measuring the temperature of their oil the withstand capacity of the transformer




Back-to-back test on two identical single-phase transformers under high temperature is determined.

**Determination of Iron Loss**

The wattmeter $W_1$ measures the power loss which is equal to the iron loss of the transformer. For determining the iron loss, the primary circuit of the transformer is kept closed. Because of the primary closed circuit, no current flows through the secondary windings of the transformer. The secondary winding behaves like an open circuit. The wattmeter is connected to their secondary terminal for the measurement of iron loss.

**Determination of Copper Loss**

The copper loss of the transformer is determined when the full load current flows through their primary and secondary windings. The additional regulating transformer is used for exciting the secondary windings. The full load current flows from the secondary to the primary winding. The wattmeter $W_2$ measures the full load copper loss of the two transformers.

$$\begin{matrix}\text{\% full load efficiency} \\ \text{of each transformer}\end{matrix} = \frac{\text{output}}{\text{output} + \frac{W_1}{2} + \frac{W_2}{2}} \times 100$$

## Testing of Transformers

For confirming the specifications and performances of an electrical power transformer it has to go through numbers of testing procedures. Some tests are done at manufacturer premises before delivering the transformer. Mainly two types of transformer testing are done at manufacturer premises- type test of transformer and routine test of transformer. In addition to that some transformer tests are also carried out at the consumer site before commissioning and also periodically in regular and emergency basis throughout its service life.

**Type of Transformer Testing**

Tests done at factory

1. Type tests
2. Routine tests
3. Special tests

***Tests done at site***

1. Pre-commissioning tests
2. Periodic/condition monitoring tests
3. Emergency tests

**Type tests of transformer includes**

1. Transformer winding resistance measurement
2. Transformer ratio test.

3. Transformer vector group test.
4. Measurement of impedance voltage/short circuit impedance (principal tap) and load loss (Short circuit test).
5. Measurement of no load loss and current (Open circuit test).
6. Measurement of insulation resistance.
7. Dielectric tests of transformer.
8. Temperature rise test of transformer.
9. Tests on on-load tap-changer.
10. Vacuum tests on tank and radiators.

**Routine tests of transformer include**

1. Transformer winding resistance measurement.
2. Transformer ratio test.
3. Transformer vector group test.
4. Measurement of impedance voltage/short circuit impedance (principal tap) and load loss (Short circuit test).
5. Measurement of no load loss and current (Open circuit test)
6. Measurement of insulation resistance.
7. Dielectric tests of transformer.
8. Tests on on-load tap-changer.
9. Oil pressure test on transformer to check against leakages past joints and gaskets.

That means Routine tests of transformer include all the type tests except temperature rise and vacuum tests. The oil pressure test on transformer to check against leakages past joints and gaskets is included.

**Special Tests of transformer include**

1. Dielectric tests.
2. Measurement of zero-sequence impedance of three-phase transformers
3. Short-circuit test.
4. Measurement of acoustic noise level.
5. Measurement of the harmonics of the no-load current.
6. Measurement of the power taken by the fans and oil pumps.
7. Tests on bought out components / accessories such as buchholz relay, temperature indicators, pressure relief devices, oil preservation system etc.

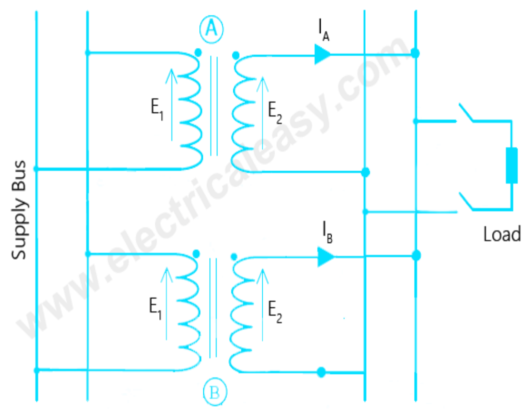
## Parallel Operation of a Single Phase Transformer

Parallel Operation of a Single Phase Transformer means that the two or more transformers having same polarities, same turn ratios, same phase sequence and the same voltage ratio are connected in parallel with each other.

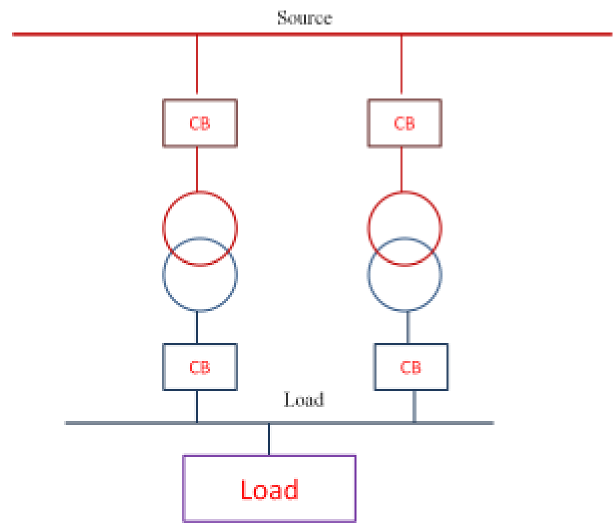
**Necessity of Parallel Operation of Transformers**

Why parallel operation of transformers is needed?

- Increased Load: When load is increased and it exceeds the capacity of existing transformer, another transformer may be connected in parallel with the existing transformer to supply the increased load.
- Non-availability of large transformer: If a large transformer is not available which can meet the total requirement of load, two or more small transformers can be connected in parallel to increase the capacity.
- Increased reliability: If multiple transformers are running in parallel, and a fault occurs in one transformer, then the other parallel transformers still continue to serve the load. And the faulty transformer can be taken out for the maintenance.
- Transportation is easier for small transformers: If installation site is located far away, then transportation of smaller units is easier and may be economical.




Parallel Operation of Single Phase Transformers




**Essential Conditions for Parallel Operation**

**(1) The polarity of both transformers must be same**

- If the transformers are not connected in correct polarity, dead short circuit occurs. Let us know how to connect two transformers with correct polarity.
- The primaries of both transformers are connected in parallel.
- Connect the secondary of transformers as shown in Figure A.
- The rating of voltmeter must be double that of secondary rated voltage of the transformer.
- If the voltmeter indicates zero, it is "correct" polarity.
- If the voltmeter indicates double voltage that of secondary rated voltage of a transformer, it is "incorrect" polarity. In that case anyone connection of the secondary winding is interchanged.

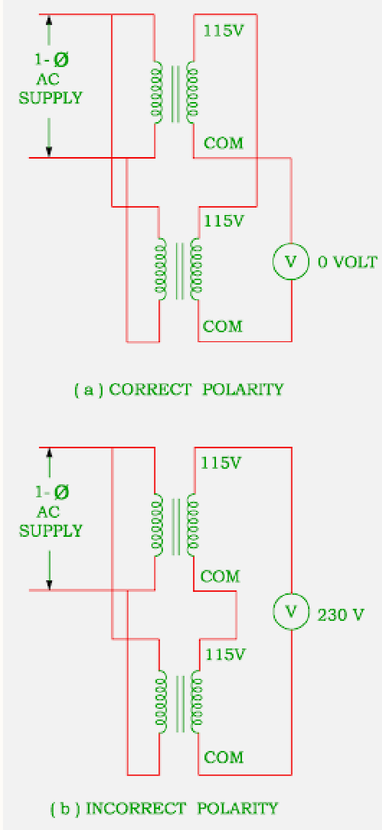


FIG A : POLARITY CHECK OF THE TRANSFORMER

**(2) The turns - ratio of both transformers are the same**

- If the voltage ratio of the both transformer is not identical the secondary emf will induce resulting circulating current flow in the secondary circuit.
- Therefore the primaries of the transformer will draw reflected secondary circulating current, in addition to the magnetizing current.
- This additional current cause copper losses on both winding of the transformers.

**(3) Percentage impedance of the transformers is the same or X / R ratio should be the same for each transformer**

- If the percentage impedances of the transformers are not the same, a transformer with smaller percentage impedance will carry more load than its actual share load and other transformer carry only part of load.
- The impedance of the transformer is inversely proportional to its kVA rating.
- If the X/R ratios of the transformers are different, one transformer will be operating with a higher power factor and the other transformer with a lower power factor that of total load.
- It means that kW load is not proportionally shared by them.

## Transformer Loading

When the transformer is on loaded condition, the secondary of the transformer is connected to load. The load can be resistive, inductive or capacitive. The current $I_2$ flows through the secondary winding of the transformer. The magnitude of the secondary current depends on the terminal voltage $V_2$ and the load impedance. The phase angle between the secondary current and voltage depends on the nature of the load.

### Phasor Diagram of Transformer on Inductive Load

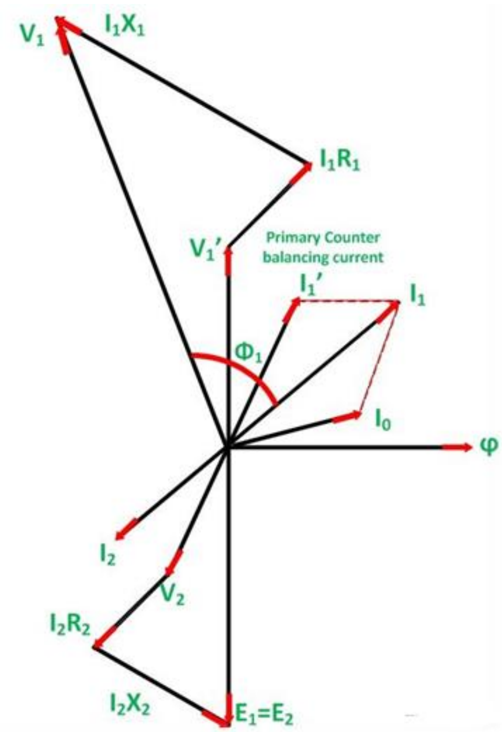
The phasor diagram of the actual transformer when it is loaded inductively is shown below

### Steps to draw the phasor diagram

- Take flux $\phi$ a reference
- Induces emf $E_1$ and $E_2$ lags the flux by 90 degrees.
- The component of the applied voltage to the primary equal and opposite to induced emf in the primary winding. $E_1$ is represented by $V_1$'.
- Current $I_0$ lags the voltage $V_1$' by 90 degrees.
- The power factor of the load is lagging. Therefore current $I_2$ is drawn lagging $E_2$ by an angle $\phi_2$.
- The resistance and the leakage reactance of the windings result in a voltage drop, and hence secondary terminal voltage $V_2$ is the phasor difference of $E_2$ and voltage drop.

