Transformers and Generators

MODULE - 1

Single phase Transformers: Review of Principle of operation, constructional details of shell type and core type single-phase transformers, EMF equation, losses and commercial efficiency, conditions for maximum efficiency (No question shall be set from the review portion). Salient features of ideal transformer, operation of practical transformer under no - load and on - load with phasor diagrams. Equivalent circuit, Open circuit and Short circuit tests, calculation of equivalent circuit parameters and predetermination of efficiency Commercial and all-day. Voltage regulation and its significance.

Three-phase Transformers: Introduction, Constructional features of three-phase transformers. Choice between single unit three-phase transformer and a bank of three single-phase transformers. Transformer connection for three phase operation – star/star, delta/delta, star/delta, zigzag/star and V/V, choice of connection. Phase conversion – Scott connection for three-phase to two-phase conversion. Labelling of three-phase transformer terminals, vector groups. Equivalent circuit of three phase transformers.

MODULE - 2

Tests,Parallel Operation of Transformers: polarity test, Sumpner's test ,separation of core loss, Necessity of Parallel operation, conditions for parallel operation – Single phase and three phase. Load sharing in case of similar and dissimilar transformers.

Auto transformers and Tap changing transformers: Introduction to auto transformer - copper economy, equivalent circuit, three phase auto connection and voltage regulation. Voltage regulation by tap changing – off circuit and on load.

MODULE – 3

Tertiary winding Transformers and cooling of transformer: Three winding transformer and cooling of transformer,

Direct current Generator Armature reaction, Commutation and associated problems

Synchronous generators Armature windings, winding factors, emf equation. Harmonics – causes, reduction and elimination. Armature reaction, Synchronous reactance, Equivalent circuit.

MODULE – 4

Synchronous generators Analysis: Generator load characteristic. Voltage regulation, excitation control for constant terminal voltage. Assessment of reactance- short circuit ratio, synchronous reactance, Voltage regulation by EMF, MMF, ZPF and ASA methods.

MODULE – 5

Synchronous generators (salient pole): Effects of saliency, two-reaction theory, Parallel operation of generators and load sharing. Synchronous generator on infinite busbars Power angle characteristic and synchronizing power. Direct and Quadrature reactance, slip test.

Open circuit and short circuit characteristics, and adjusted synchronous reactance and Potier reactance.

Performance of synchronous generators: , Power angle diagram, reluctance power Capability curve for large turbo generators and salient pole generators. Starting, synchronizing and control. Hunting and dampers.

MODULE - 1

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Single phase Transformers

Transformers:

The static electrical device which transfers the voltage from one level to another level by the principle of self and mutual induction without change in frequency.

Michael Faraday propounded the principle of electro-magnetic induction in 1831.It states that a voltage appears across the terminals of an electric coil when the flux linked with the same changes. The magnitude of the induced voltage is proportional to the rate of change of the flux linkages. This finding forms the basis for many magneto electric machines

The earliest use of this phenomenon was in the development of induction coils. These coils were used to generate high voltage pulses to ignite the explosive charges in the mines. As the d.c. power system was in use at that time, very little of transformer principle was made use of. In the d.c. supply system the generating station and the load center have to be necessarily close to each other due to the requirement of economic transmission of power.

Transformers can link two or more electric circuits. In its simple form two electric circuits can be linked by a magnetic circuit, one of the electric coils is used for the creation of a time varying magnetic field. The second coil which is made to link this field has a induced voltage in the same. The magnitude of the induced emf is decided by the number of turns used in each coil. Thus the voltage level can be increased or decreased by changing the number of turns. This excitation winding is called a primary and the output winding is called a secondary. As a magnetic medium forms the link between the primary and the secondary windings there is no conductive connection between the two electric circuits. The transformer thus provides an electric isolation between the two circuits. The frequency on the two sides will be the same. As there is no change in the nature of the power, the re sulting machine is called a ‘transformer’ and not a ‘converter’. The electric power at one Voltage/current level is only ‘transformed’ into electric power, at the same frequency, to another voltage/current level.

Even though most of the large-power transformers can be found in the power systems, the use of the transformers is not limited to the power systems. The use of the principle of transformers is universal. Transformers can be found operating in the frequency range starting from a few hertz going up to several mega hertz. Power ratings vary from a few miliwatts to several hundreds of megawatts. The use of the transformers is so wide spread that it is virtually impossible to think of a large power system without transformers. Demand on electric power generation doubles every decade in a developing country. For every MVA of generation the installed capacity of transformers grows by about 7MVA.

Classification of Transformer:

The transformers are classified according to:

1. The Type of Construction:
   (a) Core Type Transformer

(b) Shell Type Transformer

2. The Number of Phases:
   (a) Single Phase Transformer
   (b) Three Phase Transformer
3. The Placements:
   (a) Indoor Transformer
   (b) Outdoor Transformer
4. The Load:
   (a) Power Transformer
   (b) Distribution Transformer

Ideal Transformer

To understand the working of a transformer it is always instructive, to begin with the concept of an *ideal* transformer with the following properties.

1. Primary and secondary windings have no resistance.

2. All the flux produced by the primary links the secondary winding i.e., there is no leakage flux.

3. Permeability μ_r of the core is infinitely large. In other words, to establish flux in the core vanishingly small (or zero) current is required.

4. Core loss comprising of *eddy current* and *hysteresis* losses are neglected.

Construction of a Transformer

There are two basic parts of a transformer:

1. Magnetic core
2. Winding or coils

- **MAGNETIC CORE:** The core of a transformer is either square orrectangular in size. It is further divided in two parts. The vertical portion on which the coils are bound is called limb, while the top and bottom horizontal portion is called yoke of the core as shown in

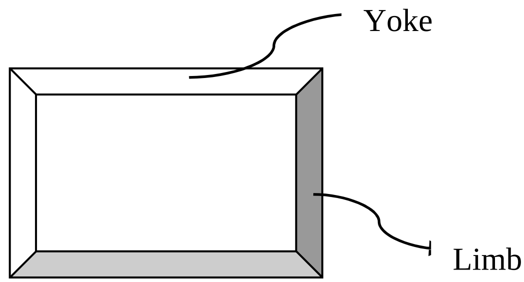


Fig. 2

Core is made up of laminations. Because of laminated type of construction, eddy current losses get minimized. Generally high grade silicon steel laminations (0.3 to 0.5 mm thick) are used. These laminations are insulated from each other by using insulation like varnish. All laminations are varnished. Laminations are overlapped so that to avoid the air gap at the joints. For this generally ‘L’ shaped or ‘I’ shaped laminations are used which are shown in the fig. 3 below.

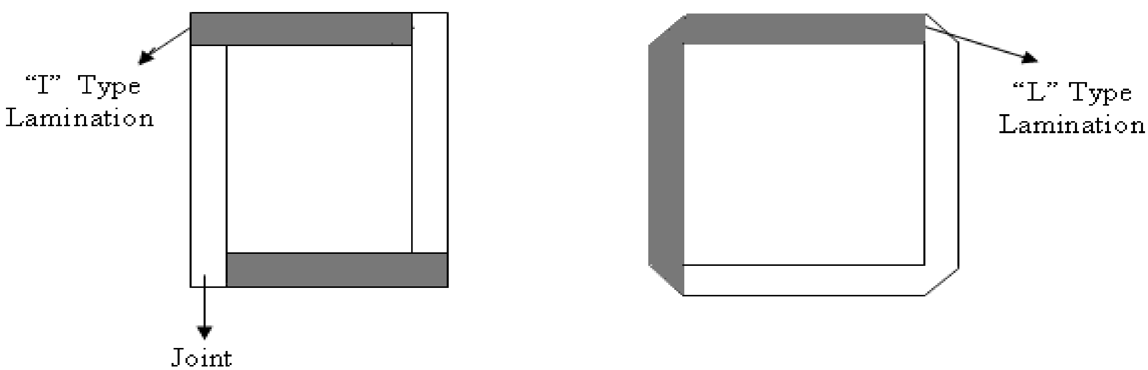


Fig. 3

WINDING: There are two windings, which are wound on the two limbs of the core, which are insulated from each other and from the limbs as shown in fig. 4. The windings are made up of copper, so that, they possess a very small resistance. The winding which is connected to the load is called secondary winding and the winding which is connected to the supply is called primary winding. The primary winding has N_1 number of turns and the secondary windings have N_2 number of turns.

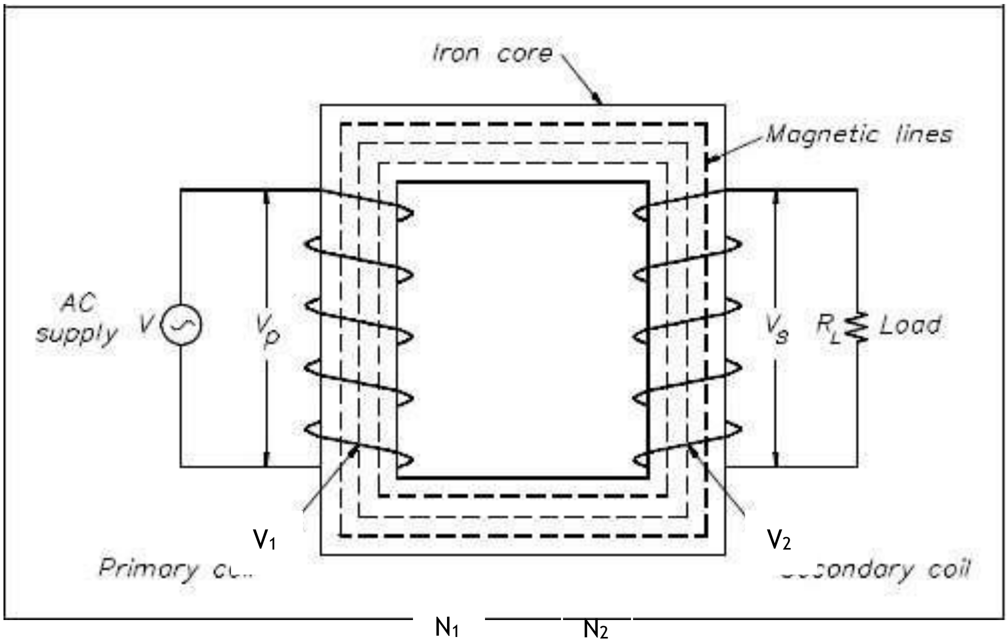


Fig. 4. Single Phase Transformer

TYPES OF TRANSFORMERS:

The classification of transformer is based on the relative arrangement or disposition of the core and the windings. There are two main types of transformers.

1. Core type
2. Shell type

CORE TYPE:

Fig 5(a)& (b) shows the simplified representation of a core type transformer, where the primary and secondary winding have been shown wound on the opposite sides. However, in actual practise, half the primary and half the secondary windings are situated side by side on each limb,so as to reduce leakage flux as shown in fig 6. This type of core construction is adopted for small rating transformers.

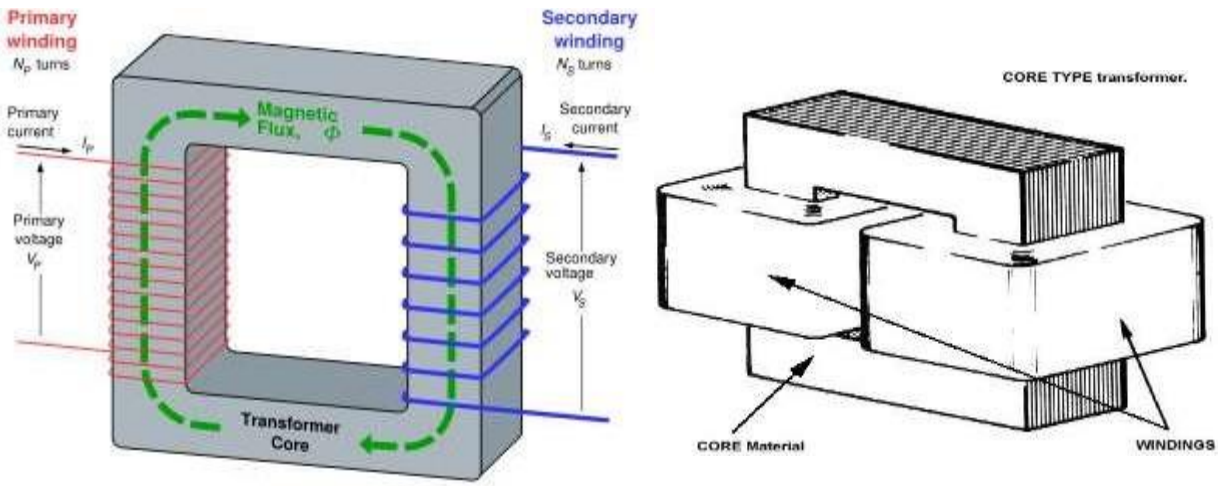
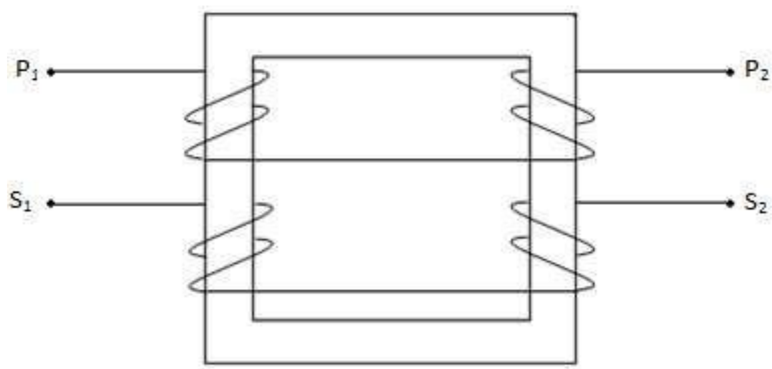
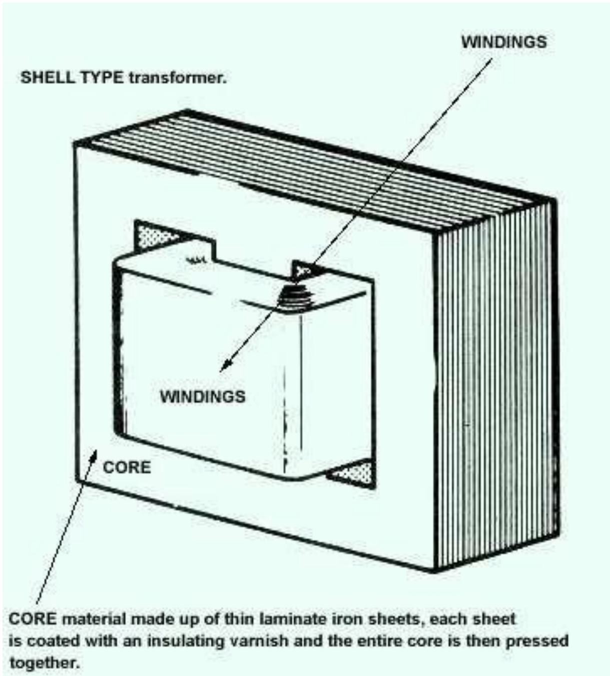


Fig. 5(a) & (b) Single Phase Core Type Transformer



SHELL TYPE:

In this type, the windings occupy a smaller portion of the core as shown in fig 5. The entire flux passes through the central part of the core, but outside of this a central core, it divides half, going in each direction. The coils are form wound, multilayer disc-type, each of the multilayer discs is insulated from the other by using paper. This type of construction is generally preferred for high voltage transformers.