  $V_2 = E_2$ – voltage drops
  $I_2 R_2$ is in phase with $I_2$ and $I_2X_2$ is in quadrature with $I_2$.

- The total current flowing in the primary winding is the phasor sum of $I_1$' and $I_0$.




*Phasor Diagram of the Transformer on Inductive Load*

- Primary applied voltage $V_1$ is the phasor sum of $V_1$' and the voltage drop in the primary winding.
- Current $I_1$' is drawn equal and opposite to the current $I_2$

  $V_1 = V_1' +$ voltage drop
  $I_1R_1$ is in phase with $I_1$ and $I_1X_I$ is in quadrature with $I_1$.

- The phasor difference between $V_1$ and $I_1$ gives the power factor angle $\phi_1$ of the primary side of the transformer.
- The power factor of the secondary side depends upon the type of load connected to the transformer.

- If the load is inductive as shown in the above phasor diagram, the power factor will be lagging, and if the load is capacitive, the power factor will be leading. Where $I_1R_1$ is the resistive drop in the primary windings
  $I_2X_2$ is the reactive drop in the secondary winding

**Phasor Diagram of Transformer on Capacitive Load**

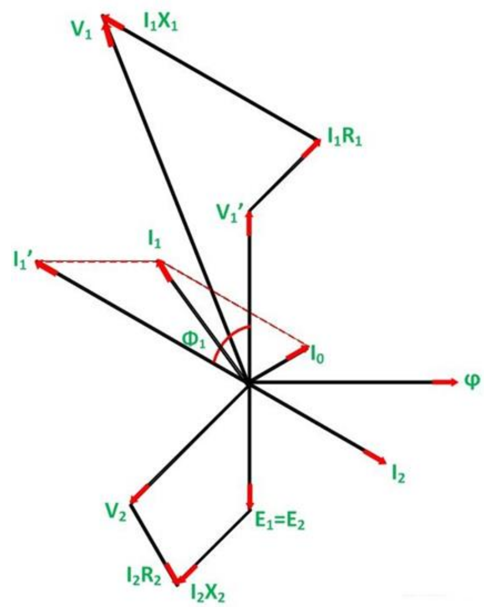
The Transformer on Capacitive load (leading power factor load) is shown below in the phasor diagram.

**Steps to draw the phasor diagram at capacitive load**

- Take flux $\phi$ a reference
- Induces emf $E_1$ and $E_2$ lags the flux by 90 degrees.
- The component of the applied voltage to the primary equal and opposite to induced emf in the primary winding. $E_1$ is represented by $V_1$'.
- Current $I_0$ lags the voltage $V_1$' by 90 degrees.
- The power factor of the load is leading. Therefore current $I_2$ is drawn leading $E_2$
- The resistance and the leakage reactance of the windings result in a voltage drop, and hence secondary terminal voltage $V_2$ is the phasor difference of $E_2$ and voltage drop.

  $V_2 = E_2$ – voltage drops
  $I_2 R_2$ is in phase with $I_2$ and $I_2X_2$ is in quadrature with $I_2$.

- Current $I_1$' is drawn equal and opposite to the current $I_2$




***Phasor Diagram of the Transformer on Capacitive Load***

- The total current $I_1$ flowing in the primary winding is the phasor sum of $I_1$' and $I_0$.
- Primary applied voltage $V_1$ is the phasor sum of $V_1$' and the voltage drop in the primary winding.

  $V_1 = V_1' +$ voltage drop
  $I_1R_1$ is in phase with $I_1$ and $I_1X_I$ is in quadrature with $I_1$.

- The phasor difference between $V_1$ and $I_1$ gives the power factor angle $\phi_1$ of the primary side of the transformer.
- The power factor of the secondary side depends upon the type of load connected to the transformer.

1. Which of the following does not change in a transformer?
   (a) Current
   (b) Voltage
   (c) Frequency
   (d) All of the above
2. In a transformer the energy is conveyed from primary to secondary
   (a) Through cooling coil
   (b) Through air
   (c) By the flux
   (d) None of the above

3. A transformer core is laminated to
   (a) Reduce hysteresis loss
   (b) Reduce eddy current losses
   (c) Reduce copper losses
   (d) Reduce all above losses

4. The no-load current drawn by transformer is usually what per cent of the full-load current?
   (a) 0.2 to 0.5 per cent
   (b) 2 to 5 per cent
   (c) 12 to 15 per cent
   (d) 20 to 30 per cent
5. The path of a magnetic flux in a transformer should have
   (a) high resistance
   (b) high reluctance
   (c) low resistance
   (d) low reluctance
6. No-load on a transformer is carried out to determine
   (a) Copper loss
   (b) Magnetizing current
   (c) Magnetizing current and loss
   (d)efficiency of the transformer
7. The dielectric strength of transformer oil is expected to be
   (a) lkV
   (b) 33 kV
   (c) 100 kV
   (d) 330 kV
8. Sumpner's test is conducted on trans-formers to determine
   (a) Temperature
   (b) Stray losses
   (c ) All-day efficiency
   (d) None of the above
9. The efficiency of a transformer will be maximum when
   (a) copper losses = hysteresis losses
   (b) hysteresis losses = eddy current losses
   (c) eddy current losses = copper losses
   (d) copper losses = iron losses
10. The purpose of providing an iron core in a transformer is to
    (a) provide support to windings
    (b) reduce hysteresis loss

(c) decrease the reluctance of the magnetic path
(d) reduce eddy current losses

11. Which of the following is not a part of transformer installation ?
(a) Conservator
(b) Breather
(c) Buchholz relay
(d) Exciter
12. While conducting short-circuit test on a transformer the following side is short circuited
(a) High voltage side
(b) Low voltage side
(c) Primary side
(d) Secondary side
13. A transformer transforms
(a) voltage
(b) current
(c) power
(d) frequency
14. A transformer cannot raise or lower the voltage of a D.C. supply because
(a) there is no need to change the D.C. voltage
(b) a D.C. circuit has more losses
(c) Faraday's laws of electromagnetic induction are not valid since the rate of change of flux is zero
(d) none of the above
15. Primary winding of a transformer
(a) is always a low voltage winding
(b) is always a high voltage winding
(c) could either be a low voltage or high voltage winding
(d) none of the above
16. Which winding in a transformer has more number of turns ?
(a) Low voltage winding
(b) High voltage winding
(c) Primary winding
(d) Secondary winding

17. A common method of cooling a power transformer is
(a) natural air cooling
(b) air blast cooling
(c) oil cooling
(d) any of the above
18. In the transformer the function of a conservator is to
(a) provide fresh air for cooling the transformer
(b) supply cooling oil to transformer in time of need
(c) protect the transformer from damage when oil expends due to heating
(d) none of the above
19. If R2 is the resistance of secondary winding of the transformer and K is the transformation ratio then the equivalent secondary resistance referred to primary will be
(a) R2/VK
(b) R2/K2

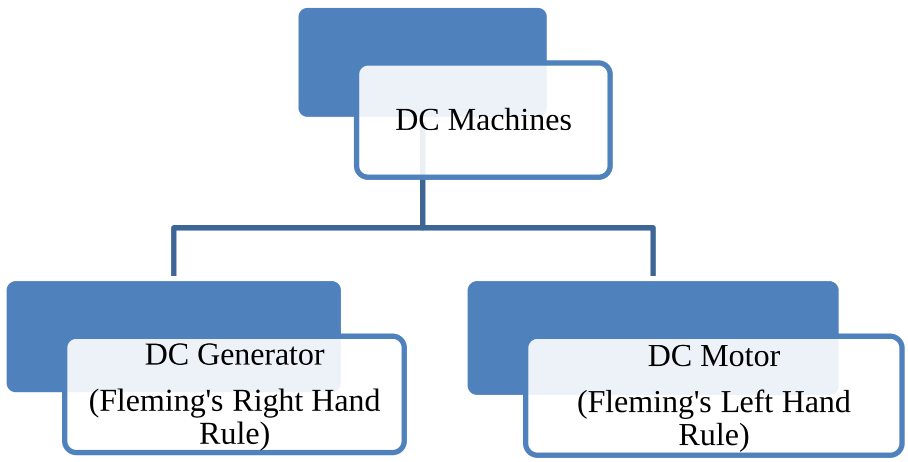
(c) R22/K2
(d) R22/K

20. The chemical used in breather for transformer should have the quality of
    (a) ionizing air
    (b) absorbing moisture
    (c) cleansing the transformer oil
    (d) cooling the transformer oil.
21. The transformer ratings are usually expressed in terms of
    (a) volts
    (b) amperes
    (c) kW
    (d) Kva
22. Hysteresis loss in a transformer varies as Bmax = maximum flux density)
    (a) Bmax
    (b) Bmax1-6
    (C) Bmax1-83
    (d) B max
23. Material used for construction of transformer core is usually
    (a) wood
    (b) copper
    (c) aluminum
    (d) silicon steel
24. The thickness of laminations used in a transformer is usually
    (a) 0.4 mm to 0.5 mm
    (b) 4 mm to 5 mm
    (c) 14 mm to 15 mm
    (d) 25 mm to 40 mm
25. In a transformer the resistance between its primary and secondary is
    (a) zero
    (b) 1 ohm
    (c) 1000 ohms
    (d) infinite
26. A transformer oil must be free from
    (a) sludge
    (b) odor
    (c) gases
    (d) moisture
27. A Buchholz relay can be installed on
    (a) auto-transformers
    (b) air-cooled transformers
    (c) welding transformers
    (d) oil cooled transformers
28. The leakage flux in a transformer depends upon
    (a) load current
    (b) load current and voltage
    (c) load current, voltage and frequency

load current, voltage, frequency and power factor

# DC Machine 1

A DC Machine is an electro-mechanical energy conversion device. There are two types of DC machines; one is DC generator, and another one is known as DC motor. A DC generator converts mechanical power (ωT) into DC electrical power (EI), whereas, a DC motor convert's d.c electrical power into mechanical power. The AC motor is invariably applied in the industry for conversion of electrical power into mechanical power, but at the places where the wide range of speeds and good speed regulation is required, like in electric traction system, a DC motor is used.




The construction of dc motor and generator is nearly same. The generator is employed in a very protected way. Hence there is open construction type. But the motor is used in the location where they are exposed to dust and moisture, and hence it requires enclosures for example dirt proof, fire proof, etc. according to requirement.

Although the battery is an important source of DC electric power, it can only supply limited power to any machines. There are some applications where large quantities of DC power are required, such as electroplating, electrolysis, etc. Hence, at such places, DC generators are used to deliver power.

## Basic Structure of Electrical Machines

The rotating electrical or DC machine has mainly two parts; one is Stator, and another one is Rotar. The stator and rotor are separated from each other by an air gap. The stator is the outer frame of the machine and is immovable. The rotor is free to move and is the inner part of the machine.

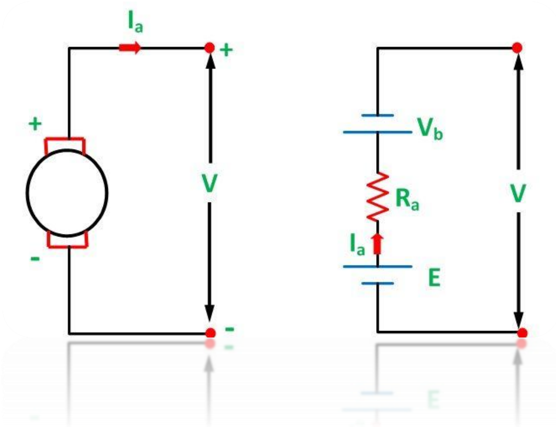
Both the stator and the rotor are made of ferromagnetic materials. Slots are cut on the inner periphery of the stator and the outer periphery of the rotor. Conductors are placed in the slots of the stator or rotor. They are interconnected to form windings.

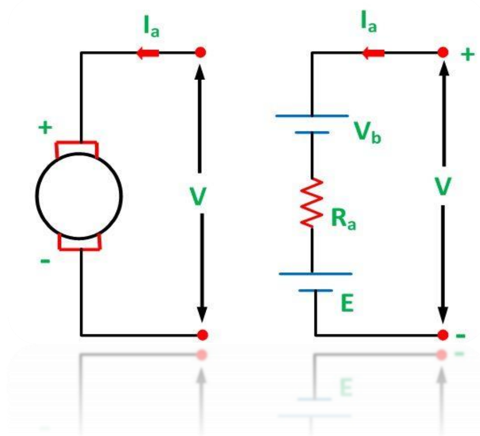
The windings in which voltage is induced is called the Armature windings.The winding through which a current is passed to produce the main flux is called the Field windings. To provide main flux in some of the machine permanent magnets is also used.

Equivalent Circuit of a DC Machine Armature

The armature of a DC generator can be represented by an equivalent electrical circuit. It can be represented by three series-connected elements E, Ra and Vb.

The equivalent circuit of the armature of a DC generator is shown below in the figure.




The equivalent circuit of the armature of a DC Motor is shown below in the figure.

The element E in the equivalent circuit diagrams is the generated voltage, Ra is the armature resistance, and Vb is the brush contact voltage drop.

## Difference between Motor and Generator

The Electric **Motor** and **Generator** are differentiated on various factors like the main principle of working or function of the motor and generator. Consumption or production of electricity, its driven element, the existence of the current in the winding. Fleming's rule followed by the motor and generator.

The **Difference Between** the Motor and the Generator are explained below in the tabulated form.

| BASIS | MOTOR | GENERATOR |
|---|---|---|
| Function | The Motor converts Electrical energy into Mechanical Energy | Generator converts Mechanical energy to Electrical energy. |

| BASIS | MOTOR | GENERATOR |
|---|---|---|
| Electricity | It uses electricity. | It generates electricity |
| Driven element | The Shaft of the motor is driven by the magnetic force developed between armature and field. | The Shaft is attached to the rotor and is driven by mechanical force. |
| Current | In a motor the current is to be supplied to the armature windings. | In the generator current is produced in the armature windings. |
| Rule Followed | Motor follows Fleming's Left hand rule. | Generator follows Fleming's Right hand rule. |
| Example | An electric car or bike is an example of electric motor. | Energy in the form of electricity is generated at the power stations. |

he motor and the generator are almost similar from the construction point of view, as both have stator and rotor. The main difference between the two is that the Motor is an electric device which converts electrical energy into mechanical energy. The generator is vice versa of that motor. It converts mechanical energy into electrical energy.

The Difference between Motor and Generator are as follows:-.

- The Motor converts electric energy into mechanical energy, whereas generator does the opposite.
- Electricity is used in the motor, but the generator produces the electricity.
- The Shaft of the motor is driven by the magnetic force developed between armature and field windings whereas, in the case of the Generator the Shaft is attached to the rotor and is driven by mechanical force.
- The current is to be supplied to the armature windings in case of a Motor, and in Generator, current is produced in the armature windings.
- Motor follows Fleming's Left hand rule while Generator follows Fleming's Right hand rule.
- The example of Motor is an electric car or bike where electric current is supplied to the machine or device, and it gets converted into mechanical motion and, as a result, the car or bike moves. The example of Generator is that in power stations the turbine is used as a device which converts mechanical energy of force of water falling from the dam to generate electric energy.

# Applications of DC Machines

In the present day world, the electrical energy is generated in bulk in the form of an alternating current. Hence, the use of DC machines, i.e., DC generators and motors are very limited. They are mainly used in supplying excitation of small and medium range alternators. The Industrial Applications of DC are in Electrolytic Processes, Welding processes and Variable speed motor drives.

Now days, the alternating current is generated first and then it is converted into DC by the rectifiers. Thus, DC generator has generally been suppressed by a rectified AC supply for many applications.

Direct current motors are very commonly used as variable speed drives and in applications where severe torque variations occur.

### Applications of DC Motors

The main applications of the three types of direct current motors are given below.

#### Series Motors

The series DC motors are used where high starting torque is required, and variations in speed are possible. For example – the series motors are used in Traction system, Cranes, air compressors, Vacuum Cleaner, Sewing machine, etc.

#### Shunt Motors

The shunt motors are used where constant speed is required and starting conditions are not severe. The various applications of DC shunt motor are in Lathe Machines, Centrifugal Pumps, Fans, Blowers, Conveyors, Lifts, Weaving Machine, Spinning machines, etc.

#### Compound Motors

The compound motors are used where higher starting torque and fairly constant speed is required. The examples of usage of compound motors are in Presses, Shears, Conveyors, Elevators, Rolling Mills, Heavy Planners, etc.

The small DC machines whose ratings are in fractional kilowatt are mainly used as control device such in Techno generators for speed sensing and in Servo motors for positioning and tracking.

### Applications of DC Generators

The applications of the various types of DC Generators are as follows:-

#### Separately Excited DC Generators

- Separately excited DC Generators are used in laboratories for testing as they have a wide range of voltage output.
- Used as a supply source of DC motors.

**Shunt wound Generators**

- DC shunt wound generators are used for lighting purposes.
- Used to charge the battery.
- Providing excitation to the alternators.

**Series Wound Generators**

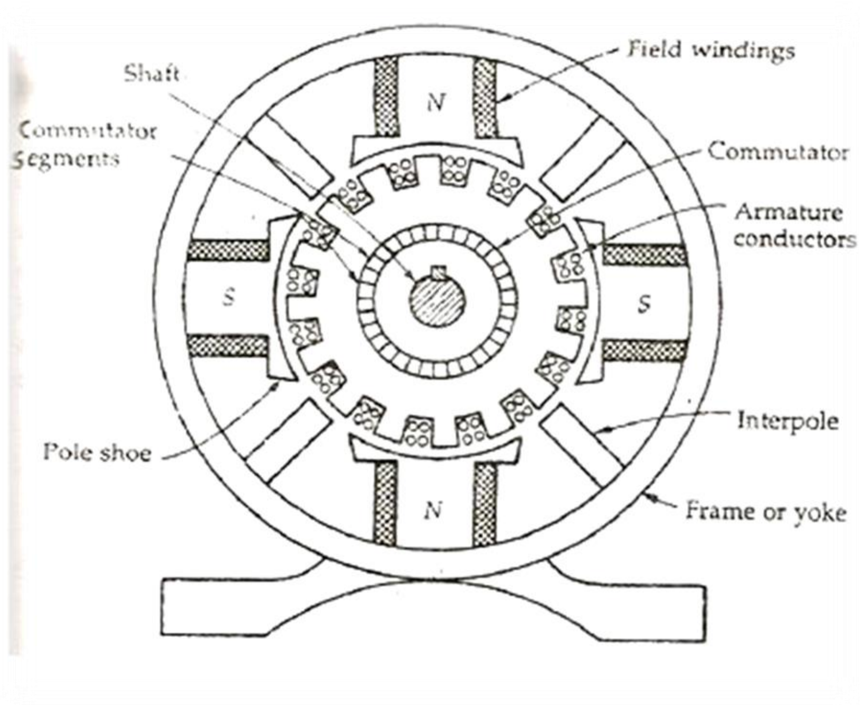
- DC series wound generators are used in DC locomotives for regenerative braking for providing field excitation current.
- Used as a booster in distribution networks.
- Over compounded cumulative generators are used in lighting and heavy power supply.
- Flat compounded generators are used in offices, hotels, homes, schools, etc.
- Differentially compounded generators are mainly used for arc welding purpose.

# DC Machine 2

## Construction of a DC Machines

A DC Generator is an electrical device which converts mechanical energy into electrical energy. It mainly consists of three main parts, i.e. Magnetic field system, Armature and Commutator and Brush gear. The other parts of a DC Generator are Magnetic frame and Yoke, Pole Core and Pole Shoes, Field or Exciting coils, Armature Core and Windings, Brushes, End housings, Bearings and Shafts.

The diagram of the main parts of a 4 pole DC Generator or DC Machine is shown below.




### Magnetic Field System of DC Generator

The Magnetic Field System is the stationary or fixed part of the machine. It produces the main magnetic flux. The magnetic field system consists of Mainframe or Yoke, Pole core and Pole shoes and Field or Exciting coils. These various parts of DC Generator are described below in detail.

### Magnetic Frame and Yoke

The outer hollow cylindrical frame to which main poles and inter-poles are fixed and by means of which the machine is fixed to the foundation is known as Yoke. It is made of cast steel or rolled steel for the large machines and for the smaller size machine the yoke is generally made of cast iron.