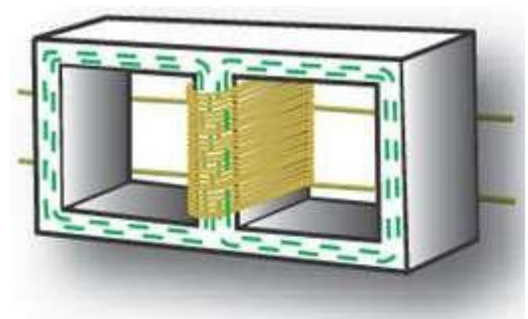
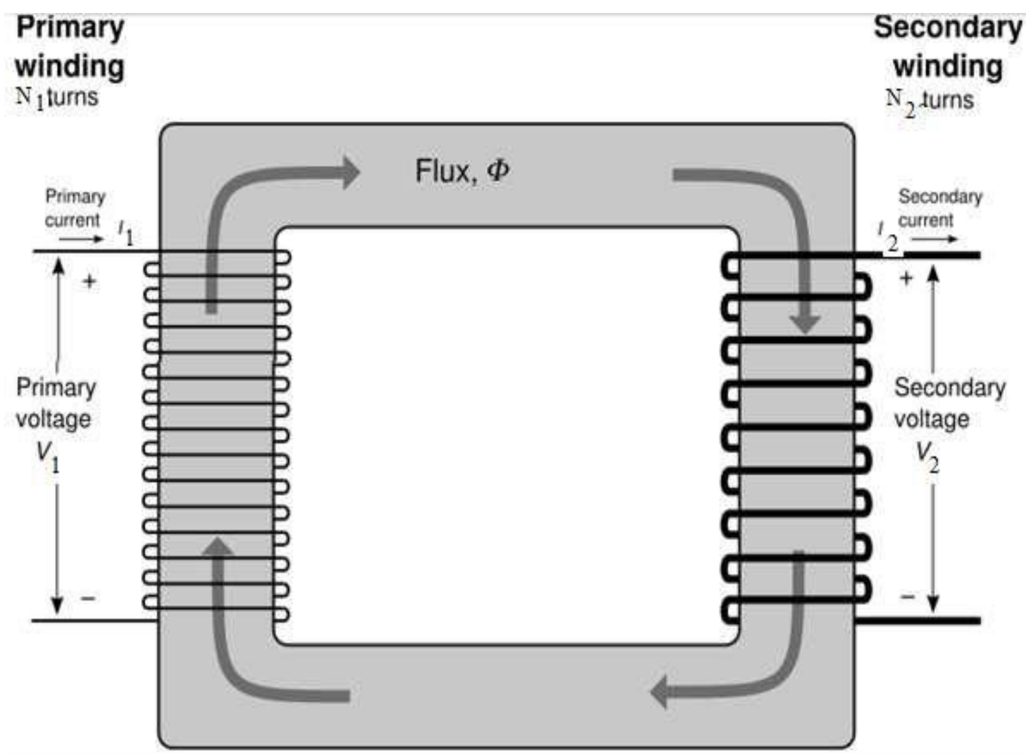


Fig. 7 (a) & (b) Single Phase Shell Type Transforme

Principle of Operation of a Single Phase Transformer



A single phase

transformer works on the principle of mutual induction between two magnetically coupled coils. When the primary winding is connected to an alternating voltage of r.m.s value, V1 volts, an alternating current flows through the primary winding and setup an alternating flux ϕ in the material of the core. This alternating flux ϕ, links not only the primary windings but also the secondary windings. Therefore, an e.m.f e_1 is induced in the primary winding and an

e_2 is induced in the secondary winding, e_1 and e_2 are given $e1 = -N1\frac{d\varphi}{dt}$ ---------

(a) $e2 = -N2\frac{d\varphi}{dt}$ ----------(b)

If the induced e.m.f is e_1 and e_2 are represented by their rms values E_1 and E_2 respectively, then

$E1 = -N1\frac{d\varphi}{dt}$ --------- (1)

$E2 = -N2\frac{d\varphi}{dt}$ ---------- (2)

Therefore, $\frac{E2}{E1} = \frac{N2}{N1} = k$ ---------------- (3)

K is known as the transformation ratio of the transformer. When a load is connected to the secondary winding, a current I_2 flows through the load, V_2 is the terminal voltage across the load. As the power transfered from the primary winding to the secondary winding is same,

Power input to the primary winding = Power output from the secondary winding.

$E_1I_1 = E_2I_2$

(Assuming that the power factor of the primary is equal to the secondary).

Or, $\frac{E2}{E1} = \frac{I1}{I2} = k$ ------- (4)

From eqn (3) and (4), we have

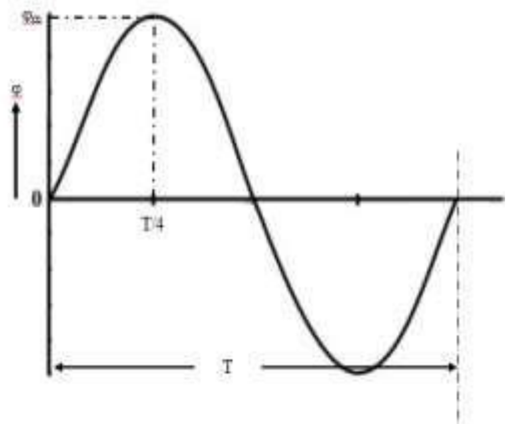
$\frac{E2}{E1} = \frac{N2}{N1} = \frac{I1}{I2} = k$ --------------- (5)

The directions of emf's E_1 and E_2 induced in the primary and secondary windings are such that, they always oppose the primary applied voltage V_1.

<u>EMF Equation of a transformer:</u>

Consider a transformer having,

N_1 =Primary turns
N_2 = Secondary turns
Φ_m = Maximum flux in the core
$\Phi_m = B_m \times A$ webers
f= frequency of ac input in hertz (Hz)



The flux in the core will vary sinusoidally as shown in figure, so that it increases from zero to maximum "ϕ_m" in one quarter of the cycle i.e, $^1/_{4f}$ second

Therefore, average rate of change of flux = $^{\phi m}/_{1/4f}$

$$= 4f\varphi_m$$

We know that, the rate of change of flux per turn means that the induced emf in volts.

Therefore, average emf induced per turn = $4f\varphi_m$ volts.

Since the flux is varying sinusoidally, the rms value of induced emf is obtained by multiplying the average value by the form factor .

Therefore, rms value of emf induced per turns = $1.11\times4f\times\varphi_m$

= $4.44f\varphi_m$ volts

The rms value of induced emfin the entire primary winding = (induced emf per turn) × number of primary turns

$$\text{i.e, } E_1 = 4.44f\varphi_m \times N_1 \quad = 4.44fB_m \times A \times N_1$$

Similarly;

$$E_2 = 4.44\, f\, \varphi_m \times N_2 \quad = 4.44\, f\, B_m \times A \times N_2$$

Transformation Ratio:

(1) Voltage Transformation Ratio
(2) Current Transformation Ratio

Voltage Transformation Ratio:

Voltage transformation ratio can be defined as the ratio of the secondary voltage to the primary voltage denoted by *K*

Mathematically given as $K = \frac{Secondary\ Voltage}{PrimarPrimar\ Voltage} = \frac{V_2}{V_1}$

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

$$K = \frac{V_2}{V_1} = \frac{E_2}{E_1} = \frac{N_2}{N_1}$$

Current Transformation Ratio:

Consider an ideal transformer and we have the input voltampere is equal to output voltampere.

Mathematically, *Input Voltampere = Output Voltampere*

$$V_1 I_1 = V_2 I_2$$

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

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

Coupled circuits

- When two coils separated by each other, a change in current in one coil will effect the voltage in another coil by mutual induction
- Self Inductance: A coil capable of inducing an emf in itself by changing current flowing through it, this property of coil is known as self inductance.
- The self induced emf is directly proportional to the rate of change of current.

$$e \alpha \ di/dt; \ e = L \ di/dt$$

- Where L=coefficient of self inductance.

Mutual Inductance

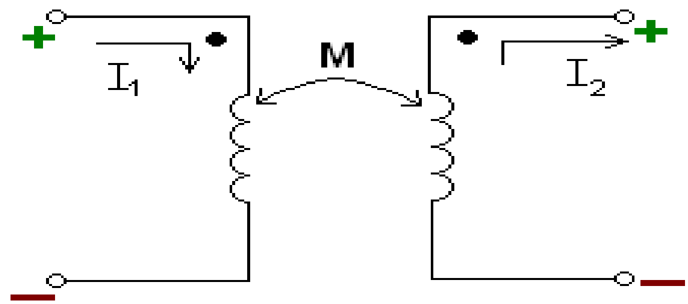
- Current in one coil changes, there occurs a change in flux linking with other as result an emf is induced in the adjacent coils.
- The mutually induced emf e2 in the second coil id dependent on the rate of change of current in the first coil.
- $e2 \ \alpha \ di1/dt; \ e2=Mdi1/dt$

COEFFCIENT OF COUPLING

- $K= M/(L1L2)$
- The two coils is said to be tightly or perfectly coupled only when K=1 and therefore M=L1L2 it's said to be maximum mutual inductance
- When the distance between the two coils is greater than the coils are said to be loosely packed
- Coefficient of coupling will help in deciding whether the coils are closely packed or loosely packed.

Derivation for Co-efficient of coupling

Dot Convention

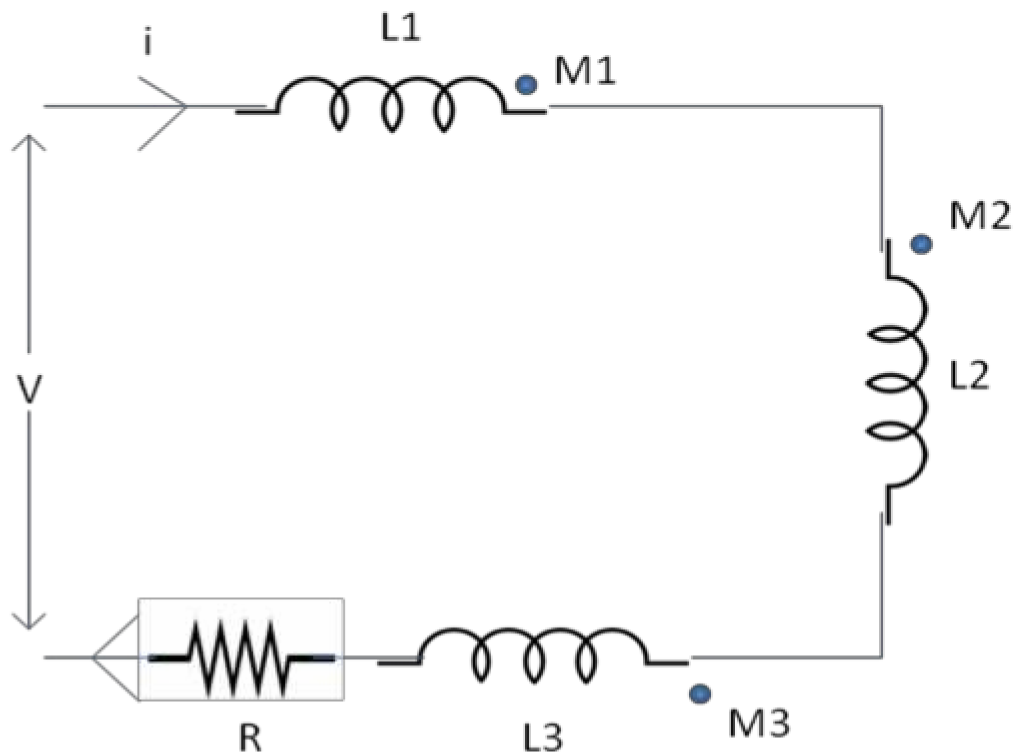


- A current entering the dotted terminal of one coil produces an open-circuit voltage which is positively sensed at the dotted terminal of the second coil
- A current entering the undotted terminal of one coil produces an open-circuit voltage which is positively sensed at the undotted terminal of the second coil.
- The advantage of dot convention is to find out the direction of the winding and direction of flux linking the coil
- The direction of the flux due to rate of change of flux can be analyzed by right hand thumb rule.

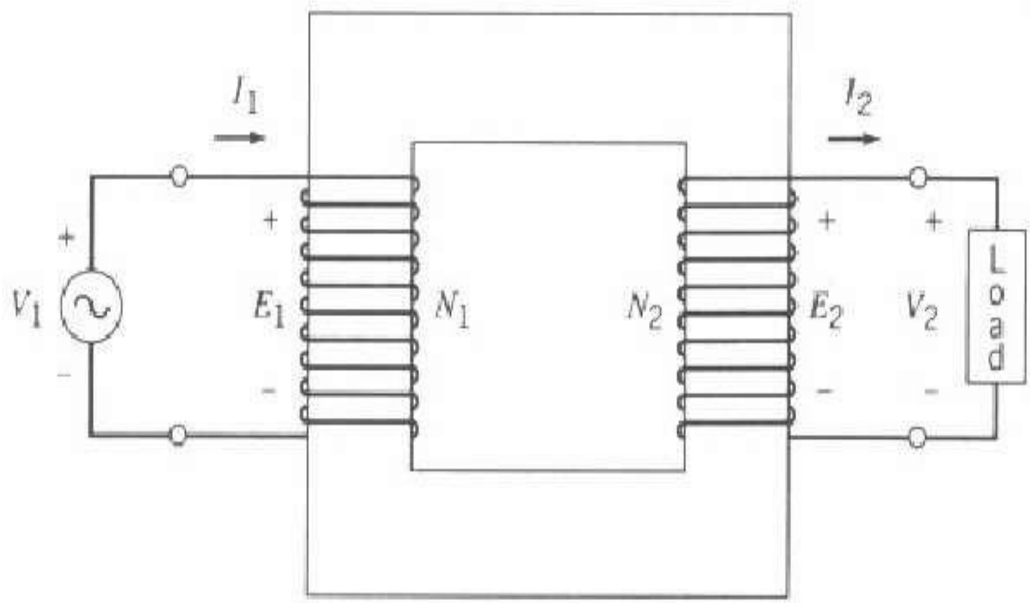
Different connections of coupled circuits

- Series Aiding:
- Series Opposing:
- Parallel Aiding:
- Parallel Opposing
- **Refer Circuit diagram and derivation for the class notes.**

Equilibrium Equations



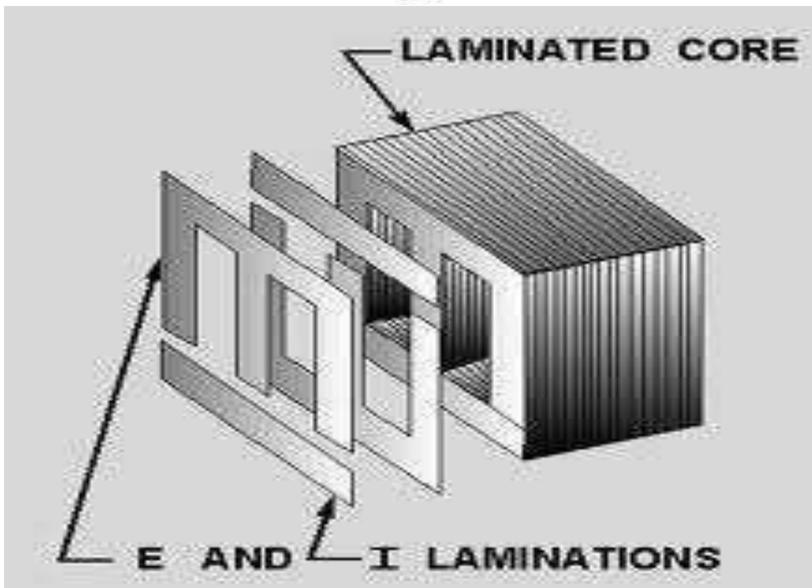
- The coil where electrical energy is fed is considered as Primary
- The coil where load is connected to draw the current from mutual induction is Secondary
- There are Two main part in Transformer 1) Core 2) Windings
- Core: The top and bottom part of the core is Yoke, The side limbs are considered as Legs. The core is made up of Silicon steel to avoid the Eddy current and Hystersis Loss.
- Windings: Basically it is made up of Copper and depends on the current value based on this it is of two types Low Voltage and High Voltage Winding.



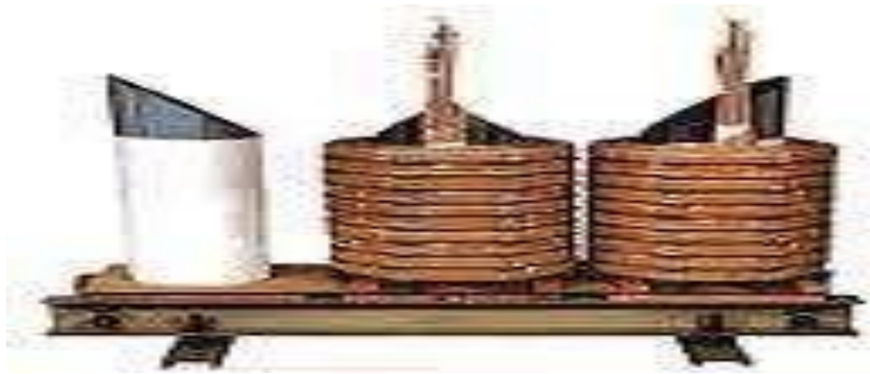
- There are Two main part in Transformer

1) Core 2) Windings

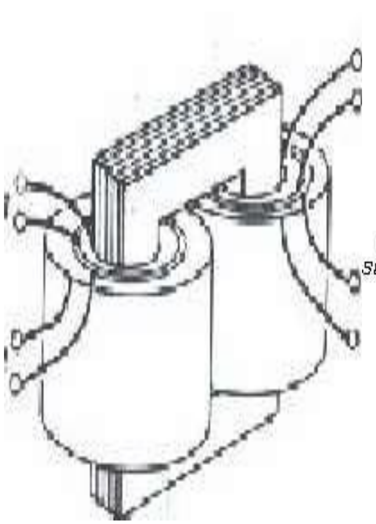
- Core: The top and bottom part of the core is Yoke, the Vertical portions are considered as of Limbs Legs.
- The core is made up of Silicon steel laminations of thickness 0.33m (CRGO) to avoid the Eddy current and Hysteresis Loss.
- Each laminations are varnished one another and bolted to form a L or T or I shaped structures.