The two main purposes of the yoke are as follows:-

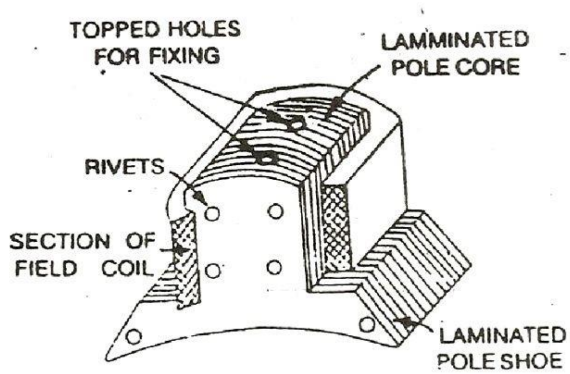
- It supports the pole cores and provides mechanical protection to the inner parts of the machines.

- It provides a low reluctance path for the magnetic flux.

### Pole Core and Pole Shoes

The Pole Core and Pole Shoes are fixed to the magnetic frame or yoke by bolts. Since the poles, project inwards they are called salient poles. Each pole core has a curved surface. Usually, the pole core and shoes are made of thin cast steel or wrought iron laminations which are riveted together under hydraulic pressure. The poles are laminated to reduce the Eddy Current loss.

The figure of pole core and pole shoe is shown below.

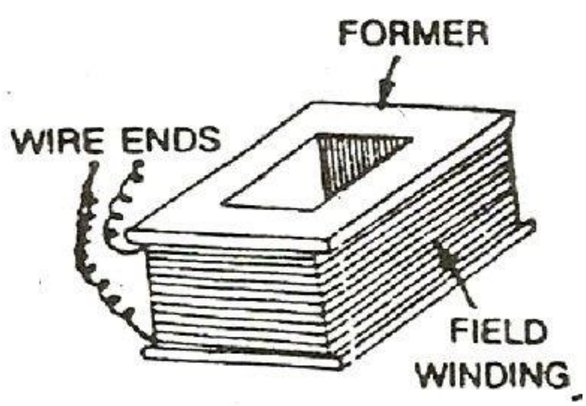



The poles core serves the following purposes given below.

- It supports the field or exciting coils.
- They spread out the magnetic flux over the armature periphery more uniformly.
- It increases the cross-sectional area of the magnetic circuit; as a result, the reluctance of the magnetic path is reduced.

### Field or Exciting Coils

Each pole core has one or more field coils (windings) placed over it to produce a magnetic field. The enameled copper wire is used for the construction of field or exciting coils. The coils are wound on the former and then placed around the pole core.



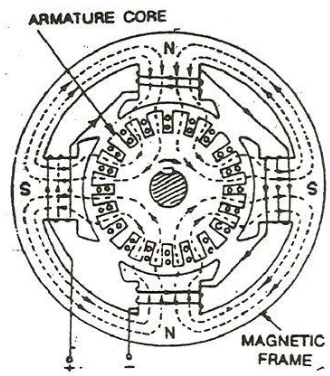

When direct current passes through the field winding, it magnetizes the poles, which in turns produces the flux. The field coils of all the poles are connected in series in such a way that when current flows through them, the adjacent poles attain opposite polarity.

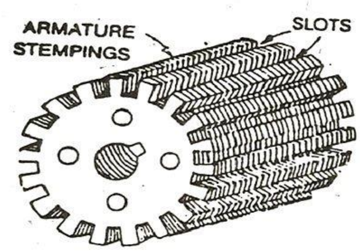
### Armature of DC Generator

The rotating part of the DC machine or a DC Generator is called the Armature. The armature consists of a shaft upon which a laminated cylinder, called Armature Core is placed.

### Armature Core

The armature core of DC Generator is cylindrical in shape and keyed to the rotating shaft. At the outer periphery of the armature have grooves or slots which accommodate the armature winding as shown in the figure below.




The armature core of a DC generator or machine serves the following purposes.

- It houses the conductors in the slots.
- It provides an easy path for the magnetic flux.

As the armature is a rotating part of the DC Generator or machine, the reversal of flux takes place in the core, hence hysteresis losses are produced. The silicon steel material is used for the construction of the core to reduce the hysteresis losses.

The rotating armature cuts the magnetic field, due to which an emf is induced in it. This emf circulates the eddy current which results in Eddy Current loss. Thus to reduce the loss the armature core is laminated with a stamping of about 0.3 to 0.5 mm thickness. Each lamination is insulated from the other by a coating of varnish.

### Armature Winding

The insulated conductors are placed in the slots of the armature core. The conductors are wedged, and bands of steel wire wound around the core and are suitably connected. This arrangement of conductors is called Armature Winding. The armature winding is the heart of the DC Machine.

Armature winding is a place where conversion of power takes place. In the case of a DC Generator here, mechanical power is converted into electrical power. On the basis of connections, the windings are classified into two types named as Lap Winding and Wave Winding.

- **Lap Winding**

In lap winding, the conductors are connected in such a way that the number of parallel paths is equal to the number of poles. Thus, if a machine has P poles and Z armature conductors, then there will be P parallel paths; each path will have Z/P conductors connected in series.

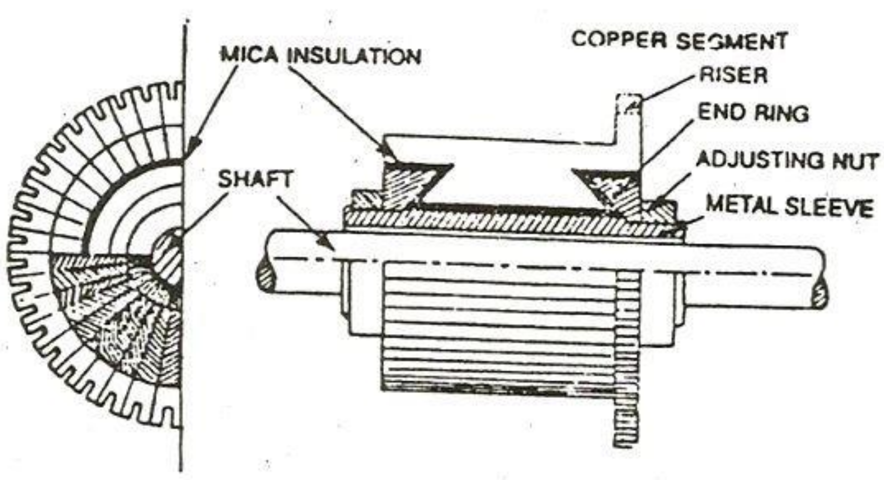
In lap winding, the number of brushes is equal to the number of parallel paths. Out of which half the brushes are positive and the remaining half is negative.

- **Wave Winding**

In wave winding, the conductors are so connected that they are divided into two parallel paths irrespective of the number of poles of the machine. Thus, if the machine has Z armature conductors, there will be only two parallel paths each having Z/2 conductors in series. In this case number of brushes is equal to two, i.e. number of parallel paths.

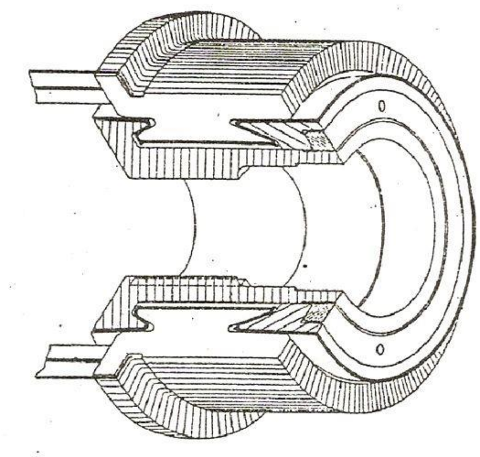
**Commutator in DC Generator**

The Commutator, which rotates with the armature, is cylindrical in shape and is made from a number of wedge-shaped hard drawn copper bars or segments insulated from each other and from the shaft. The segments form a ring around the shaft of the armature. Each Commutator segment is connected to the ends of the armature coils.




It is the most important part of a DC machine and serves the following purposes.

- It connects the rotating armature conductors to the stationary external circuit through brushes.
- It converts the induced alternating current in the armature conductor into unidirectional current in the external load circuit in DC Generator action, whereas it converts the alternating torque into unidirectional (continuous) torque produced in the armature in motor action.



### Brushes

Carbon brushes are placed or mounted on the Commutator and with the help of two or more carbon brushes current is collected from the armature winding. Each brush is supported in a metal box called a **brush box** or **brush holder**. The brushes are pressed upon the Commutator and form the connecting link between the armature winding and the external circuit.

The pressure exerted by the brushes on the Commutator can be adjusted and is maintained at a constant value by means of springs. With the help of the brushes the current which is produced on the windings, is passed on to the Commutator and then to the external circuit.

They are usually made of high-grade carbon because carbon is conducting material and at the same time in powdered form provides a lubricating effect on the Commutator surface.

### End Housings

End housings are attached to the ends of the Mainframe and provide support to the bearings. The front housings support the bearing and the brush assemblies where as the rear housings usually support the bearings only.

### Bearings

The ball or roller bearings are fitted in the end housings. The function of the bearings is to reduce friction between the rotating and stationary parts of the machine. Mostly high carbon steel is used for the construction of bearings as it is very hard material.

## Shaft

The shaft is made of mild steel with a maximum breaking strength. The shaft is used to transfer mechanical power from or to the machine. The rotating parts like armature core, Commutator, cooling fans, etc. are keyed to the shaft.

# DC Machine 3

## Types of DC Generator

The DC generator converts the electrical power into electrical power. The magnetic flux in a DC machine is produced by the field coils carrying current. The circulating current in the field windings produces a magnetic flux, and the phenomenon is known as **Excitation**. DC Generator is classified according to the methods of their field excitation.

By excitation, the DC Generators are classified as separately excited DC Generators and Self-excited DC Generators. There is also Permanent magnet type DC generators. The self-excited DC Generators are further classified as Shunt wound DC generators; Series wound DC generators and Compound wound DC generators. The Compound Wound DC generators are further divided as long shunt wound DC generators, and short shunt wound DC generators.

The field pole of the DC generator is stationary, and the armature conductor rotates. The voltage generated in the armature conductor is of alternating nature, and this voltage is converted into the direct voltage at the brushes with the help of the Commutator.