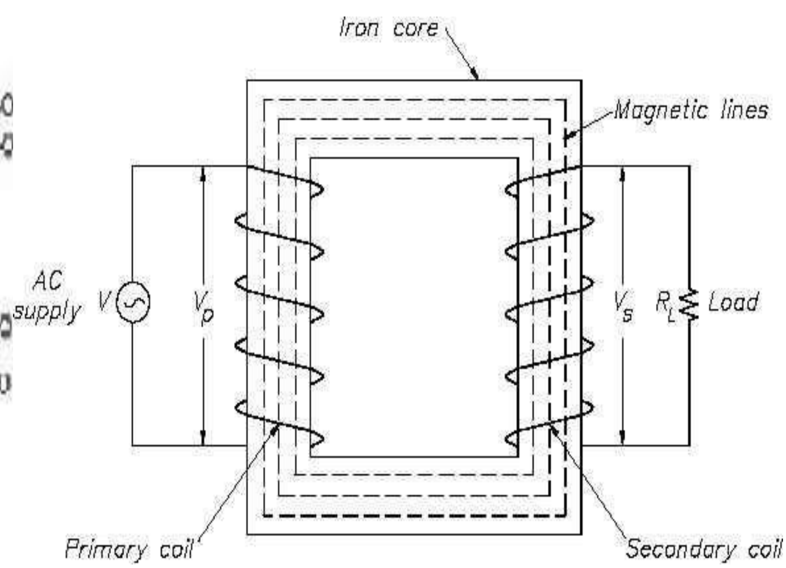


- Windings: Basically it is made up of Copper and depends on the current value based on this it is of two types Low Voltage and High Voltage Winding.
- The LV and HV coils should be placed close to each other as to increase the mutual induction.
- The two coils are separated by insulated materials such as paper, cloth or mica
- Coils maybe placed Helically(Cylindrical) or Sandwiched in the window of transformer

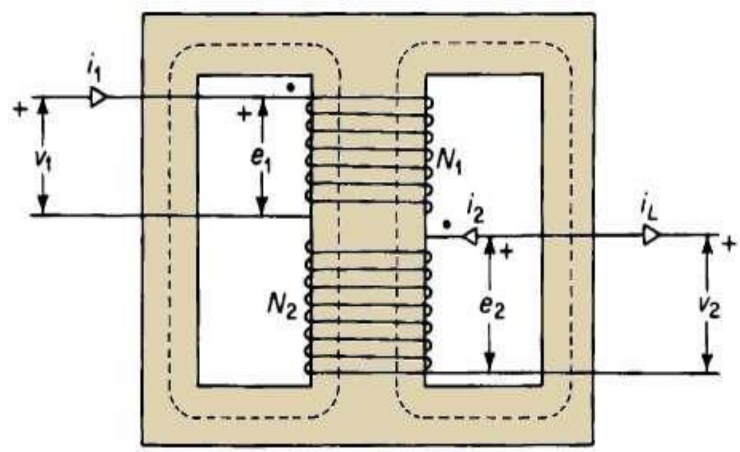


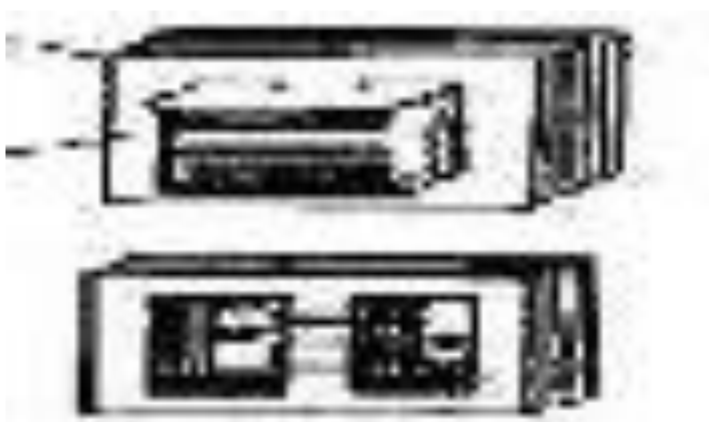
- Rectangular core, two limbs.
- Winding encircles core and Low voltage coil is placed near the limb and insulation by paper and High voltage on it.
- Windings are distributive type and natural cooling is effective and top laminations can be removed for maintenance work.



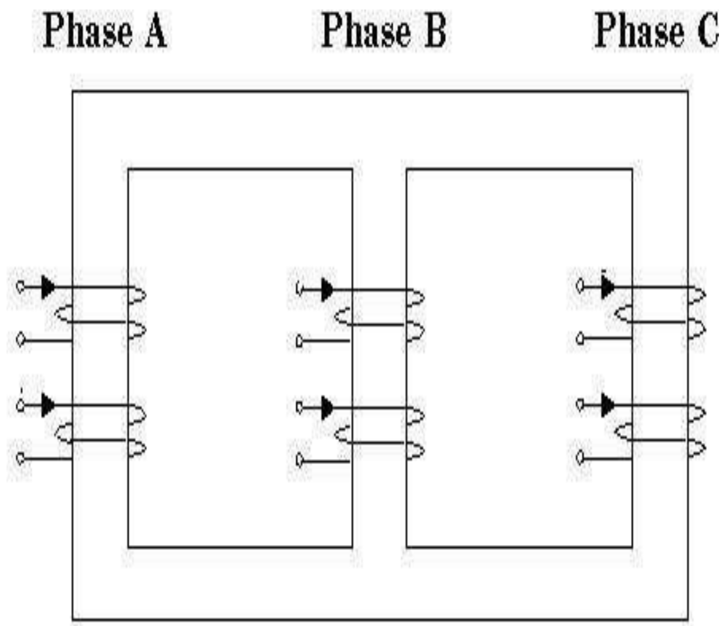


- Core Encircles most of windings
- Natural cooling is not possible
- Maintenance work is difficult
- For HV Transformers
- 1- ϕ requires three limbs
- Double magnetic circuit

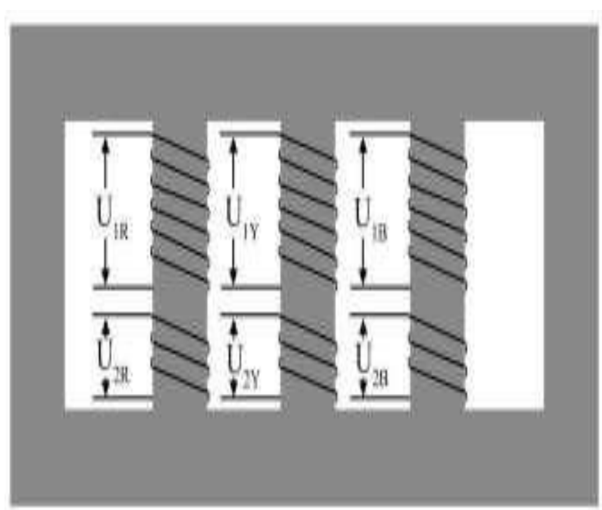




- Core consists of three limbs, top and bottom yokes.
- Each limb consists of primary and secondary winding(LV and HV winding)
- Three phase transformer can also designed by arranging three single phase transformer in series.



- Shell type(five limb)is used for large transformer because they can be made with a reduced height.
- The cost of three phase shell type transformer is more.
- For cooling of transformer fans are fixed at the radiators.



Core type

- Winding encircles core
- Cylindrical coils
- Natural cooling is effective
- Maintenance work is easy
- Single magnetic circuit
- Low Voltage and distribution type
- Two limbs for 1-phase and three for 3-phase

Shell type

- Core encircles windings
- Disc type

- Natural cooling is not effective
- Maintenance work is difficult
- Double magnetic circuit
- High Voltage transformer
- Three limbs for 1-phase and 6-limbs for three phase

Types of Transformer

- Power Transformer
- Distribution Transformer
- Constant Voltage Transformer
- Constant Current Transformer
- Variable Frequency Transformer
- Auto Transformer

Power transformer of rating 500 mVA 11kv/230v

- Transformer having rating more than 200kva is power transformers
- Usually this transformers are placed near the generating and substations to either step up or step down voltage levels
- The transformers which are used to transform the transmission voltage to the voltage level of primary feeders are called substation transformers

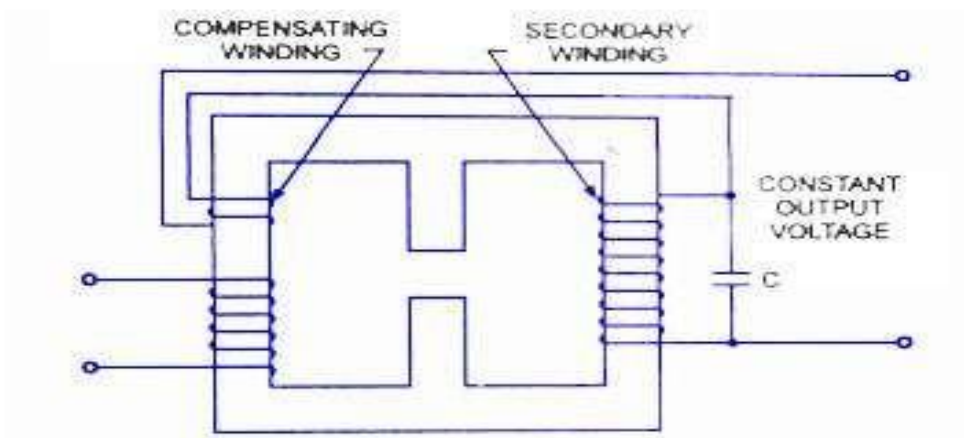
Fig: Power Transformer

Pad mounted & pole mounted distribution transformer

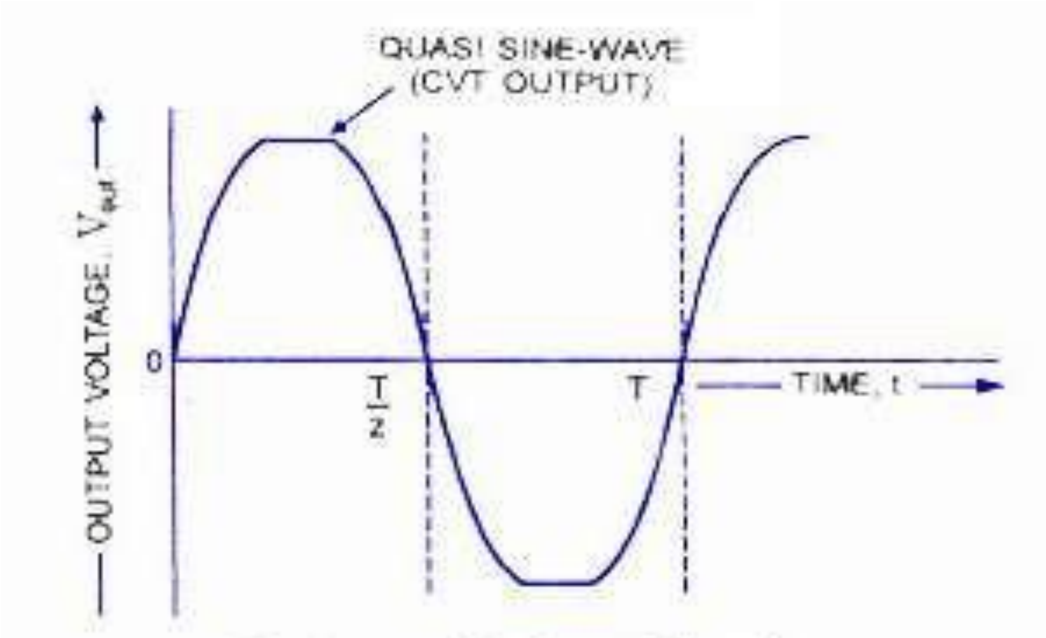
- It changes feeder voltage to the utilization voltage for customer requirements.
- This transformers operate throughout the day therefore iron loss will be throughout the day and copper loss occur only when it is loaded.
- These are low load high efficiency machines.
- It is designed in such way to maintain the small leakage reactance to get good voltage regulation as it want to operate throughout the day.
- Depending on the installation it is of pole mounted or pad mounted as shown in the diagram.

Constant voltage transformer and its output

- It uses the leakage inductance of its secondary windings in combination with external capacitors to create one or more resonant circuits.
- It consists of linear inductor which is unsaturated and this will be primary.
- The non linear inductor(saturated) forms the secondary of the transformer.
- The capacitor connected in parallel saturates by drawing the secondary current due to saturation a constant output voltage is produced.
- Since the output is a quasi sine wave because of the constant in output voltage and this is improved by the compensating winding.



(a) Contructional Details



(b) Output Voltage Waveform

Constant Current transformer

- It consists of Primary and secondary winding but one is movable and mounted on the same core
- A counter weight is used to balance the moving winding.
- The principle is production of two oppositely directed magnetic field
- If load impedance decreases load current increases due to this large opposition between two magnetic fields produced by primary and secondary
- Due to repulsion movable winding moves up and further gets separated from stationary and large leakage flux reduces and in turn mutual flux reduces thus secondary voltage reduces

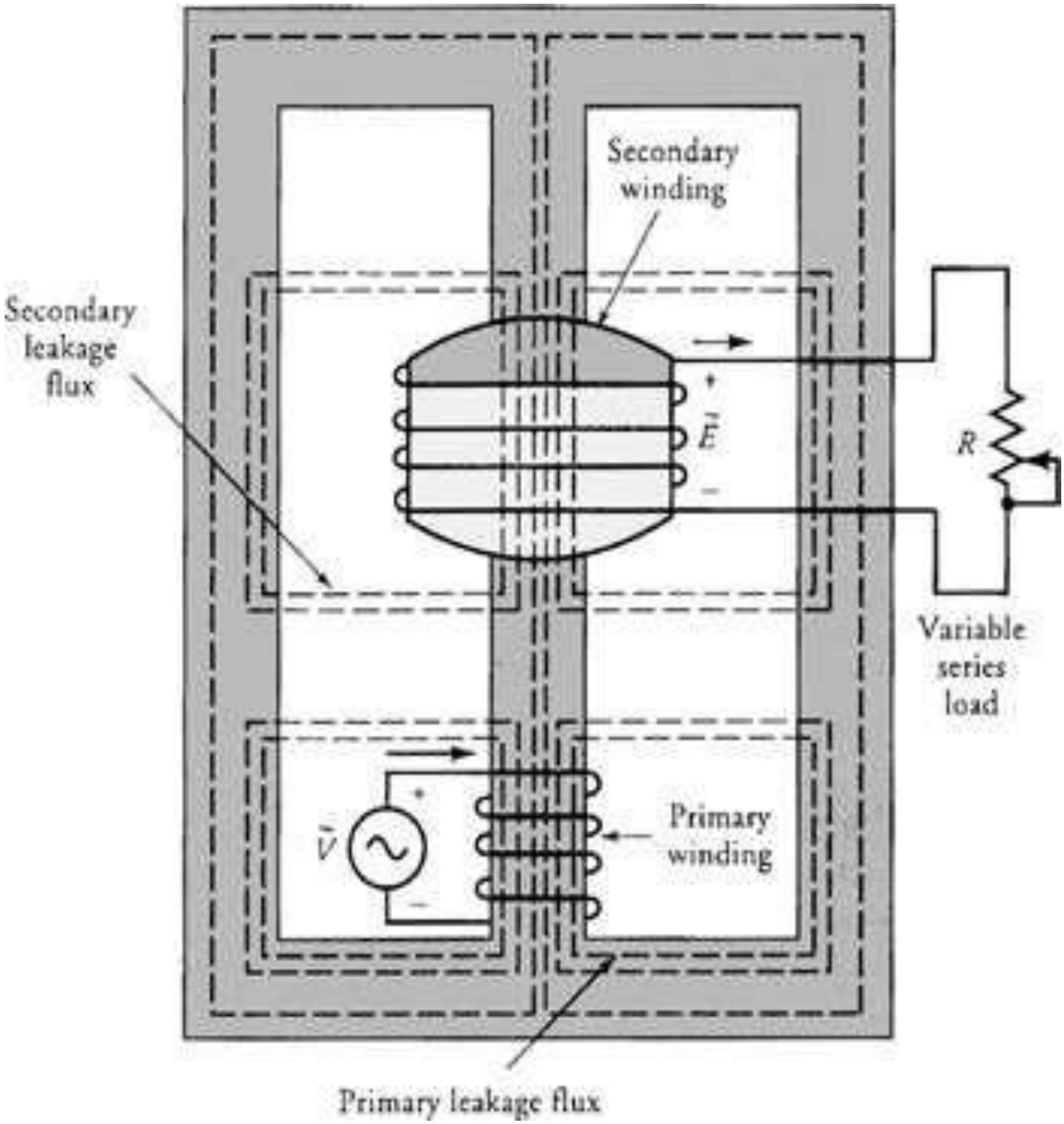


Fig**: Constant Current Transformer**

Variable frequency transformer

- The variable frequency transformer (VFT) is essentially a continuously variable phase shifting transformer that can operate at an adjustable phase angle
- A **variable frequency transformer** is used to transmit electricity between two asynchronous alternating current domains.
- A variable frequency transformer is a doubly-fed electric machine resembling a vertical shaft hydroelectric generator with a three-phase wound rotor, connected by slip rings to one external power circuit. A direct-current torque motor is mounted on the same shaft
- The phase shift between input and output voltage should also be small over the range of frequencies.
- The applications of VFT are Electronic circuits, Communication, Control and measurement which uses wide band of frequencies.

Losses in Transformer:

Losses of transformer are divided mainly into two types:

1. Iron Loss
2. Copper Losses

Iron Loss:

This is the power loss that occurs in the iron part. This loss is due to the alternating frequency of the emf. Iron loss in further classified into two other losses.

a) Eddy current loss **b) Hysterisis loss**

a) EDDY CURRENT LOSS: This power loss is due to the alternating flux linking the core, which will induced an emf in the core called the eddy emf, due to which a current called the eddy current is being circulated in the core. As there is some resistance in the core with this eddy current circulation converts into heat called the eddy current power loss. Eddy current loss is proportional to the square of the supply frequency.

b) HYSTERISIS LOSS: This is the loss in the iron core, due to the magnetic reversal of the flux in the core, which results in the form of heat in the core. This loss is directly proportional to the supply frequency.

Eddy current loss can be minimized by using the core made of thin sheets of silicon steel material, and each lamination is coated with varnish insulation to suppress the path of the eddy currents.

Hysterisis loss can be minimized by using the core material having high permeability.

Copper Loss:

This is the power loss that occurs in the primary and secondary coils when the transformer is on load. This power is wasted in the form of heat due to the resistance of the coils. This loss is proportional to the sequence of the load hence it is called the Variable loss where as the Iron loss is called as the Constant loss as the supply voltageand frequency are constants

Efficiency:

It is the ratio of the output power to the input power of a transformer

Input = Output + Total losses

= Output + Iron loss + Copper loss

Efficiency =

$$\eta = \frac{outputpower}{outputpower + Ironloss + copperloss}$$

$$= \frac{V_2 I_2 \cos\phi}{V_2 I_2 \cos\phi + W_{eron} + W_{copper}}$$

Where, V_2 is the secondary (output) voltage, I_2 is the secondary (output) current and cos**Φ** is the power factor of the load.

The transformers are normally specified with their ratings as KVA,

Therefore,

$$Efficiency; \eta = \frac{(KVA) \times 10^3 \times cos\varphi}{(KVA) \times 10^3 \times cos\varphi \times W_{iron} + W_{copper}}$$

Since the copper loss varies as the square of the load the efficiency of the transformer at any desired load *n* is given by

$$Efficiency; \eta = \frac{n \times (KVA) \times 10^3 \times cos\varphi}{n \times (KVA) \times 10^3 \times cos\varphi \times W_{iron} + n^2 \times W_{copper}}$$

where W_{copper} is the copper loss at full load

$W_{copper} = I^2R$ watts

CONDITION FOR MAXIMUM EFFICIENCY:

In general for the efficiency to be maximum for any device the losses must be minimum. Between the iron and copper losses the iron loss is the fixed loss and the copper loss is the variable loss. When these two losses are equal and also minimum the efficiency will be maximum.

Therefore the condition for maximum efficiency in a transformer is

Copper loss== Iron loss (whichever is minimum)

VOLTAGE REGULATION:

The voltage regulation of a transformer is defined as the change in the secondary terminal voltage between no load and full load at a specified power factor expressed as a percentage of the full load terminal voltage.

$$\%Voltage\ Regulation = \frac{(no\ load\ Sec.Voltage) - (full\ load\ Sec.Voltage)}{full\ load\ Sec.Voltage} \times 100$$

Voltage regulation is a measure of the change in the terminal voltage of a transformer between No load and Full load. A good transformer has least value of the regulation of the order of **±5%**

If a load is connected to the secondary, an electric current will flow in the secondary winding and electrical energy will be transferred from the primary circuit through the transformer to the load. In an ideal transformer, the induced voltage in the secondary winding (V_s) is in proportion to the primary voltage (V_p), and is given by the ratio of the number of turns in the secondary (N_s) to the number of turns in the primary (N_p) as follows:

$$\frac{V_s}{V_p} = \frac{N_s}{N_p}$$

Earlier it is seen that a voltage is induced in a coil when the flux linkage associated with the same changed. If one can generate a time varying magnetic field any coil placed in the field of influence linking the same experiences an induced emf. A time varying field can be created by passing an alternating current through an electric coil. This is called mutual induction. The medium can even be air. Such an arrangement is called air cored transformer.

Indeed such arrangements are used in very high frequency transformers. Even though the principle of transformer action is not changed, the medium has considerable influence on the working of such devices. These effects can be summarized as the followings.

1. The magnetizing current required to establish the field is very large, as the reluctance of the medium is very high.

2. There is linear relationship between the mmf created and the flux produced.

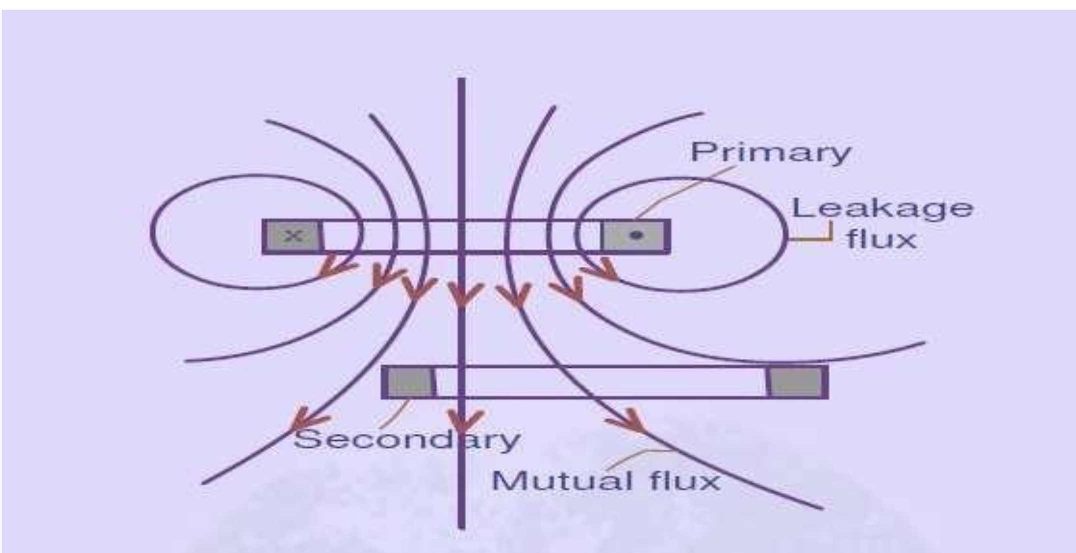
3. The medium is non-lossy and hence no power is wasted in the medium.

4. Substantial amount of leakage flux exists.

5. It is very hard to direct the flux lines as we desire, as the whole medium is homogeneous.

If the secondary is not loaded the energy stored in the magnetic field finds its way back to the source as the flux collapses. If the secondary winding is connected to a load then part of the power from the source is delivered to the load through the magnetic field as a link.

The medium does not absorb and lose any energy. Power is required to create the field and not to maintain the same. As the winding losses can be made very small by proper choice of material, the ideal efficiency of a transformer approaches 100%. The large magnetizing current requirement is a major deterrent.



(a)

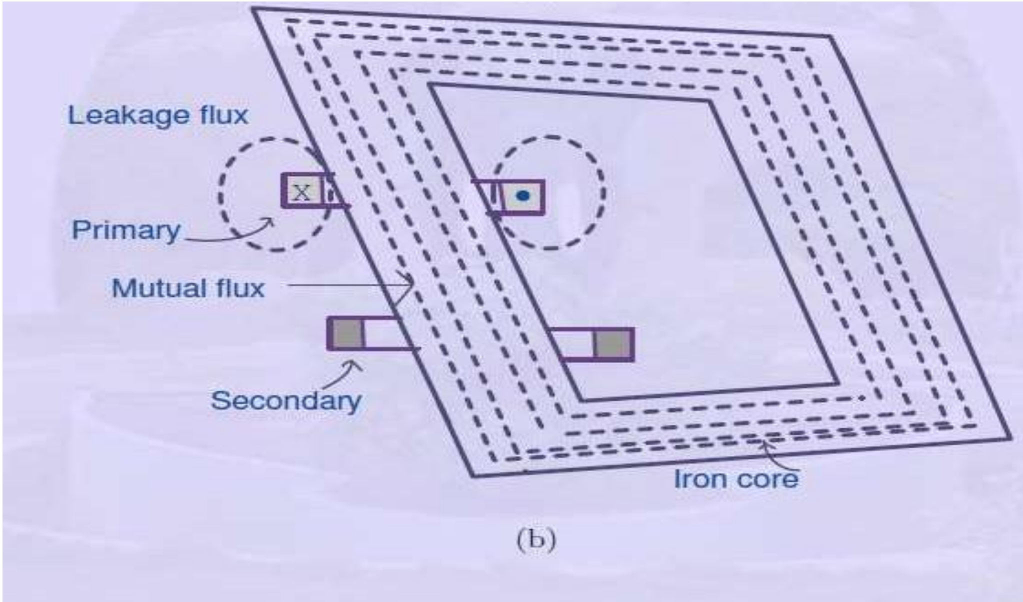


Figure 10: Mutual Induction a) air core b) iron core

1. Due to the large value for the permeance (μr of the order of 1000 as compared to air) the magnetizing current requirement decreases dramatically. This can also be visualized as a dramatic increase in the flux produced for a given value of magnetizing current.

2. The magnetic medium is linear for low values of induction and exhibits saturation type of non-linearity at higher flux densities.

3. The iron also has hysteresis type of non-linearity due to which certain amount of power is lost in the iron (in the form of hysteresis loss), as the B H characteristic is traversed.

4. Most of the flux lines are confined to iron path and hence the mutual flux is increased very much and leakage flux is greatly reduced.

5. The flux can be easily ‘directed’ as it takes the path through steel which gives great freedom for the designer in physical arrangement of the excitation and output windings.

6. As the medium is made of a conducting material eddy currents are induced in the same and produce losses. These are called ‘eddy current losses’. To minimize the eddy current losses the steel core is required to be in the form of a stack of insulated laminations.

From the above it is seen that the introduction of magnetic core to carry the flux introduced two more losses. Fortunately the losses due to hysteresis and eddy current for the available grades of steel are very small at power frequencies. Also the copper losses in the winding due to magnetization current are reduced to an almost insignificant fraction of the full load losses. Hence steel core is used in power transformers.

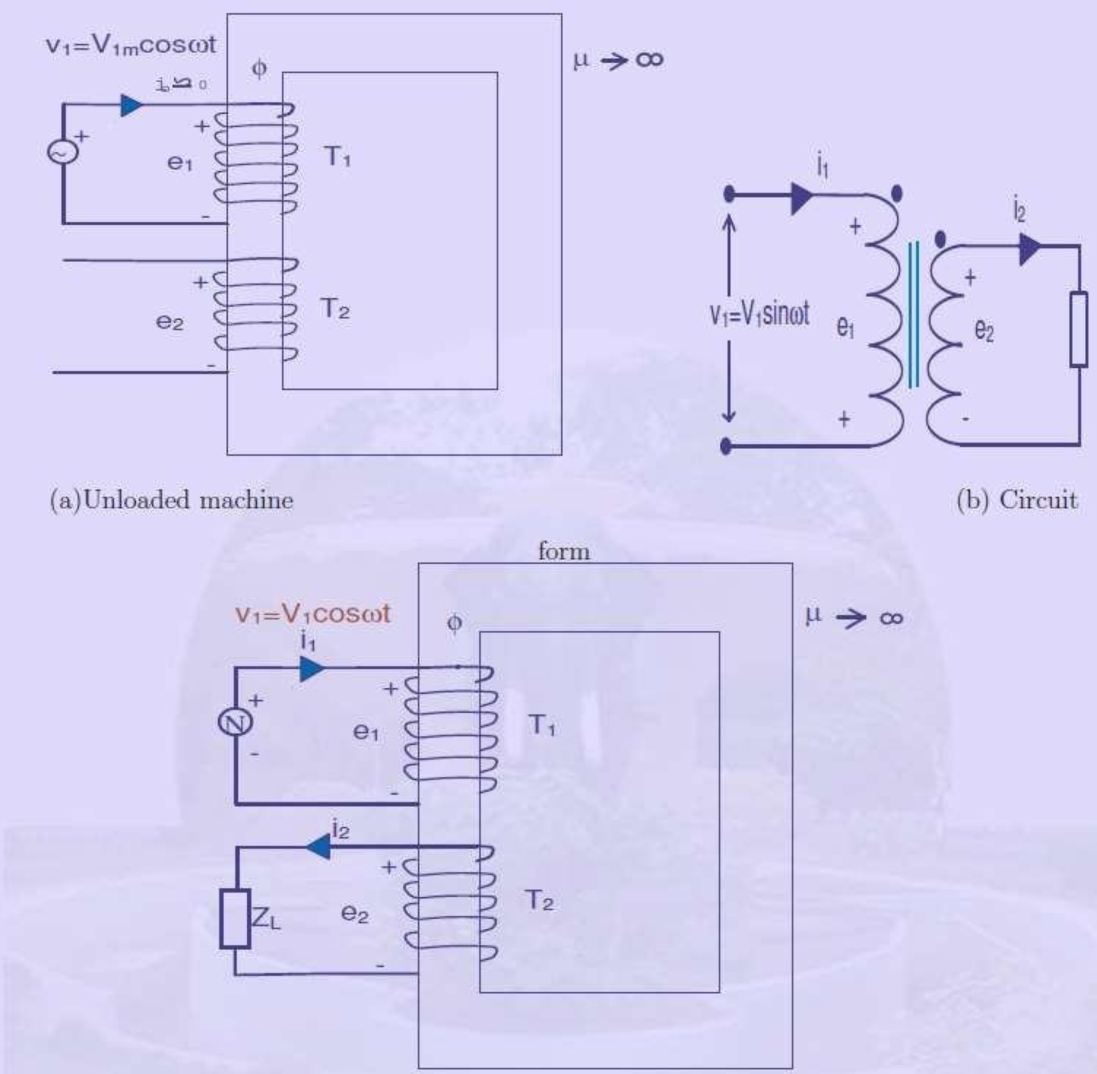
In order to have better understanding of the behavior of the transformer, initially certain idealizations are made and the resulting 'ideal' transformer is studied. These idealizations are as follows:

1. Magnetic circuit is linear and has infinite permeability. The consequence is that a vanishingly small current is enough to establish the given flux. Hysteresis loss is negligible. As all the flux generated confines itself to the iron, there is no leakage flux.

2. Windings do not have resistance. This means that there are no copper losses, nor there is any ohmic drop in the electric circuit.

In fact the practical transformers are very close to this model and hence no major departure is made in making these assumptions. Fig 11 shows a two winding ideal transformer. The primary winding has T_1 turns and is connected to a voltage source of V_1 volts. The secondary has T_2 turns. Secondary can be connected to load impedance for loading the transformer. The primary and secondary are shown on the same limb and separately for clarity.

As a current I_0 amps is passed through the primary winding of T1 turns it sets up an MMF of I_0T1 ampere which is in turn sets up a flux _ through the core. Since the reluctance of the iron path given by R = l/μA is zero as μ −1, a vanishingly small value of current I_0 is enough to setup a flux which is finite. As I_0 establishes the field inside the transformer



(a)Unloaded machine (b) Circuit (c)Loaded machine

Figure 11: Two winding Ideal Transformer unloaded and loaded

it is called the magnetizing current of the transformer.

$$Flux \quad \phi = \frac{mmf}{Reluctance} = \frac{I_0 T_1}{\frac{l}{\mu A}} = \frac{I_0 T_1 A \mu}{l}.$$

This current is the result of a sinusoidal voltage V applied to the primary. As the current through the loop is zero (or vanishingly small), at every instant of time, the sum of the voltages must be zero inside the same. Writing this in terms of instantaneous values we have, $v_1 - e_1 = 0$ where v_1 is the instantaneous value of the applied voltage and e1 is the induced emf due to Faradays principle. The negative sign is due to the application of the Lenz's law and shows that it is in the form of a voltage drop. Kirchoff's law application to the loop will result in the same thing.

This equation results in $v_1 = e_1$ or the induced emf must be same in magnitude to the applied voltage at every instant of time. Let $v_1 = V_{1peak}$ cosωt where V_1peak is the peak value and ω= 2πf t. f is the frequency of the supply. As $v_1 = e_1$; e_1 = d 1/dt but $e_1 = E_{1peak}$ cosωt) $E_1 = V_1$. It can be easily seen that the variation of flux linkages can be obtained as $\psi_1 = \psi_{1peak}$ sinωt. Here ψ_{1peak} is the peak value of the flux linkages of the primary.

Thus the RMS primary induced EMF is

$$
\begin{aligned}
e_1 &= \frac{d\psi_1}{dt} = \frac{d(\psi_{1peak} \sin \omega t)}{dt} \\
&= \psi_{1peak}.\omega.\cos \omega t \quad \text{or the rms value} \\
E_1 &= \frac{\psi_{1peak}.\omega}{\sqrt{2}} = \frac{2\pi f T_1 \phi_m}{\sqrt{2}} = 4.44 f \phi_m T_1 \quad \text{volts}
\end{aligned}
$$

Here ψ1peak is the peak value of the flux linkages of the primary. The same mutual flux links the secondary winding. However the magnitude of the flux linkages will be ψ2peak =T2φm. The induced emf in the secondary can be similarly obtained as

$$
\begin{aligned}
e_2 &= \frac{d\psi_2}{dt} = \frac{d(\psi_{2peak} \sin \omega t)}{dt} \\
&= \psi_{2peak}.\omega.\cos \omega t \quad \text{or the rms value} \\
E_2 &= \frac{2\pi f T_2 \phi_m}{\sqrt{2}} = 4.44 f \phi_m T_2 \quad \text{volt}
\end{aligned}
$$

,

Which yields the voltage ratio as E1/E2=T1/T2

Transformer at loaded condition.

So far, an unloaded ideal transformer is considered. If now a load impedance ZL is connected across the terminals of the secondary winding a load current flows as marked in Fig. 11(c).This load current produces a demagnetizing mmf and the flux tends to collapse. However this is detected by the primary immediately as both E2 and E1 tend to collapse.

The current drawn from supply increases up to a point the flux in the core is restored back to its original value. The demagnetizing mmf produced by the secondary is neutralized by additional magnetizing mmf produces by the primary leaving the mmf and flux in the core as in the case of no-load. Thus the transformer operates under constant induced emf mode. Thus

$$\begin{aligned} i_1T_1 - i_2T_2 &= i_0T_1 \quad \text{but} \quad i_0 \to 0 \\ i_2T_2 &= i_1T_1 \quad \text{and the rms value} \quad I_2T_2 = I_1T_1. \end{aligned}$$

If the reference directions for the two currents are chosen as in the Fig. 12, then the above equation can be written in phasor form as,

$$\begin{aligned} \bar{I}_1T_1 &= \bar{I}_2T_2 \quad \text{or} \quad \bar{I}_1 = \frac{T_2}{T_1}.\bar{I}_2 \\ \text{Also} \quad \frac{E_1}{E_2} &= \frac{T_1}{T_2} = \frac{I_2}{I_1} \quad E_1I_1 = E_2I_2 \end{aligned}$$

Thus voltage and current transformation ratio are inverse of one another. If an impedance of ZL is connected across the secondary,

$$\bar{Z}_i = \frac{\bar{E}_1}{\bar{I}_1} = (\frac{T_1}{T_2})^2.\frac{\bar{E}_2}{\bar{I}_2} = (\frac{T_1}{T_2})^2.\bar{Z}_L$$

An impedance of ZL when viewed ‘through’ a transformer of turns ratio (T1/T2) is seen as $(T1/T2)^2.ZL$. Transformer thus acts as an impedance converter. The transformer can be interposed in between a source and a load to ‘match’ the impedance.