The detailed description of the various types of generators is explained below.

### Permanent Magnet type DC Generator

In this type of DC generator, there is no field winding is placed around the poles. The field produced by the poles of these machines remains constant. Although these machines are very compact but are used only in small sizes like dynamos in motorcycles, etc. The main disadvantage of these machines is that the flux produced by the magnets deteriorates with the passage of time which changes the characteristics of the machine.

### Separately Excited DC Generator

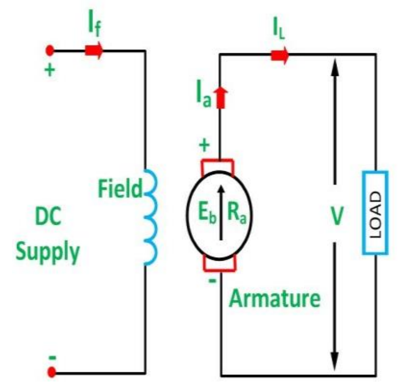
A DC generator whose field winding or coil is energized by a separate or external DC source is called a separately excited DC Generator. The flux produced by the poles depends upon the field current with the unsaturated region of magnetic material of the poles. I.e. flux is directly proportional to the field current. But in the saturated region, the flux remains constant.

The figure of self-excited DC Generator is shown below.

Here,

$I_a = I_L$ where $I_a$ is the armature current and $I_L$ is the line current.

Terminal voltage is given as




*Separately Excited DC Generator*

$$V = E_g - I_a R_a \quad \ldots\ldots(1)$$

If the contact brush drop is known, then the equation (1) is written as

$$V = E_g - I_a R_a - 2v_b \quad \ldots\ldots(2)$$

The power developed is given by the equation shown below.

$$\text{Power developed} = E_g I_a \quad \ldots\ldots\ldots(3)$$

$$\text{Power output} = VI_L = VI_a \quad \ldots\ldots\ldots(4)$$

Power output is given by the equation (4) shown above.

### Self Excited DC Generator

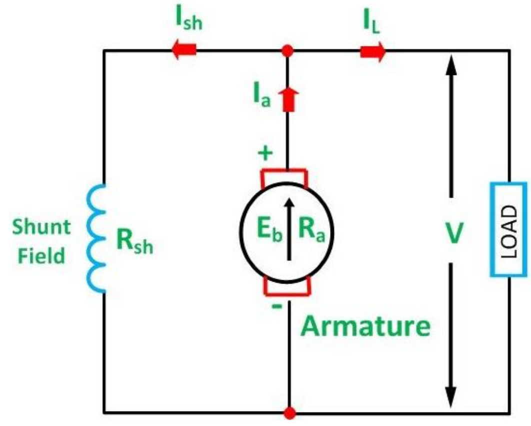
Self-excited DC Generator is a device, in which the current to the field winding is supplied by the generator itself. In self-excited DC generator, the field coils mat be connected in parallel with the armature in the series, or it may be connected partly in series and partly in parallel with the armature windings.

**The self-excited DC Generator is further classified as**

## Shunt Wound Generator

In a **shunt wound generator,** the field winding is connected across the armature winding forming a parallel or shunt circuit. Therefore, full terminal voltage is applied across it. A very small field current $I_{sh}$, flows through it because this winding has many turns of fine wire having very high resistance $R_{sh}$ of the order of 100 ohms.

The connection diagram of shunt wound generator is shown below.




*Shunt Wound DC Generator*

Shunt field current is given as

$$I_{sh} = \frac{V}{R_{sh}}$$

Where $R_{sh}$ is the shunt field winding resistance.

The current field $I_{sh}$ is practically constant at all loads. Therefore, the DC shunt machine is considered to be a constant flux machine.

Armature current is given as

$$I_a = I_L + I_{sh}$$

Terminal voltage is given by the equation shown below.

$$V = E_g - I_a R_a$$

If the brush contact drop is included, the equation of the terminal voltage becomes

$$V = E_g - I_a R_a - 2v_b$$

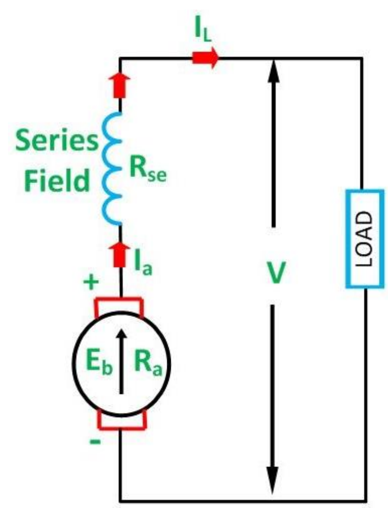
$$\text{Power developed} = E_g I_a$$

$$\text{Power output} = V I_L$$

### Series Wound Generator

A **series-wound generator** the field coils are connected in series with the armature winding. The series field winding carries the armature current. The series field winding consists of a few turns of wire of thick wire of larger cross-sectional area and having low resistance usually of the order of less than 1 ohm because the armature current has a very large value.

Its convectional diagram is shown below.




*Series Wound DC Generator*

Series field current is given as

$$I_{se} = I_L = I_a$$

$R_{se}$ is known as the series field winding resistance.

Terminal voltage is given as

$$V = E_g - I_a R_a - I_{se} R_{se}$$

$$V = E_g - I_a (R_a + R_{se})$$

If the brush contact drop is included, the terminal voltage equation is written as

$$V = E_g - I_a (R_a + R_{se}) - 2V_b$$

$$\text{Power developed} = E_g I_a$$

$$\text{Power output} = V I_L = V I_a$$

The flux developed by the series field winding is directly proportional to the current flowing through it. But it is only true before magnetic saturation after the saturation flux becomes constant even if the current flowing through it is increased.

### Compound Wound Generator

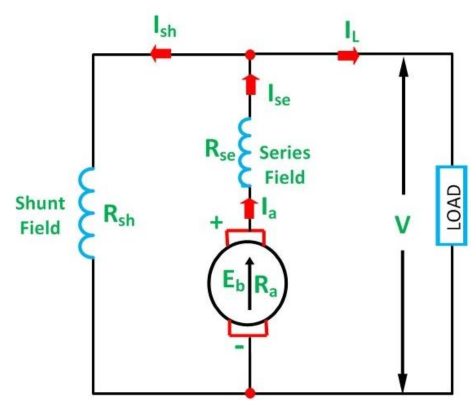
In a compound-wound generator, there are two field windings. One is connected in series, and another is connected in parallel with the armature windings. There are two types of compound-wound generator.

- Long shunt compound-wound generator
- Short shunt compound-wound generator

For a detailed study of the compound-wound generator, refer the topic Compound Wound Generator.

### Long Shunt Compound Wound Generator

In a long shunt wound generator, the shunt field winding is parallel with both armature and series field winding. The connection diagram of long shunt wound generator is shown below.




*Long Shunt Compound Wound Generator*

Shunt field current is given as

$$I_{sh} = \frac{V}{R_{sh}}$$

Series field current is given as

$$I_{se} = I_a = I_L + I_{sh}$$

Terminal voltage is given as

$$V = E_g - I_a R_a - I_{se} R_{se} = E_g - I_a (R_a + R_{se})$$

If the brush contact drop is included, the terminal voltage equation is written as

$$V = E_g - I_a (R_a + R_{se}) - 2V_b$$

$$\text{Power developed} = E_g I_a$$

$$\text{Power output} = VI_L$$

### Short Shunt Compound Wound Generator

In a Short Shunt Compound Wound Generator, the shunt field winding is connected in parallel with the armature winding only. The connection diagram of short shunt wound generator is shown below.

Series field current is given as

$$I_{se} = I_L$$

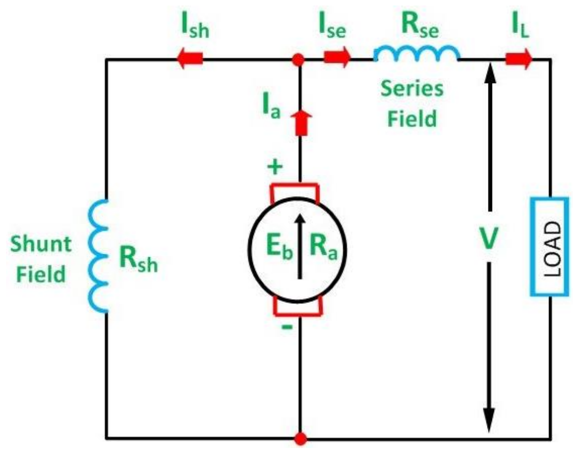
Shunt field current is given as

$$I_{sh} = \frac{V + I_L R_{se}}{R_{sh}} = \frac{E_g - I_a R_a}{R_{sh}}$$

$$I_a = I_L + I_{sh}$$

Terminal voltage is given as

$$V = E_g - I_a R_a - I_L R_{se}$$




*Short Shunt Compound Wound Generator*

If the brush contact drop is included, the terminal voltage equation is written as

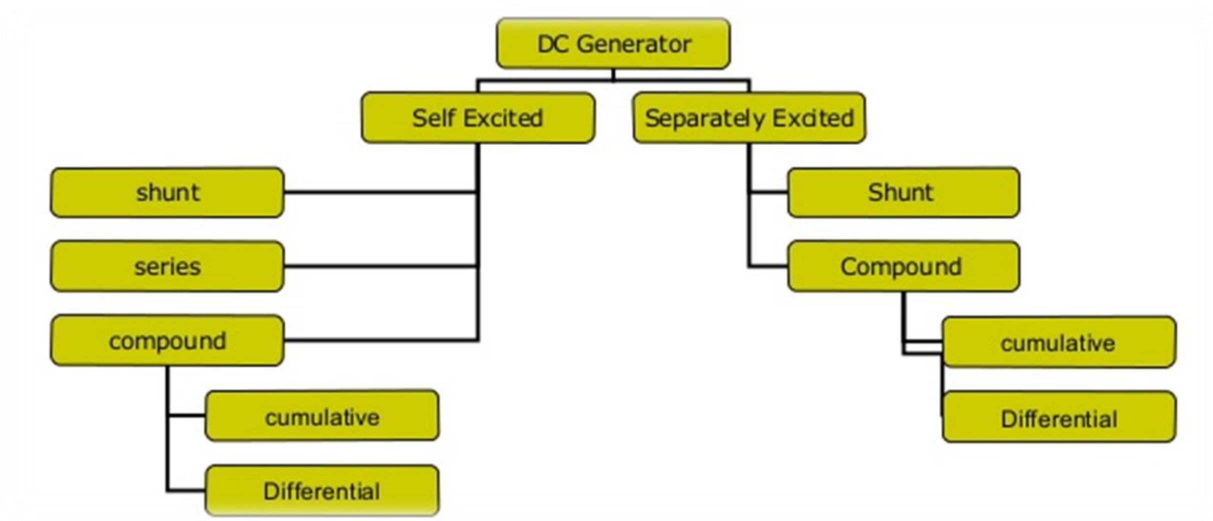
$$V = E_g - I_a R_a - I_L R_{se} - 2V_b$$