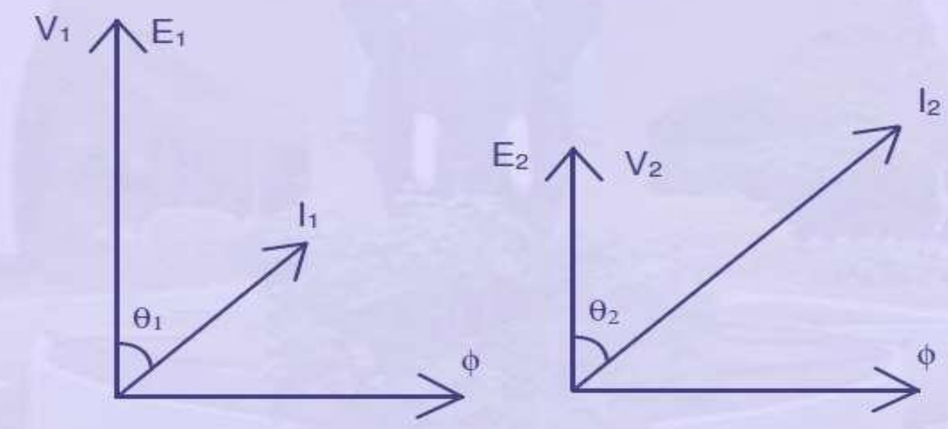


Figure 13: Phasor diagram of Operation of an Ideal Transformer

Finally, the phasor diagram for the operation of the ideal transformer is shown in

Fig. 13 in which θ 1 and θ 2 are power factor angles on the primary and secondary sides. As the transformer itself does not absorb any active or reactive power it is easy to see that $\theta_1 = \theta_2$.

Thus, from the study of the ideal transformer it is seen that the transformer provides electrical isolation between two coupled electric circuits while maintaining power invariance at its two ends. However, grounding of loads and one terminal of the transformer on the secondary/primary side are followed with the provision of leakage current detection devices to safe guard the persons working with the devices. Even though the isolation aspect is a desirable one its utility cannot be over emphasized. It can be used to step up or step down the voltage/current at constant volt-ampere. Also, the transformer can be used for impedance matching. In the case of an ideal transformer the efficiency is 100% as there are no losses inside the device.

Practical Transformer

An ideal transformer is useful in understanding the working of a transformer. But it cannot be used for the computation of the performance of a practical transformer due to the non-ideal nature of the practical transformer. In a working transformer the performance aspects like magnetizing current, losses, voltage regulation, efficiency etc are important. Hence the effects of the non-idealization like finite permeability, saturation, hysteresis and winding resistances have to be added to an ideal transformer to make it a practical transformer.

Conversely, if these effects are removed from a working transformer what is left behind is an ideal transformer.

Finite permeability of the magnetic circuit necessitates a finite value of the current to be drawn from the mains to produce the mmf required to establish the necessary flux.

The current and mmf required is proportional to the flux density B that is required to be established in the core.

$$B = \mu H; \quad B = \frac{\phi}{A}$$

where A is the area of cross section of the iron core m2. H is the magnetizing force which is given by,

$$H = i.\frac{T_1}{l}$$

where l is the length of the magnetic path, m. or

$$\phi = B.A = \frac{A\mu(iT_1)}{l} \quad = \quad permeance * mmf(here \quad that \quad of \quad primary)$$

The magnetizing force and the current vary linearly with the applied voltage as long as the magnetic circuit is not saturated. Once saturation sets in, the current has to vary in a nonlinear manner to establish the flux of sinusoidal shape. This non-linear current can be resolved into fundamental and harmonic currents. This is discussed to some extent under harmonics. At present the effect of this non-linear behavior is neglected as a secondary effect. Hence the current drawn from the mains is assumed to be purely sinusoidal and directly proportional to the flux density of operation. This current can be represented by a current drawn by an inductive reactance in the circuit as the net energy associated with the same over a cycle is zero. The energy absorbed when the current increases are returned to the electric circuit when the current collapses to zero. This current is called the magnetizing current of the transformer. The magnetizing current Im is given by Im = E1/Xm where Xm is called the magnetizing reactance. The magnetic circuit being lossy absorbs and dissipates the power depending upon the flux density of operation. These losses arise out of hysteresis, eddy current inside the magnetic core. These are given by the following expressions:

$$P_h \propto B^{1.6} f$$

$$P_e \propto B^2 f^2 t^2$$

P_h -Hysteresis loss, Watts

B- Flux density of operation Tesla.

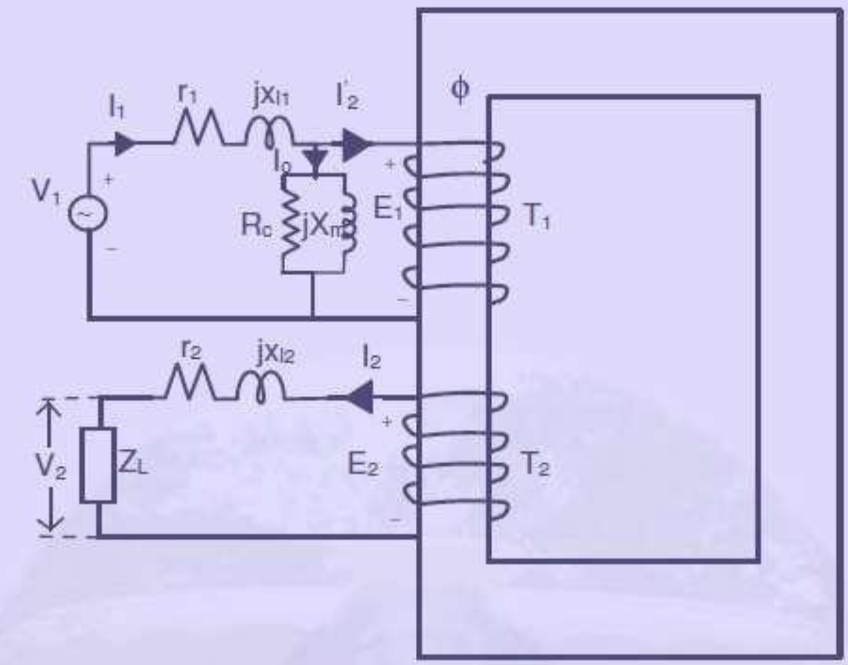
f - Frequency of operation, Hz

t - Thickness of the laminations of the core, m.

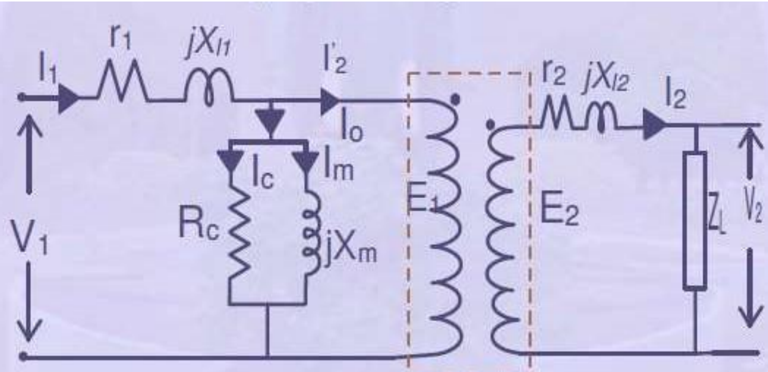
For a constant voltage, constant frequency operation B is constant and so are these losses. An active power consumption by the no-load current can be represented in the input circuit as a resistance Rc connected in parallel to the magnetizing reactance X_m. Thus the no-load current I0 may be made up of I_c (loss component) and I_m (magnetizing component as) $I_0 = Ic - jImI^2cRc$– gives the total core losses (i.e. hysteresis + eddy current loss) I^2mXm- Reactive volt amperes consumed for establishing the mutual flux.

Finite μ of the magnetic core makes a few lines of flux take to a path through the air. Thus these flux lines do not link the secondary winding. It is called as leakage flux. As the path of the leakage flux is mainly through the air the flux produced varies linearly with the primary current I_1. Even a large value of the current produces a small value of flux. This flux produces a voltage drop opposing its cause, which is the current I_1. Thus this effect of the finite permeability of the magnetic core can be represented as a series inductive element jxl_1. This is termed as the reactance due to the primary leakage flux. As this leakage flux varies linearly with I_1, the flux linkages per ampere and the primary leakage inductance are constant (This is normally represented by ll_1 Henry). The primary leakage reactance therefore becomes $xl_1 = 2\pi fll_1$ ohm.

A similar effect takes place on the secondary side when the transformer is loaded. The secondary leakage reactance jxl_2 arising out of the secondary leakage inductance ll_2 is given by $xl_2 = 2\pi fll_2$ Finally, the primary and secondary windings are wound with copper (sometimes aluminum in small transformers) conductors; thus the windings have a finite resistance (though small). This is represented as a series circuit element, as the power lost and the drop produced in the primary and secondary are proportional to the respective currents. These are represented by r_1 and r_2 respectively on primary and secondary side. A practical transformers ans these imperfections (taken out and represented explicitly in the electric circuits) is an ideal transformer of turns ratio $T_1 : T_2$ (voltage ratio $E_1 : E_2$). This is seen in Fig. 14. I'_2 in the circuit represents the primary current component that is required to flow from the mains in the primary T_1 turns to neutralize the demagnetizing secondary current I_2 due to the load in the secondary turns. The total primary current



(a)Physical arrangement



(b)Equivalent circuit

Figure 14: A Practical Transformer

$$\text{vectorially is} \quad \bar{I}_1 = \bar{I}_2' + \bar{I}_0$$

$$\text{Here} \quad I_2' T_1 = I_2 T_2 \quad \text{or} \quad I_2' = I_2 \frac{T_2}{T_1}$$

$$\text{Thus} \quad \bar{I}_1 = \bar{I}_2 \frac{T_2}{T_1} + \bar{I}_0$$

By solving this circuit for any load impedance Z_L one can find out the performance of the loaded transformer.

The circuit shown in Fig. 14(b). However, it is not very convenient for use due to the presence of the ideal transformer of turns ratio $T_1 : T_2$. If the turns ratio could be made unity by some transformation the circuit becomes very simple to use. This is done here by replacing the secondary by a 'hypothetical' secondary having T_1 turns which is 'equivalent' to the physical secondary. The equivalence implies that the ampere turns, active and reactive power associated with both the circuits must be the same. Then there is no change as far as their effect on the primary is considered.

Thus

$$V_2' = aV_2, \quad I_2' = \frac{I_2}{a}, \quad r_2' = a^2 r_2, \quad x_{l2}' = a^2 x_{l2} \quad Z_L' = a^2 Z_L.$$

where a -turns ratio T_1/T_2

As the ideal transformer in this case has a turns ratio of unity the potentials on either side are the same and hence they may be conductively connected dispensing away with the ideal transformer. This particular equivalent circuit is as seen from the primary side. It is also possible to refer all the primary parameters to secondary by making the hypothetical equivalent primary winding on the input side having the number of turns to be T_2. Such an equivalent circuit having all the parameters referred to the secondary side is shown in fig.

The equivalent circuit can be derived, with equal ease, analytically using the Kirchoff's equations applied to the primary and secondary. Referring to fig. 14(a), we have (by neglecting the shunt branch)

$$
\begin{aligned}
V_1 &= E_1 + I_1(r_1 + jx_{l1}) \\
E_2 &= V_2 + I_2(r_2 + jx_{l2}) \\
T_1 I_0 &= T_1 I_1 + T_2 I_2 \quad \text{or} \quad I_1 = -\frac{I_2}{a} + I_0 \\
&= -\frac{I_2}{a} + I_c + I_m \\
a &= \frac{T_1}{T_2}.
\end{aligned}
$$

Multiply both sides of Eqn.34 by ‘a’ [This makes the turns ratio unity and retains the power invariance].

$$
aE_2 = aV_2 + aI_2(r_2 + jx_{l2}) \qquad \text{but} \quad aE_2 = E_1
$$

Substituting in Eqn we have

$$
\begin{aligned}
V_1 &= aV_2 + aI_2(r_2 + jx_{l2}) + I_1(r_1 + jx_{l1}) \\
&= V_2' + I_1(a^2 r_2 + ja^2 x_{l2}) + I_1(r_1 + jx_{l1}) \\
&= V_2' + I_1(\overline{r_1 + r_2'} + j\overline{x_{l1} + x_{l2}'})
\end{aligned}
$$

A similar procedure can be used to refer all parameters to secondary side. (Shown in fig)

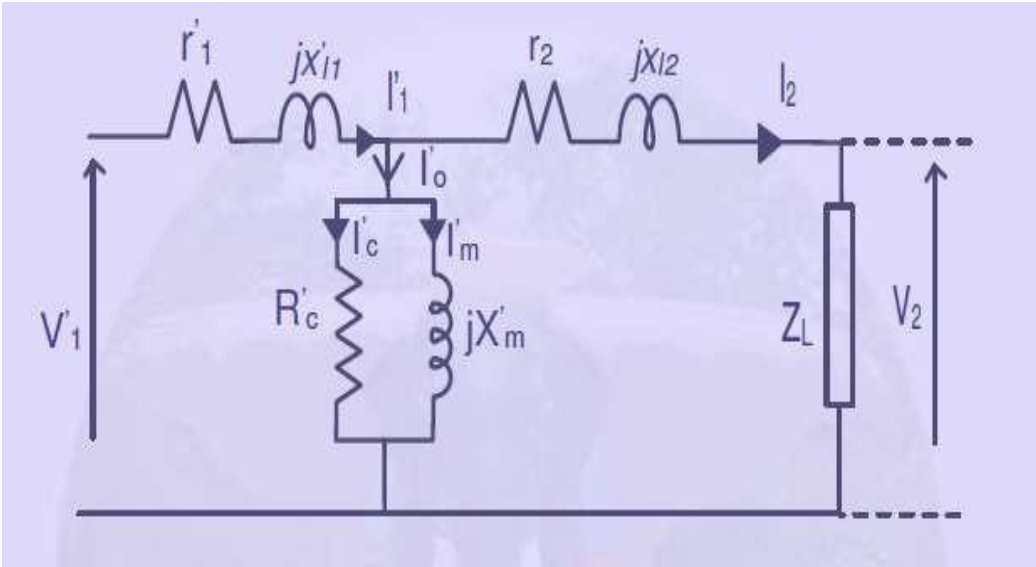


Figure 15: Equivalent Circuit Referred to the Secondary Side

Phasor Diagrams

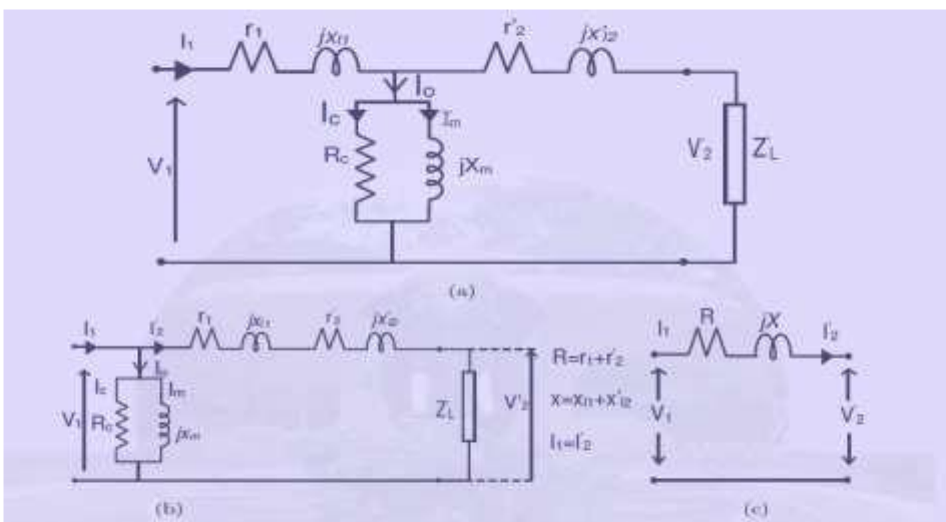
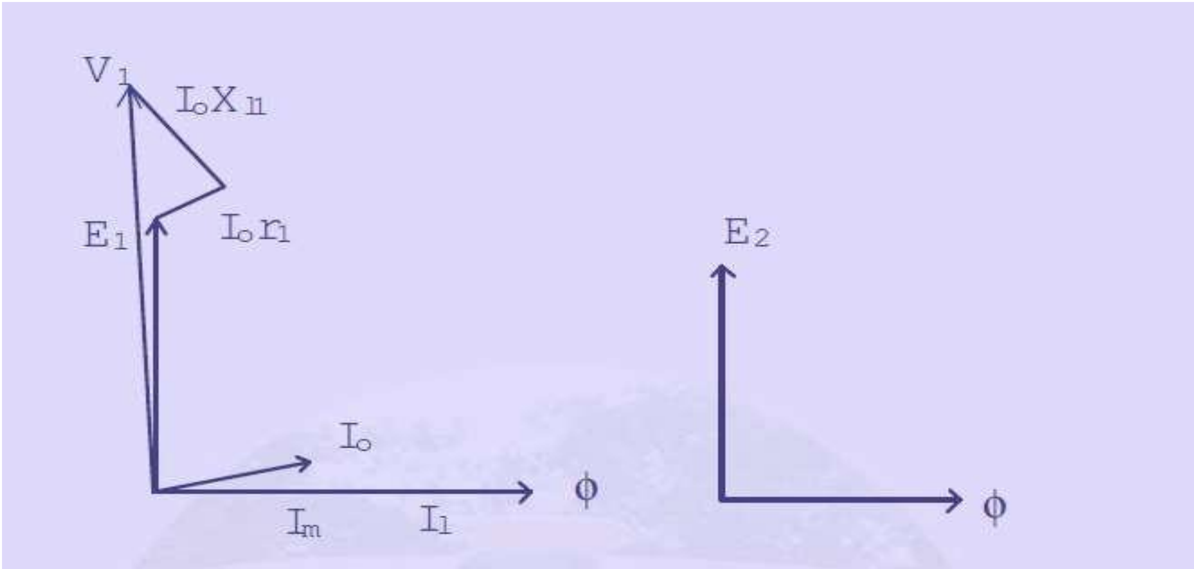