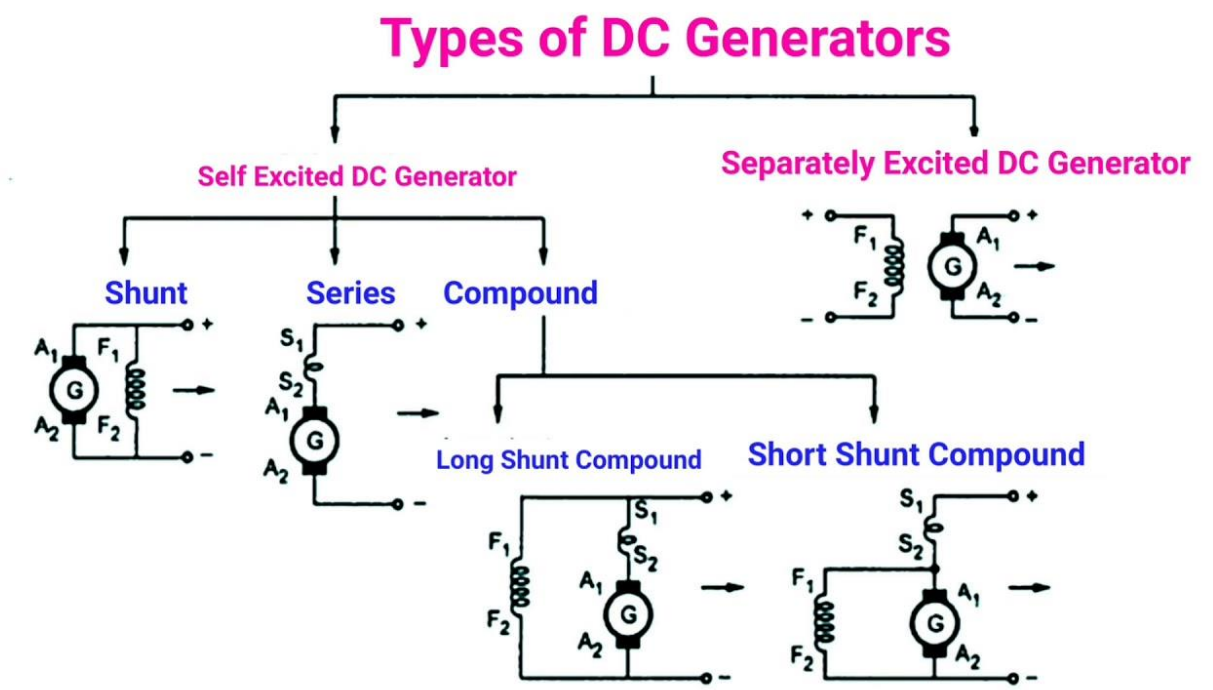
$$\text{Power developed} = E_g I_a$$

$$\text{Power output} = V I_L$$

In this type of DC generator, the field is produced by the shunt as well as series winding. The shunt field is stronger than the series field. If the magnetic flux produced by the series winding assists the flux produced by the shunt field winding, the generator is said to be Cumulatively Compound Wound generator.

If the series field flux opposes the shunt field flux, the generator is said to be Differentially Compounded.

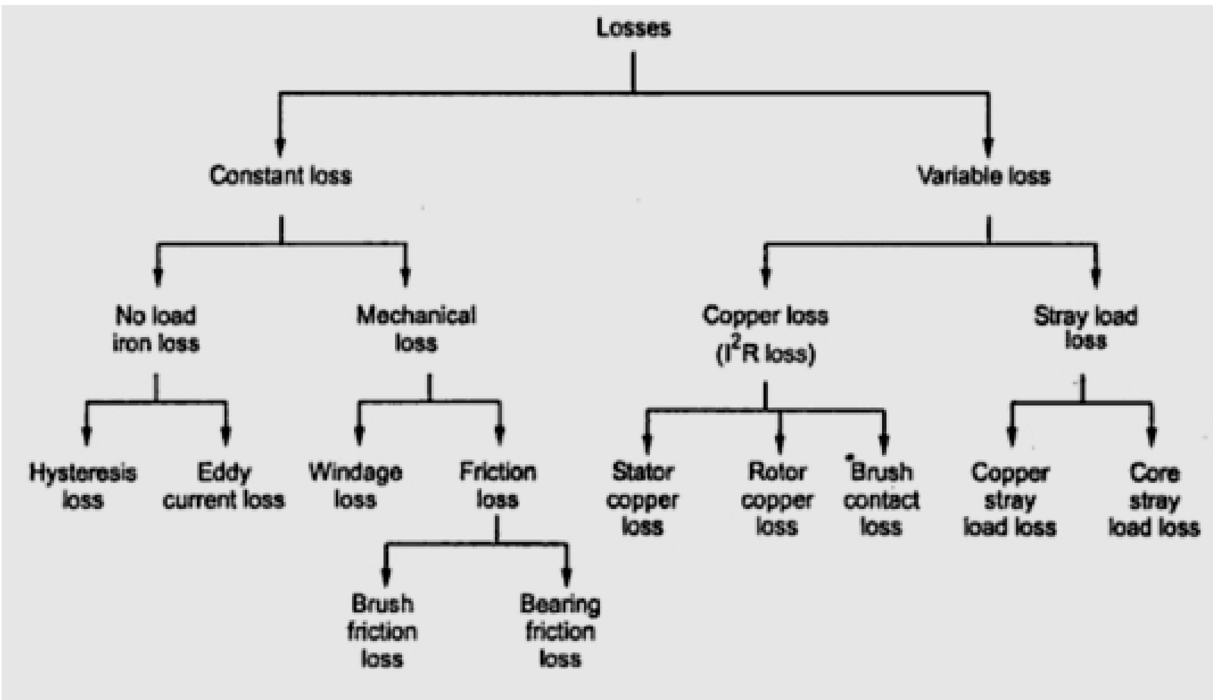


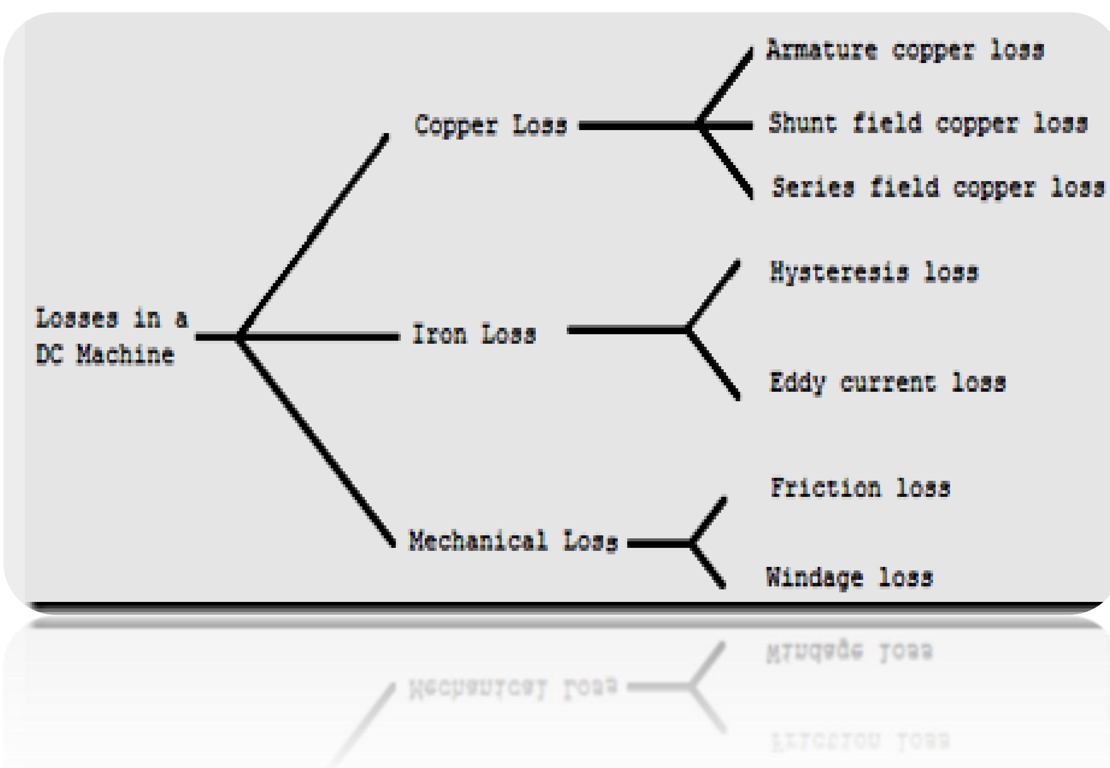

Types of DC Generators
Self Excited DC Generator
Separately Excited DC Generator
Shunt
Series
Compound
Long Shunt Compound
Short Shunt Compound

# DC Machine 4

## Losses in DC Machine

The losses that occur in a DC Machine is divided into five basic categories. The various losses are Electrical or Copper losses (I2R losses), Core lossesor Iron losses, Brush losses, Mechanical losses, Stray load losses. These losses are explained below in detail.



**Electrical or Copper Losses in dc machine**

These losses are also known as Winding losses as the copper loss occurs because of the resistance of the windings. The ohmic loss is produced by the current flowing in the windings. The windings that are present in addition to the armature windings are the field windings, interlopes and compensating windings.

Armature copper losses = $I_a^2R_a$ where $I_a$ is armature current, and Ra is the armature resistance. These losses are about 30 percent of the total full load losses.

In shunt machine, the Copper loss in the shunt field is $I^2_{sh}R_{sh}$, where $I_{sh}$ is the current in the shunt field, and $R_{sh}$ is the resistance of the shunt field windings. The shunt regulating resistance is included in $R_{sh}$.