Figure 16: Exact,approximate and simplified equivalent circuits

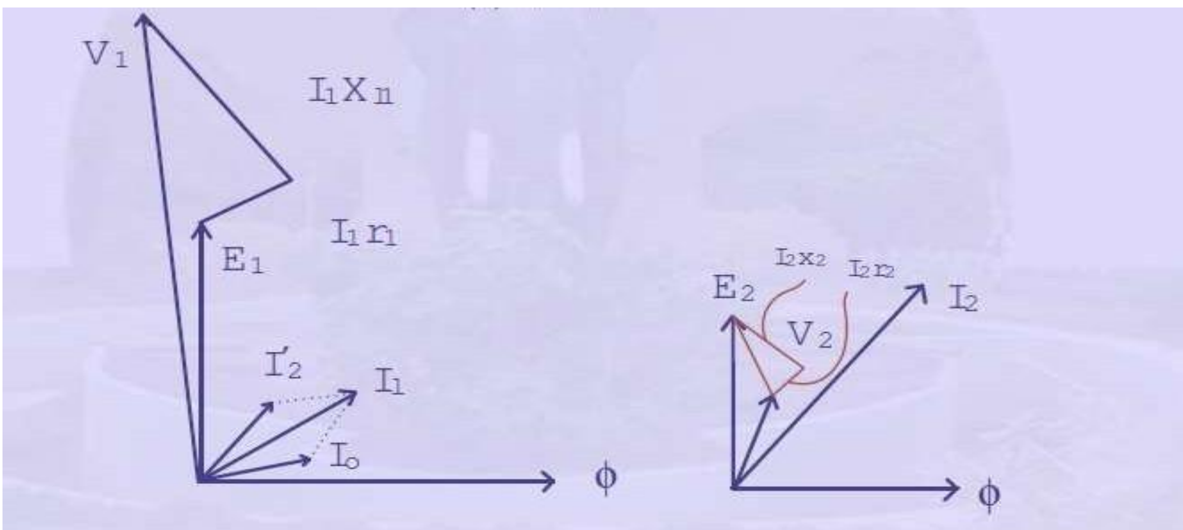
The resulting equivalent circuit as shown in Fig. 16 is known as the exact equivalent circuit. This circuit can be used for the analysis of the behavior of the transformers. As the no-load current is less than 1% of the load current a simplified circuit known as 'approximate' equivalent circuit (see Fig. 16(b)) is usually used, which may be further simplified to the one shown in Fig. 16(c).

On similar lines to the ideal transformer the phasor diagram of operation can be drawn for a practical transformer also. The positions of the current and induced emf phasor are not known uniquely if we start from the phasor V_1. Hence it is assumed that the phasor is known. The E_1 and E_2 phasor are then uniquely known. Now, the magnetizing and loss components of the currents can be easily represented. Once I_0 is known, the drop that takes place in the primary resistance and series reactance can be obtained which when added to E1 gives uniquely the position of V_1 which satisfies all other parameters. This is represented in Fig. 17(a) as phasor diagram on no-load.

Next we proceed to draw the phasor diagram corresponding to a loaded transformer. The position of the E_2 vector is known from the flux phasor. Magnitude of I_2 and the load power factor angle θ_2 are assumed to be known. But the angle θ_2 is defined with respect to the terminal voltage V_2 and not E_2. By trial and error the position of I_2 and V_2 are determined. V_2 should also satisfy the Kirchoff's equation for the secondary. Rest of the construction of the phasor diagram then becomes routine. The equivalent primary current I'_2 is added vectorially to I_0 to yield I_1. $I_1(r_1+jxl_1)$is added to E_1 to yield V_1. This is shown in fig. 17(b) as phasor diagram for a loaded transformer.



(a)No-load



(b)On-load

Figure 17: Phasor Diagram of a Practical Transformer

Open Circuit Test

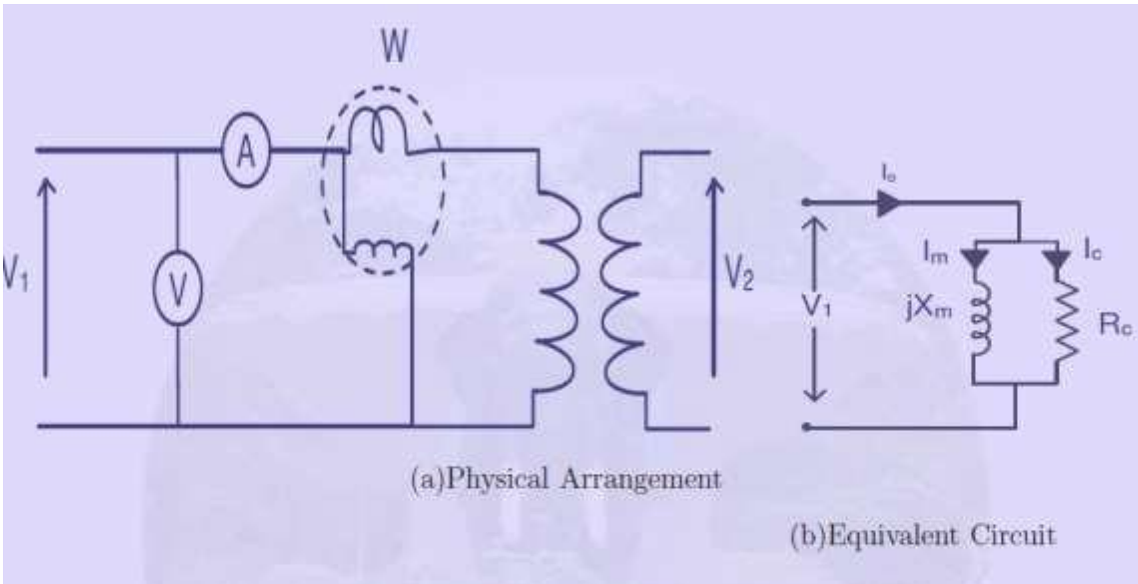


Figure 19: No Load Test

As the name suggests, the secondary is kept open circuited and nominal value of the input voltage is applied to the primary winding and the input current and power are measured. In Fig. 19(a) V,A,W are the voltmeter, ammeter and wattmeter respectively. Let these meters read V1, I0 and W0 respectively.Fig. 19(b) shows the equivalent circuit of the transformer under this test. The no load current at rated voltage is less than 1 percent of nominal current and hence the loss and drop that take place in primary impedance r1 +jxl1 due to the no load current I0 is negligible. The active component Iw of the no load current I0 represents the core losses and reactive current Im is the current needed for the magnetization.

Thus the watt meter reading

$$
\begin{aligned}
W_0 &= V_1 I_c = P_{core} \\
\therefore I_c &= \frac{W_0}{V_1} \\
\therefore I_m &= \sqrt{I_0^2 - I_c^2} \quad \text{or} \\
R_c &= \frac{V_1}{I_c} \quad \text{and} X_m = \frac{V_1}{I_m}
\end{aligned}
$$

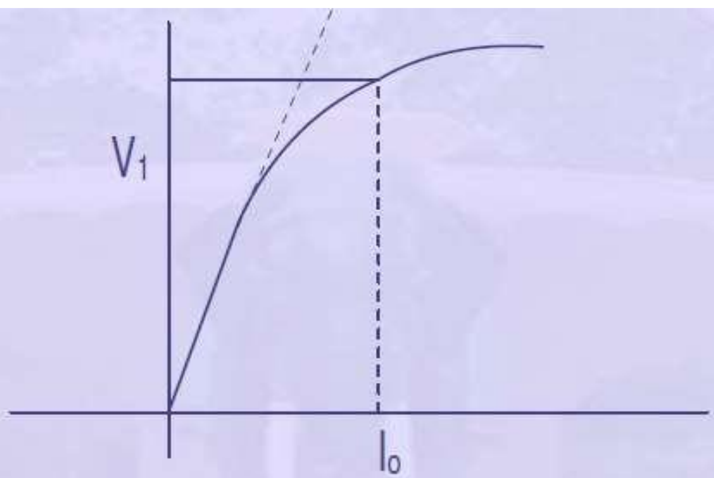


Figure 20: Open Circuit Characteristics

The parameters measured already are in terms of the primary. Sometimes the primary voltage required may be in kilo-Volts and it may not be feasible to apply nominal voltage to primary from the point of safety to personnel and equipment. If the secondary voltage is low, one can perform the test with LV side energized keeping the HV side open circuited. In this case the parameters that are obtained are in terms of LV . These have to be referred to HV side if we need the equivalent circuit referred to HV side.

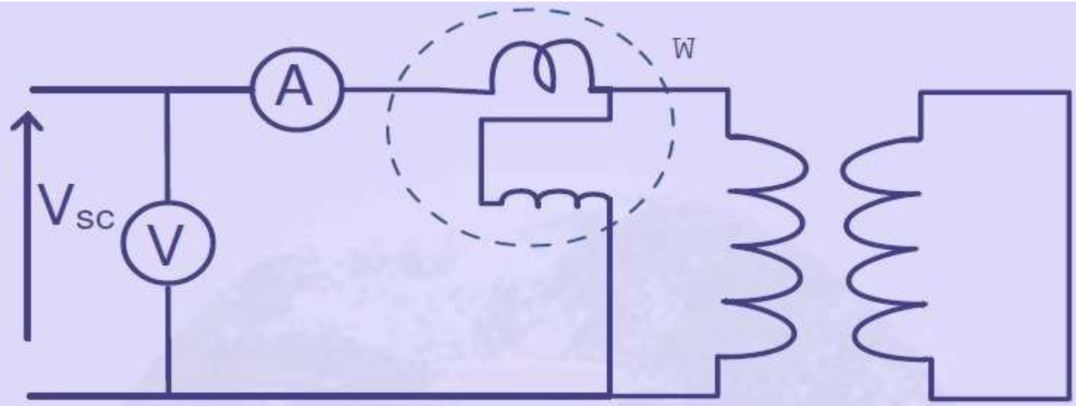
Sometimes the nominal value of high voltage itself may not be known, or in doubt, especially in a rewound transformer. In such cases an open circuit characteristics is first obtained, which is a graph showing the applied voltage as a function of the no load current.

This is a non linear curve as shown in Fig. 20. This graph is obtained by noting the current drawn by transformer at different applied voltage, keeping the secondary open circuited. The usual operating point selected for operation lies at some standard voltage around the knee point of the characteristic. After this value is chosen as the nominal value the parameters are calculated as mentioned above.

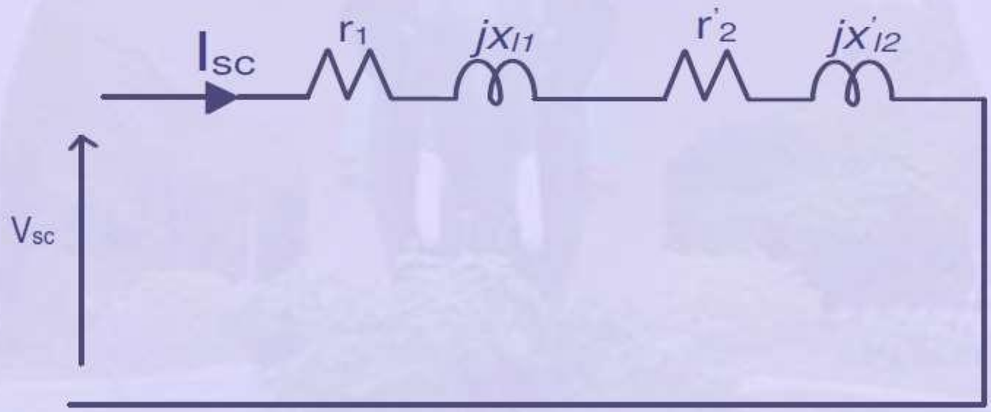
Short Circuit Test

The purpose of this test is to determine the series branch parameters of the equivalent circuit of Fig. 21(b). As the name suggests, in this test primary applied voltage, the current and power input are measured keeping the secondary terminals short circuited. Let these values be Vsc, Isc and Wsc respectively. The supply voltage required to circulate rated current through the transformer is usually very small and is of the order of a few percent of the nominal voltage. The excitation current which is only 1 percent or less even at rated voltage becomes negligibly small during this test and hence is neglected. The shunt branch is thus assumed to be absent. Also I1 = I2 as I0 $\simeq$ 0. Therefore Wsc is the sum of the copper losses in primary and secondary put together. The reactive power consumed is that absorbed by the leakage reactance of the two windings.

$$
\begin{aligned}
W_{sc} &= I_{sc}^2(r_1 + r_2') \\
Z_{sc} &= \frac{V_{sc}}{I_{sc}} \\
(x_{l1} + x_{l2}') &= \sqrt{Z_{sc}^2 - (r_1 + r_2')^2}
\end{aligned}
$$



(a)Physical Arrangement



(b)Equivalent Circuit

Figure 21: Short Circuit Test

If the approximate equivalent circuit is required then there is no need to separate r’1 and r’2 or xl1 and x’l2. However if the exact equivalent circuit is needed then either r’1 or’2 is determined from the resistance measurement and the other separated from the total.

As for the separation of xl1 and x’l2 is concerned, they are assumed to be equal. This is a fairly valid assumption for many types of transformer windings as the leakage flux paths are through air and are similar.

Load Test

Load Test helps to determine the total loss that takes place, when the transformer is loaded. Unlike the tests described previously, in the present case nominal voltage is applied across the primary and rated current is drawn from the secondary. Load test is used mainly

1. to determine the rated load of the machine and the temperature rise

2. to determine the voltage regulation and efficiency of the transformer.

Rated load is determined by loading the transformer on a continuous basis and observing the steady state temperature rise. The losses that are generated inside the transformer on load appear as heat. This heats the transformer and the temperature of the transformer increases. The insulation of the transformer is the one to get affected by this rise in the temperature. Both paper and oil which are used for insulation in the transformer start getting degenerated and get decomposed. If the flash point of the oil is reached the transformer goes up in flames. Hence to have a reasonable life expectancy the loading of the transformer must be limited to that value which gives the maximum temperature rise tolerated by the insulation. This aspect of temperature rise cannot be guessed from the electrical equivalent circuit. Further, the losses like dielectric losses and stray load losses are not modeled in the equivalent circuit and the actual loss under load condition will be in error to that extent.

Many external means of removal of heat from the transformer in the form of different cooling methods give rise to different values for temperature rise of insulation. Hence these permit different levels of loading for the same transformer. Hence the only sure way of ascertaining the rating is by conducting a load test. It is rather easy to load a transformer of small ratings. As the rating increases it becomes difficult to find a load that can absorb the requisite power and a source to feed the necessary current. As the transformers come in varied transformation ratios, in many cases it becomes extremely difficult to get suitable load impedance.

Further, the temperature rise of the transformer is due to the losses that take place 'inside' the transformer. The efficiency of the transformer is above 99% even in modest sizes which means 1 percent of power handled by the transformer actually goes to heat up the machine. The remaining 99% of the power has to be dissipated in a load impedance external to the machine. This is very wasteful in terms of energy also. (If the load is of unity power factor) Thus the actual loading of the transformer is seldom resorted to. Equivalent loss methods of loading and 'Phantom' loading are commonly used in the case of transformers.

The load is applied and held constant till the temperature rise of transformer reaches a steady value. If the final steady temperature rise is lower than the maximum permissible value, then load can be increased else it is decreased. That load current which gives the maximum permissible temperature rise is declared as the nominal or rated load current and the volt amperes are computed using the same.

In the equivalent loss method a short circuit test is done on the transformer. The short circuit current is so chosen that the resulting loss taking place inside the transformer is equivalent to the sum of the iron losses, full load copper losses and assumed stray load losses. By this method even though one can pump in equivalent loss inside the transformer, the actual distribution of this loss vastly differs from that taking place in reality. Therefore this test comes close to a load test but does not replace one.

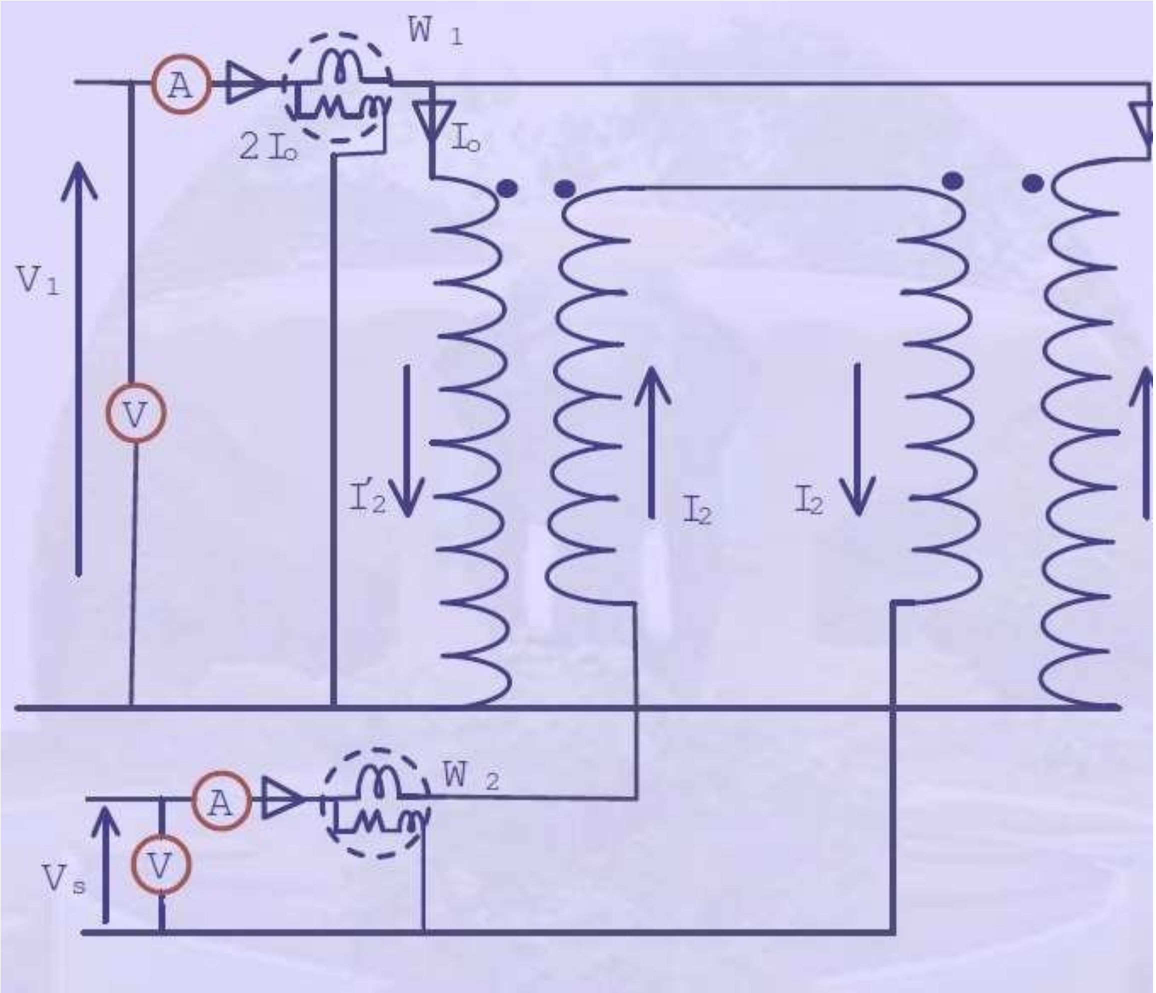


Figure 22: Back to Back Test - Phantom Loading

In Phantom loading method two identical transformers are needed. The windings are connected back to back as shown in Fig. 22. Suitable voltage is injected into the loop formed by the two secondaries such that full load current passes through them. An equivalent current then passes through the primary also. The voltage source V1 supplies the magnetizing current and core losses for the two transformers. The second source supplies the load component of the current and losses due to the same. There is no power wasted in a load (as a matter of fact there is no real load at all) and hence the name Phantom or virtual loading. The power absorbed by the second transformer which acts as a load is pushed back in to the mains. The two sources put together meet the core and copper losses of the two transformers. The transformers work with full flux drawing full load currents and hence are closest to the actual loading condition with a physical load.

Voltage Regulation

Modern power systems operate at some standard voltages. The equipments working on these systems are therefore given input voltages at these standard values, within certain agreed tolerance limits. In many applications this voltage itself may not be good enough for obtaining the best operating condition for the loads. A transformer is interposed in between the load and the supply terminals in such cases. There are additional drops inside the transformer due to the load currents. While input voltage is the responsibility of the supply provider, the voltage at the load is the one which the user has to worry about.

If undue voltage drop is permitted to occur inside the transformer the load voltage becomes too low and affects its performance. It is therefore necessary to quantify the drop that takes place inside a transformer when certain load current, at any power factor, is drawn from its output leads. This drop is termed as the voltage regulation and is expressed as a ratio of the terminal voltage (the absolute value per se is not too important).

The voltage regulation can be defined in two ways - Regulation Down and Regulation up. These two definitions differ only in the reference voltage as can be seen below. Regulation down: This is defined as ” the change in terminal voltage when a load current at any power factor is applied, expressed as a fraction of the no-load terminal voltage”.

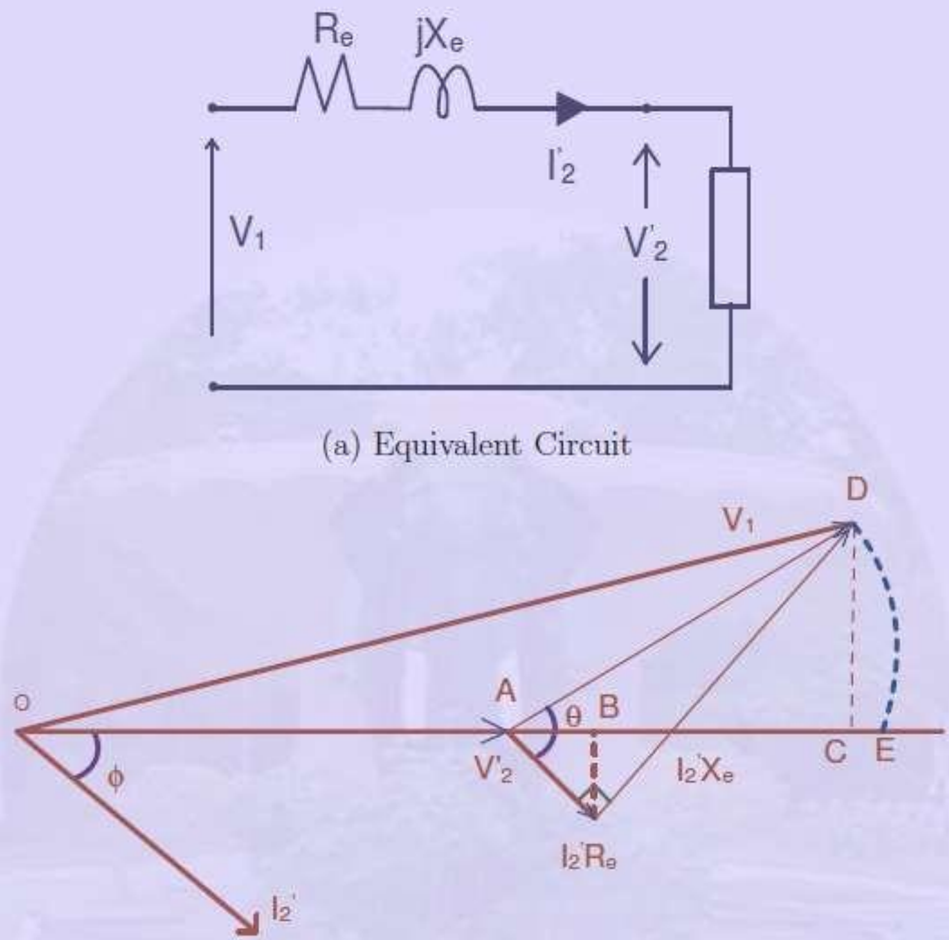
Expressed in symbolic form we have,

$$Regulation = \frac{|V_{nl}| - |V_l|}{|V_l|}$$

Vnl is the no-load terminal voltage. Vl is load voltage. Normally full load regulation is of interest as the part load regulation is going to be lower.

This definition is more commonly used in the case of alternators and power systems as the user-end voltage is guaranteed by the power supply provider. He has to generate proper no-load voltage at the generating station to provide the user the voltage he has asked for. In the expressions for the regulation, only the numerical differences of the voltages are taken and not vector differences.

In the case of transformers both definitions result in more or less the same value for the regulation as the transformer impedance is very low and the power factor of operation is quite high. The power factor of the load is defined with respect to the terminal voltage on load. Hence a convenient starting point is the load voltage. Also the full load output voltage is taken from the name plate. Hence regulation up has some advantage when it comes to its application. Fig. 23 shows the phasor diagram of operation of the transformer under loaded condition. The no-load current I0 is neglected in view of the large magnitude of I'2. Then



(b)Phasor Diagram

Figure 23: Regulation of Transformer

$I_1 = I_2'$.

$$\begin{aligned} V_1 &= I_2'(R_e + jX_e) + V_2' \\ OD &= V_1 = \sqrt{[OA + AB + BC]^2 + [CD]^2} \\ &= \sqrt{[V_2' + I_2' R_e \cos\phi + I_2' X_e \sin\phi]^2 + [I_2' X_e \cos\phi - I_2' R_e \sin\phi]^2} \end{aligned}$$

ϕ - power factor angle,

θ- internal impedance angle$=\tan^{-1}\frac{X_e}{R_e}$

Also,

$$\begin{aligned} V_1 &= V_2' + I_2'.(R_e + jX_e) \\ &= V_2' + I_2'(\cos\phi - j\sin\phi)(R_e + jX_e) \\ \therefore \text{Regulation} R &= \frac{|V_1| - |V_2'|}{|V_2'|} = \sqrt{(1+v_1)^2 + v_2^2} - 1 \end{aligned}$$

$$(1+v_1)^2 + v_2^2 \simeq (1+v_1)^2 + v_2^2.\frac{2(1+v_1)}{2(1+v_1)} + [\frac{v_2^2}{2(1+v_1)}]^2 = (1 + v_1 + \frac{v_2^2}{2(1+v_1)})$$

Taking the square root

$$\sqrt{(1+v_1)^2 + v_2^2} = 1 + v_1 + \frac{v_2^2}{2(1+v_1)}$$

where $v_1 = e_r\cos\phi + e_x\sin\phi$ and $v_2 = e_x\cos\phi - e_r\sin\phi$

$e_r = \frac{I_2' R_e}{V_2'}$=per unit resistance drop

$e_x = \frac{I_2' X_e}{V_2'}$=per unit reactance drop

as v_1 and v_2 are small.

$$\therefore R \simeq 1 + v_1 + \frac{v_2^2}{2(1+e_1)} - 1 \simeq v_1 + \frac{v_2^2}{2}$$

$$\therefore \text{regulation } R = e_r\cos\phi \pm e_x\sin\phi + \frac{(e_x\sin\phi - e_r\cos\phi)^2}{2}$$

$$\frac{v_2^2}{2(1+v_1)} \simeq \frac{v_2^2}{2}.\frac{(1-v_1)}{(1-v_1^2)} \simeq \frac{v_2^2}{2}.(1-v_1) \simeq \frac{v_2^2}{2}$$

Powers higher than 2 for v1 and v2 are negligible as v1 and v2 are already small. As v2 is small its second power may be neglected as a further approximation and the expression for the regulation of the transform boils down to regulation $R = e_r \cos\phi \pm e_x \sin\phi$

The negative sign is applicable when the power factor is leading. It can be seen from the above expression, the full load regulation becomes zero when the power factor is leading

$$e_r \cos\phi = e_x \sin\phi \text{ or } \tan\phi = e_r/e_x$$

or the power factor angle $\phi = \tan^{-1}(e_r/e_x) = \tan^{-1}(R_e/X_e)$ leading.

Similarly, the value of the regulation is maximum at a power factor angle $\phi = \tan^{-1}(e_x/e_r) = \tan^{-1}(X_e/R_e)$ lagging.

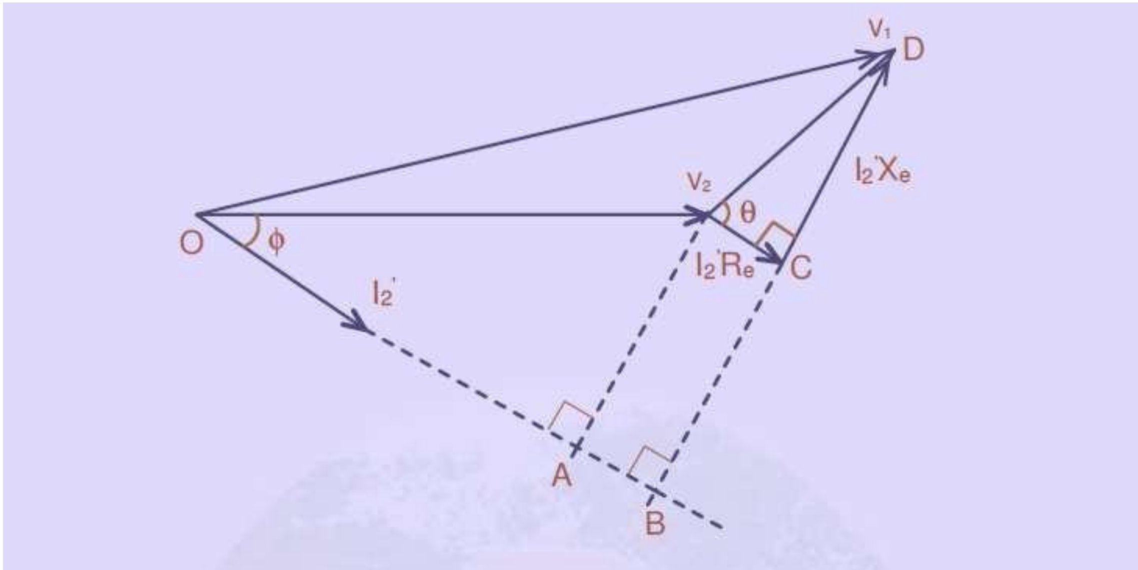
An alternative expression for the regulation of a transformer can be derived by the method shown in Fig. 24. Here the phasor are resolved along the current axis and normal to it.

We have,

$$\begin{aligned} OD^2 &= (OA + AB)^2 + (BC + CD)^2 \\ &= (V_2' \cos\phi + I_2' R_e)^2 + (V_2' \sin\phi + I_2' X_e)^2 \\ \therefore Regulation R &= \frac{OD - V_2'}{V_2'} = \frac{OD}{V_2'} - 1 \end{aligned}$$

$$\sqrt{\frac{(V_2' \cos\phi + I_2' R_e)^2}{V_2'} + \frac{(V_2' \sin\phi + I_2' X_e)^2}{V_2'}} - 1$$

$$= \sqrt{(\cos\phi + R_{p.u})^2 + (\sin\phi + X_{p.u)}^2)} - 1$$



Thus this expression may not be as convenient as the earlier one due to the square root involved. Fig. shows the variation of full load regulation of a typical transformer as the power factor is varied from zero power factor leading, through unity power factor, to zero power factor lagging.

It is seen from Fig. that the full load regulation at unity power factor is nothing but the percentage resistance of the transformer. It is therefore very small and negligible. Only with low power factor loads the drop in the series impedance of the transformer contributes substantially to the regulation. In small transformers the designer tends to keep the Xe very low (less than 5%) so that the regulation performance of the transformer is satisfactory.

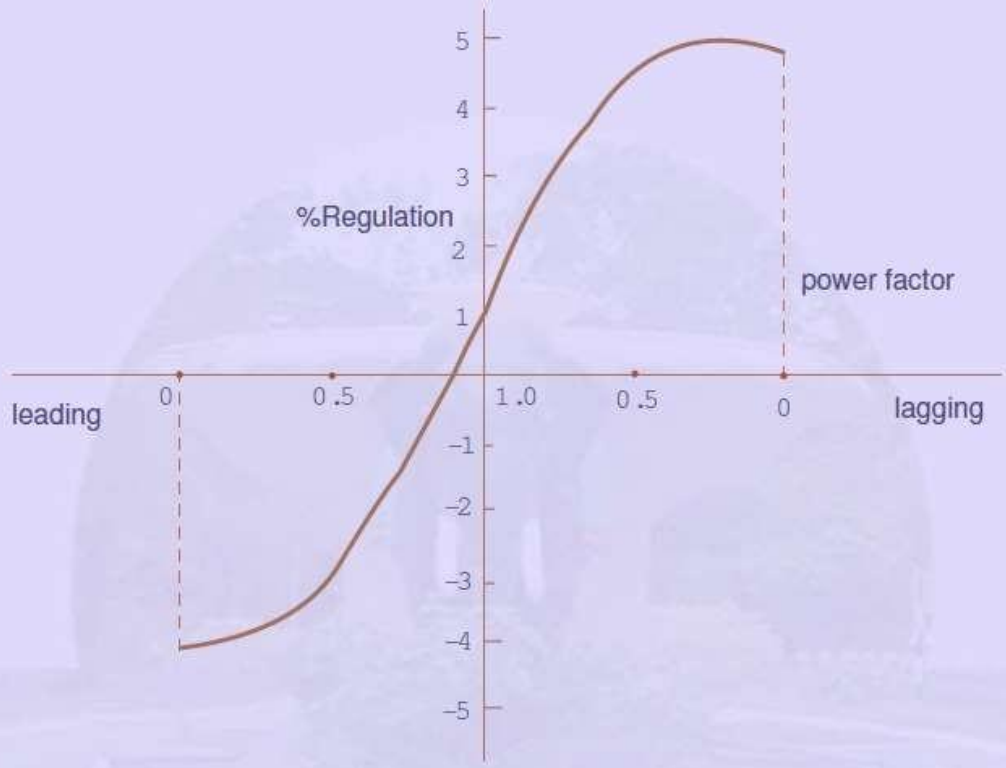


Figure 25: Variation of Full Load Regulation with Power Factor

A low value of the short circuit impedance /reactance results in a large short circuit current in case of a short circuit. This in turn results in large mechanical forces on the winding. So, in large transformers the short circuit impedance is made high to give better short circuit protection to the transformer which results in poorer regulation performance. In the case of transformers provided with taps on windings, so that the turns ratio can be changed, the voltage regulation is not a serious issue. In other cases care has to be exercised in the selection of the short circuit impedance as it affects the voltage regulation.