In a series machine, the copper loss in the series windings is $I^2_{se}R_{se}$, where, $I_{se}$ is the current through the series field windings, and $R_{se}$ is the resistance of the series field windings.

In a Compound machine, both the shunt and the series field losses occur. These losses are almost 20 percent of the full load losses.

Copper losses in the Interpole windings are written as $I_a^2R_i$ where $R_i$ is the resistance of the Interpole windings.

Copper loss in the compensating windings if any is $I_a^2R_c$ where $R_c$ is the resistance of compensating windings.

**Magnetic Losses or Core Losses or Iron Losses in dc machine**

The core losses are the hysteresis and eddy current losses. These losses are considered almost constant as the machines are usually operated at constant flux density and constant speed. These losses are about 20 percent of the full load losses.

**Brush Losses in dc machine**

Brush losses are the losses taking place between the Commutator and the carbon brushes. It is the power loss at the brush contact point. The brush drop depends upon the brush contact voltage drop and the armature current Ia. It is given by the equation shown below.

$$P_{BD} = V_{BD}I_a$$

The voltage drop occurring over a large range of armature currents, across a set of brushes is approximately constant If the value of brush voltage drop is not given than it is usually assumed to be about 2 volts. Thus, the brush drop loss is taken as $2I_a$.

**Mechanical Losses in dc machine**

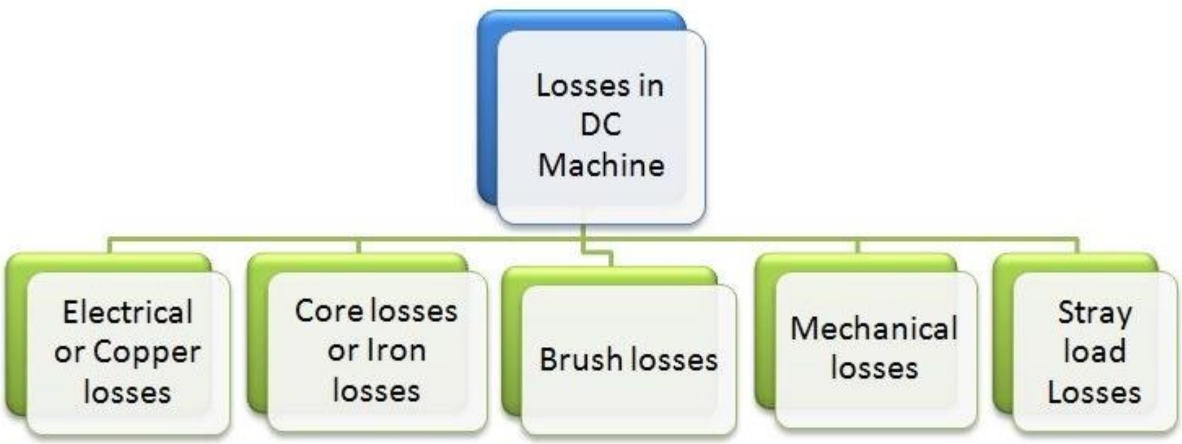
The losses that take place because of the mechanical effects of the machines are known as mechanical losses. Mechanical losses are divided into bearing friction loss and windage loss. The losses occurring in the moving parts of the machine and the air present in the machine is known as Windage losses. These losses are very small.

**Stray Losses in dc machine**

These losses are the miscellaneous type of losses. The following factors are considered in stray load losses.

- The distortion of flux because of armature reaction.
- Short circuit currents in the coil, undergoing commutation.

These losses are very difficult to determine. Therefore, it is necessary to assign the reasonable value of the stray loss. For most machines, stray losses are taken by convention to be one percent of the full load output power.



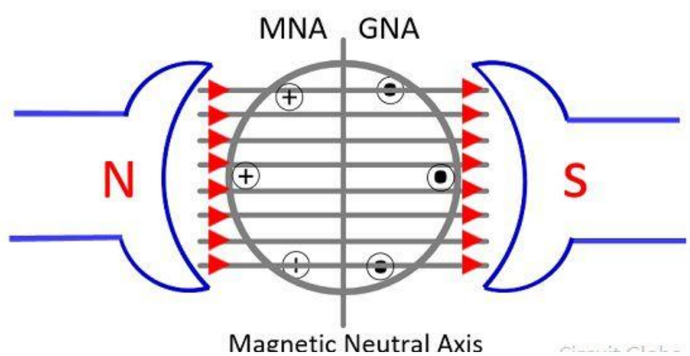
# DC Machine 5

## Armature Reaction

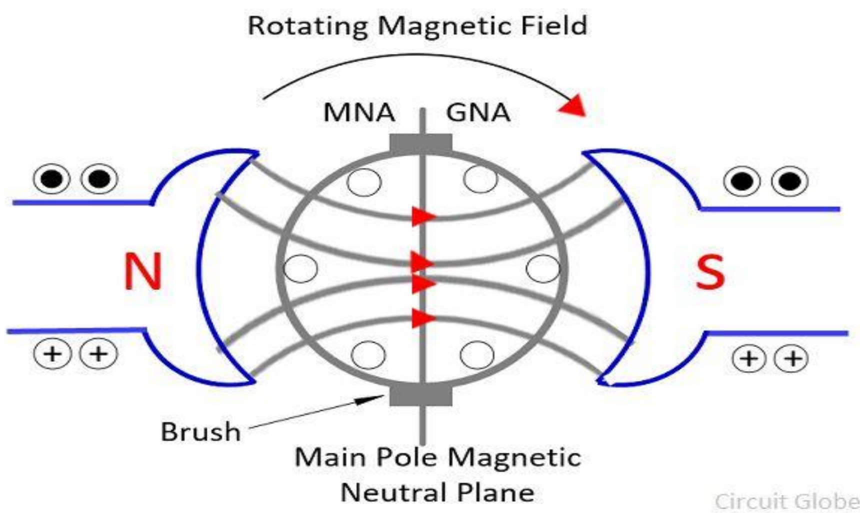
The armature reaction simply shows the effect of armature field on the main field. In other words, the armature reaction represents the impact of the armature flux on the main field flux. The armature field is produced by the armature conductors when current flows through them. And the main field is produced by the magnetic poles.

The armature flux causes two effects on the main field flux.

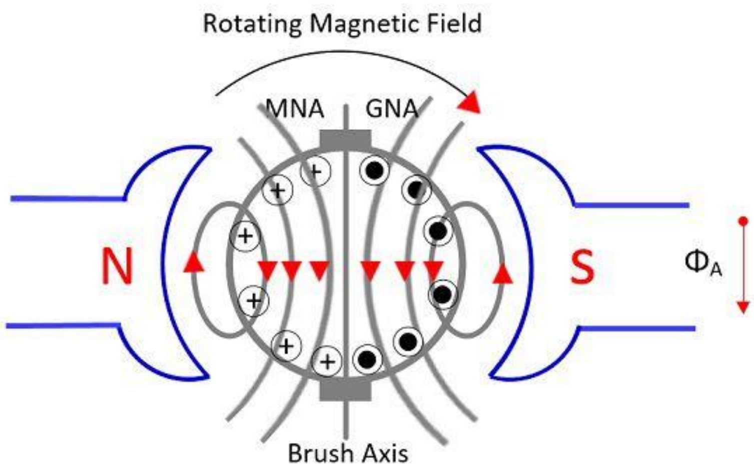
- The armature reaction distorted the main field flux
- It reduces the magnitude of the main field flux.




Consider the figure below shows the two poles dc generator. When no load connected to the generator, the armature current becomes zero. In this condition, only the MMF of the main poles exists in the generator. The MMF flux is uniformly distributed along the magnetic axis. The magnetic axis means the centre line between the north and South Pole. The arrow in the below-given image shows the direction of the magnetic flux $\Phi_M$. The magnetic neutral axis or plane is perpendicular to the axis of the magnetic flux.



The MNA coincides with the geometrical neutral axis (GNA). The brushes of the DC machines are always placed in this axis, and hence this axis is called the axis of commutation.

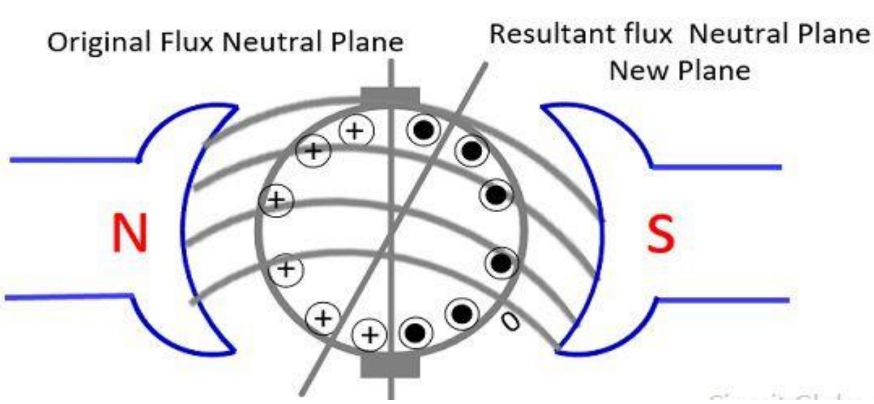



Consider the condition in which only the armature conductors carrying current and no current flows through their main poles. The direction of current remains same in all the conductors which lying under one pole. The direction of current induces in the conductor is given by the Fleming right-hand rule. And the direction of flux generates in the conductors is given by the cork-screw rule.

The direction of current on the left sides of the armature conductor goes into the paper (represented by the cross inside the circle). The armature conductors combine their MMF for generating the fluxes through the armature in the downward direction.

Similarly, the right-hand side conductors carry current, and their direction goes out of the paper (shown by dots inside the circle). The conductor on the right-hand sides is also combining their MMF for producing the flux in the downwards direction. Hence, the conductor on both the sides combines their MMF in such a way so that their flux goes downward direction. The flux induces in the armature conductor $\Phi_A$ is given by the arrow shown above.

The figure below shows the condition in which the field current and the armature current are simultaneously acting on the conductor.



This happens when machines running at no load condition. Now the machine has two fluxes, i.e., the armature flux and the field pole flux. The armature flux is produced by the current induces in the armature conductors while the field pole flux is induced because of the main field poles. These two flux combines and gives the resultants flux $\Phi_R$ as shown in the figure above.

When the field flux enters into the armature, they may get distorted. The distortion increases the density of the flux in the upper pole tip of N-pole and the lower pole tip of the south pole. Similarly, the density of flux decreases in the lower pole tip of the north pole and the upper pole tip of the south pole.

The resultant flux induces in the generator are shifted towards the direction of the rotation of generator. The magnetic neutral axis of poles is always perpendicular to the axis of the resultant flux. The MNA is continuously shifted with the resultant flux.

## Effect of Armature Reaction

The effects of Armature Reaction are as follows:-

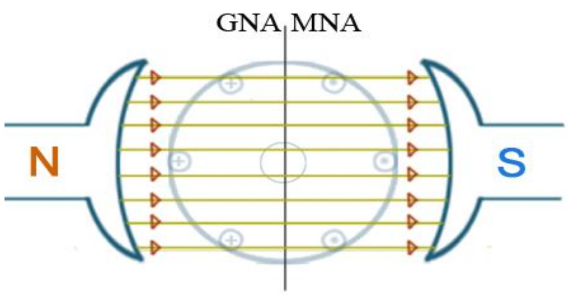
- Because of the armature reaction the flux density of over one-half of the pole increases and over the other half decreases. The total flux produces by each pole is slightly less due to which the magnitude of the terminal voltage reduces. The effect due to which the armature reaction reduces the total flux is known as the demagnetizing effect.
- The resultant flux is distorted. The direction of the magnetic neutral axis is shifted with the direction of resultant flux in case of the generator, and it is opposite to the direction of the resultant flux in case of the motor.
- The armature reaction induces flux in the neutral zone, and this flux generates the voltage that causes the commutation problem.

The MNA axis is the axis in which the value of induced MEF becomes zero. And the GNA divides the armature core into two equal parts.

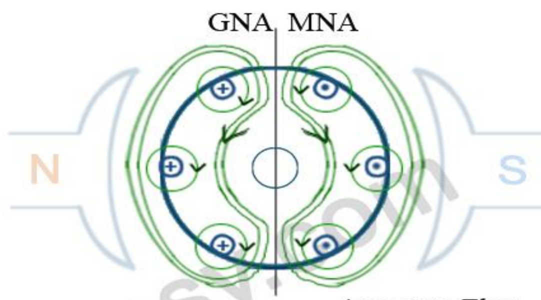
### MNA And GNA

EMF is induced in the armature conductors when they cut the magnetic field lines. There is an axis (or, you may say, a plane) along which armature conductors move parallel to the flux lines and, hence, they do not cut the flux lines while on that plane. MNA (Magnetic Neutral Axis) may be defined as the axis along which no emf is generated in the armature conductors as they move parallel to the flux lines. Brushes are always placed along the MNA because reversal of current in the armature conductors takes place along this axis.

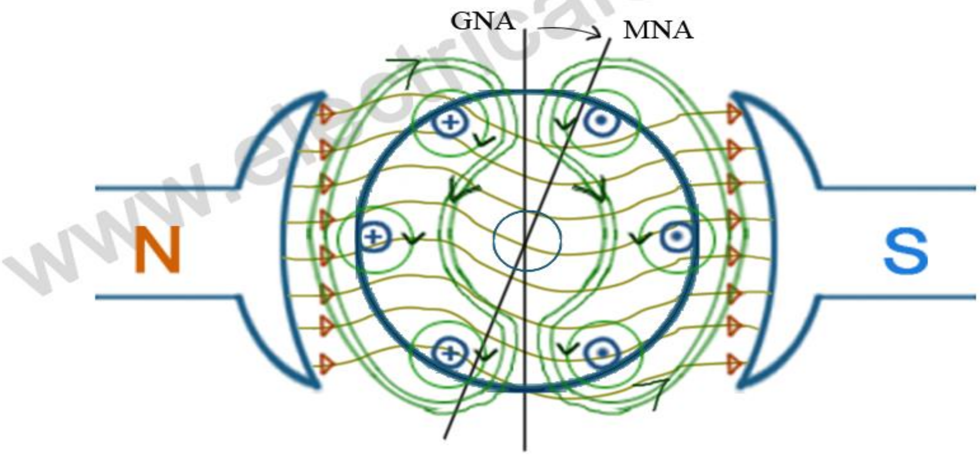
GNA (Geometrical Neutral Axis) may be defined as the axis which is perpendicular to the stator field axis.




Main field flux




Armature Flux




Distortion of main field flux due to armature flux - Armature reaction

# Remedies to Armature Reaction Effect

Usually, no special efforts are taken for small machines (up to few kilowatts) to reduce the armature reaction. But for large DC machines, compensating winding and interlopes are used to get rid of the ill effects of armature reaction.

In order to reduce the effect of armature reaction following methods are used.

**1. Compensating Winding**

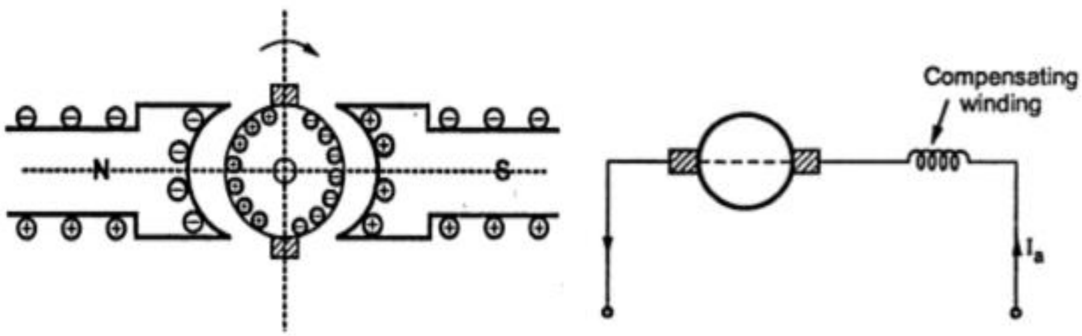
Commutation problem is not the only problem in DC machines. At heavy loads, the cross magnetizing armature reaction may cause very high flux density in the trailing pole tip in generator action and leading pole tip in the motor action. Consequently, the coil under this tip may develop induced voltage high enough to cause a flash over between the associated adjacent Commutator segments particularly, because this coil is physically close to the commutation zone (at the brushes) where the air temperature might be already high due to commutation process.
This flash over may spread to the neighboring Commutator segments, leading ultimately to a complete fire over the Commutator surface from brush to brush. Also, when the machine is subjected to rapidly fluctuating loads, then the voltage L× di/dt, that appears across the adjacent Commutator segments may reach a value high enough to cause flash over between the adjacent Commutator segments. This would start from the center of pole as the coil below it possesses the maximum inductance. This may again cause a similar fire as described above. This problem is more acute while the load is decreasing in generating action and increasing

in motor action as then, the induced emf and voltage L× di/dt will support each other. The above problems are solved by use of compensating winding.

Compensating winding consists of conductors embedded in the pole face that run parallel to the shaft and carry an armature current in a direction opposite to the direction of current in the armature conductors under that pole arc. With complete compensation the main field is restored. This also reduces armature circuit's inductor and improves system response. Compensating winding functions satisfactorily irrespective of the load, direction of rotation and mode of operation. Obviously it is help in commutation as the inter polar winding gets relieved from its duty to compensate for the armature mmf under the pole arc.

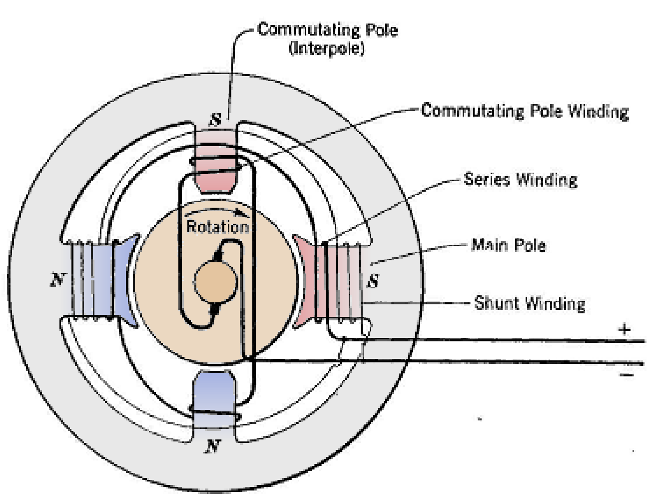
Compensating windings major drawbacks:

- In large machines subject to heavy overloads or plugging
- In small motors subject to sudden reversal and high acceleration.




**2. Inter Pole**

The limitation of brush shift has led to the use of inter poles in almost all the medium and large sized DC machines. Inter poles are long but narrow poles placed in the inter polar axis. They have the polarity of succeeding pole (coming next in sequence of rotation) in generator action and proceeding (which has passed behind in rotation sequence) pole in motor action. The inter pole is designed to neutralize the armature reaction mmf in the inter polar axis. Since inter poles are connected in series with armature, the change in direction of current in armature changes direction of inter pole.



This is because the direction of armature reaction mmf is in the inter polar axis. It also provides commutation voltage for the coil undergoing commutation such that the commutation voltage completely neutralizes the reactance voltage (L × di/dt). Thus, no sparking takes place. Inter polar windings are always kept in series with armature, so inter polar winding carries the armature current; therefore works satisfactorily irrespective of load, the direction of rotation or the mode of operation. Inter poles are made narrower to ensure that they influence only the coil undergoing commutation and its effect does not spread to the other coils. The base of the inter poles is made wider to avoid saturation and to improve response.

**3. Brush Shift**

The armature reaction causes shifting the magnetic neutral axis. Therefore there will be some flux density at brush axis which produces emf. in the coil undergoing commutation. This will lead to delayed commutation. Thus the armature reaction at brush axis must be neutralized. This requires another equal and opposite mmf. to that of armature mmf. This can be applied by interlopes which are placed at geometric neutral axis at midway between the main poles.

**4.** The armature reaction causes the distortion in main field flux. This can be reduced if the reluctance of the path of the cross-magnetizing field is increased. The armature teeth and air gap at pole tips offer reluctance to armature flux. Thus by increasing length of air gap, the armature reaction effect is reduced.

**5.** If reluctance at pole tips is increased it will reduce distorting effect of armature reaction. By using special construction in which leading and trialing pole tip portions of laminations are alternately omitted.