Efficiency

Transformers which are connected to the power supplies and loads and are in operation are required to handle load current and power as per the requirements of the load. An unloaded transformer draws only the magnetization current on the primary side, the secondary current being zero. As the load is increased the primary and secondary currents increase as per the load requirements. The volt amperes and wattage handled by the transformer also increases. Due to the presence of no load losses and I2R losses in the windings certain amount of electrical energy gets dissipated as heat inside the transformer. This gives rise to the concept of efficiency.

Efficiency of a power equipment is defined at any load as the ratio of the power output to the power input. Putting in the form of an expression,

$$Efficiency\ \eta = \frac{output\ power}{input\ power} = \frac{Input\ power - losses\ inside\ the\ machine}{Input\ power}$$

$$= 1 - \frac{losses\ inside\ the\ machine}{input\ power} = 1 - defficiency$$

$$= \frac{output\ power}{output + losses\ inside\ the\ machine}$$

More conveniently the efficiency is expressed in percentage. $\%\eta = \frac{output\ power}{input\ power} * 100$

While the efficiency tells us the fraction of the input power delivered to the load, the deficiency focuses our attention on losses taking place inside transformer. As a matter of fact the losses heat up machine. The temperature rise decides the rating of the equipment.

The temperature rise of the machine is a function of heat generated the structural configuration, method of cooling and type of loading (or duty cycle of load). The peak temperature attained directly affects the life of the insulations of the machine for any class of insulation.

These aspects are briefly mentioned under section 7.5 on load test.

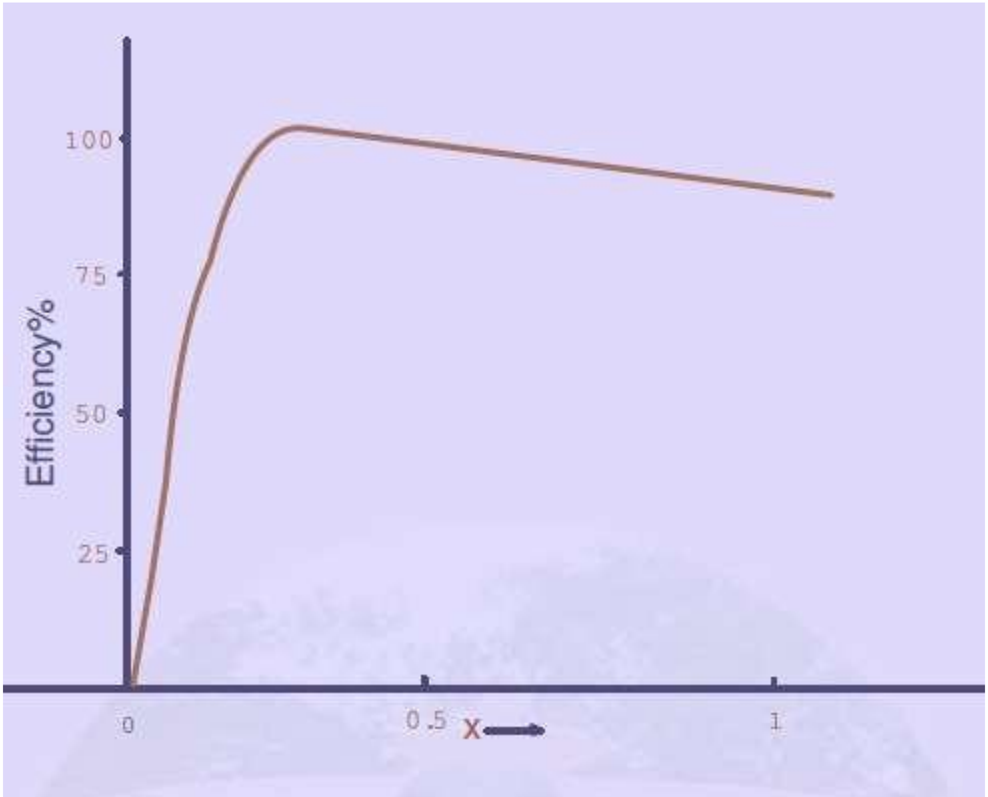


Figure 26: Efficiency

A typical curve for the variation of efficiency as a function of output is given in Fig. The losses that take place inside the machine expressed as a fraction of the input is some times termed as deficiency. Except in the case of an ideal machine, a certain fraction of the input power gets lost inside the machine while handling the power. Thus the value for the efficiency is always less than one. In the case of a.c. machines the rating is expressed in terms of apparent power. It is nothing but the product of the applied voltage and the current drawn. The actual power delivered is a function of the power factor at which this current is drawn. As the reactive power shuttles between the source and the load and has a zero average value over a cycle of the supply wave it does not have any direct effect on the efficiency. The reactive power however increases the current handled by the machine and the losses resulting from it. Therefore the losses that take place inside a transformer at any given load play a vital role in determining the efficiency. The losses taking place inside a transformer can be enumerated as below:

1. Primary copper loss

2. Secondary copper loss

3. Iron loss

4. Dielectric loss

5. Stray load loss

These are explained in sequence below.

Primary and secondary copper losses take place in the respective winding resistances due to the flow of the current in them.

$$P_c = I_1^2 r_1 + I_2^2 r_2 = I_2'^2 R_e$$

The primary and secondary resistances differ from their d.c. values due to skin effect and the temperature rise of the windings. While the average temperature rise can be approximately used, the skin effect is harder to get analytically. The short circuit test gives the value of Re taking into account the skin effect.

The iron losses contain two components - Hysteresis loss and Eddy current loss. The Hysteresis loss is a function of the material used for the core.

$$P_h = K_h B^{1.6} f$$

For constant voltage and constant frequency operation this can be taken to be constant. The eddy current loss in the core arises because of the induced emf in the steel lamination sheets and the eddies of current formed due to it. This again produces a power loss Pe in the lamination.

$$P_e = K_e B^2 f^2 t^2$$

where t is the thickness of the steel lamination used. As the lamination thickness is much smaller than the depth of penetration of the field, the eddy current loss can be reduced by reducing the thickness of the lamination. Present day laminations are of 0.25 mm thickness and are capable of operation at 2 Tesla. These reduce the eddy current losses in the core. This loss also remains constant due to constant voltage and frequency of operation. The sum of hysteresis and eddy current losses can be obtained by the open circuit test.

The dielectric losses take place in the insulation of the transformer due to the large electric stress. In the case of low voltage transformers this can be neglected. For constant voltage operation this can be assumed to be a constant.

The stray load losses arise out of the leakage fluxes of the transformer. These leakage fluxes link the metallic structural parts, tank etc. and produce eddy current losses in them. Thus they take place 'all round' the transformer instead of a definite place , hence the name 'stray'. Also the leakage flux is directly proportional to the load current unlike the mutual flux which is proportional to the applied voltage. Hence this loss is called 'stray load' loss. This can also be estimated experimentally. It can be modeled by another resistance in the series branch in the equivalent circuit. The stray load losses are very low in air-cored transformers due to the absence of the metallic tank.

Thus, the different losses fall in to two categories Constant losses (mainly voltage dependant) and Variable losses (current dependant). The expression for the efficiency of the transformer operating at a fractional load x of its rating, at a load power factor of ϴ2, can be written as

$$\eta = \frac{xS\cos\theta_2}{xS\cos\theta_2 + P_{const} + x^2 P_{var}}$$

Here S in the volt ampere rating of the transformer (V'2 I'2 at full load), Pconst being constant losses and Pvar the variable losses at full load.

For a given power factor an expression for ϴ2 in terms of the variable x is thus obtained. By differentiating ϴ2with respect to x and equating the same to zero, the condition for maximum efficiency is obtained. In the present case that condition comes out to be

$$P_{const} = x^2 P_{var} \text{ or } x = \sqrt{\frac{P_{const}}{P_{var}}}$$

That is, when constant losses equal the variable losses at any fractional load x the efficiency reaches a maximum value. The maximum value of that efficiency at any given power factor is given by,

$$\eta_{max} = \frac{xS\cos\theta_2}{xS\cos\theta_2 + 2P_{const}} = \frac{xS\cos\theta_2}{xS\cos\theta_2 + 2x^2 P_{var}}$$

From the expression for the maximum efficiency it can be easily deduced that this maximum value increases with increase in power factor and is zero at zero power factor of the load. It may be considered a good practice to select the operating load point to be at the maximum efficiency point. Thus if a transformer is on full load, for most part of the time then the ϴ2max can be made to occur at full load by proper selection of constant and variable losses. However, in the modern transformers the iron losses are so low that it is practically impossible to reduce the full load copper losses to that value. Such a design wastes lot of copper.

All day efficiency

Large capacity transformers used in power systems are classified broadly into Power transformers and Distribution transformers. The former variety is seen in generating stations and large substations. Distribution transformers are seen at the distribution substations. The basic difference between the two types arise from the fact that the power transformers are switched in or out of the circuit depending upon the load to be handled by them. Thus at 50% load on the station only 50% of the transformers need to be connected in the circuit.

On the other hand a distribution transformer is never switched off. It has to remain in the circuit irrespective of the load connected. In such cases the constant loss of the transformer continues to be dissipated. Hence the concept of energy based efficiency is defined for such

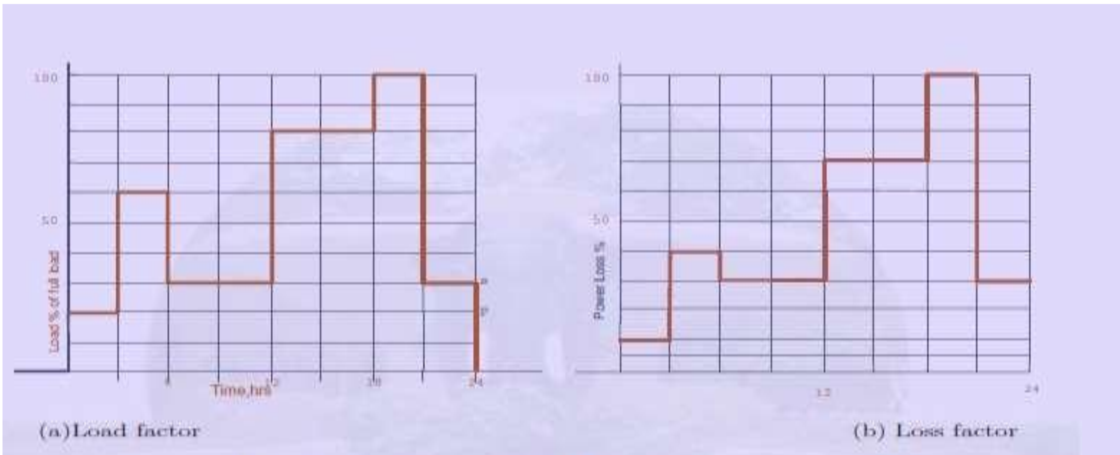


Figure 27: Calculation of Load Factor and Loss Factor

transformers. It is called 'all day' efficiency. The all day efficiency is thus the ratio of the energy output of the transformer over a day to the corresponding energy input. One day is taken as a duration of time over which the load pattern repeats itself. This assumption, however, is far from being true. The power output varies from zero to full load depending on the requirement of the user and the load losses vary as the square of the fractional loads.

The no-load losses or constant losses occur throughout the 24 hours. Thus, the comparison of loads on different days becomes difficult. Even the load factor, which is given by the ratio of the average load to rated load, does not give satisfactory results. The calculation of the all day efficiency is illustrated below with an example. The graph of load on the transformer, expressed as a fraction of the full load is plotted against time in Fig. 27. In an actual situation the load on the transformer continuously changes. This has been presented by a stepped curve for convenience. The average load can be calculated by

$$\text{Average load over a day} = \frac{\sum_{i=1}^{n} P_i}{24} = \frac{S_n \sum_{i=1}^{n} x_i t_i \cos\theta_i}{24}$$

Where Pi is the load during an interval i. n intervals are assumed. xi is the fractional load.

Si = xiSn

where Sn is nominal load. The average loss during the day is given by

$$\text{Average loss} = P_i + \frac{P_c \sum_{i=1}^{n} x_i^2 t_i}{24}$$

This is a non-linear function. For the same load factor different average loss can be there depending upon the values of xi and ti. Hence a better option would be to keep the constant losses very low to keep the all day efficiency high. Variable losses are related to load and are associated with revenue earned. The constant losses on the other hand has to be incurred to make the service available. The concept of all day efficiency may therefore be more useful for comparing two transformers subjected to the same load cycle.

The concept of minimizing the lost energy comes into effect right from the time of procurement of the transformer. The constant losses and variable losses are capitalized and added to the material cost of the transformer in order to select the most competitive one which gives minimum cost taking initial cost and running cost put together. Obviously the iron losses are capitalized more in the process to give an effect to the maximization of energy efficiency. If the load cycle is known at this stage, it can also be incorporated in computation of the best transformer.

Harmonics

In addition to the operation of transformers on the sinusoidal supplies, the harmonic behavior becomes important as the size and rating of the transformer increases. The effects of the harmonic currents are

1. Additional copper losses due to harmonic currents
2. Increased core losses
3. Increased electro magnetic interference with communication circuits.

On the other hand the harmonic voltages of the transformer cause

1. Increased dielectric stress on insulation
2. Electro static interference with communication circuits.
3. Resonance between winding reactance and feeder capacitance.

In the present times a greater awareness is generated by the problems of harmonic voltages and currents produced by non-linear loads like the power electronic converters.

These combine with non-linear nature of transformer core and produce severe distortions in voltages and currents and increase the power loss. Thus the study of harmonics is of great practical significance in the operation of transformers. The discussion here is confined to the harmonics generated by transformers only.

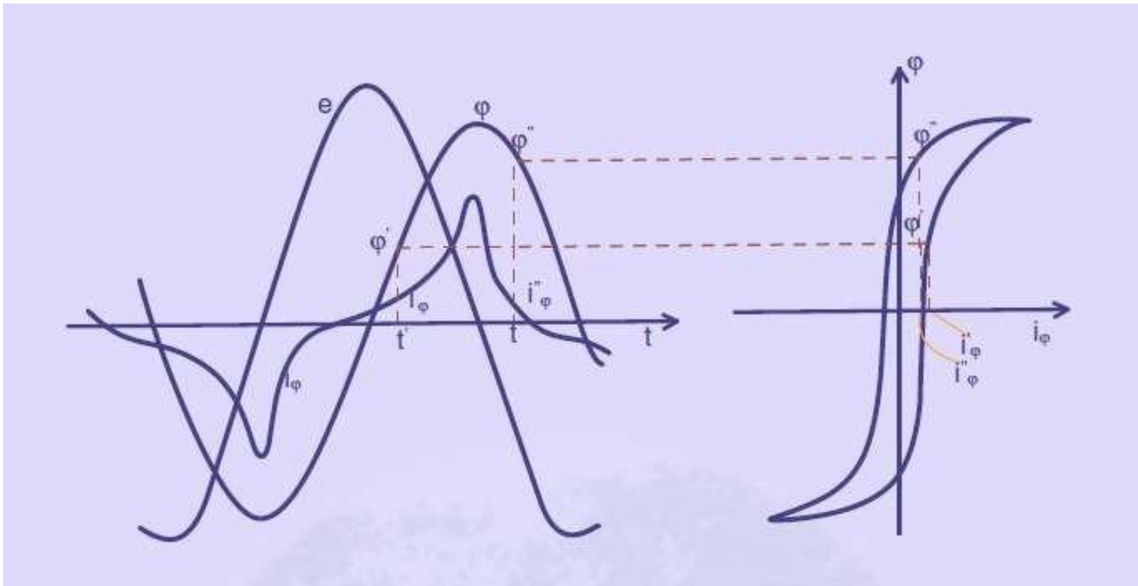


Figure 34: Harmonics Generated by Transformers

Single phase transformers

Modern transformers operate at increasing levels of saturation in order to reduce the weight and cost of the core used in the same. Because of this and due to the hysteresis, the transformer core behaves as a highly non-linear element and generates harmonic voltages and currents. This is explained below. Fig. 34 shows the manner in which the shape of the magnetizing current can be obtained and plotted. At any instant of the flux density wave the ampere turns required to establish the same is read out and plotted, traversing the hysteresis loop once per cycle. The sinusoidal flux density curve represents the sinusoidal applied voltage to some other scale. The plot of the magnetizing current which is peaky is analyzed using Fourier analysis. The harmonic current components are obtained from this analysis. These harmonic currents produce harmonic fields in the core and harmonic voltages in the windings. Relatively small value of harmonic fields generates considerable magnitude of harmonic voltages. For example a 10% magnitude of 3rd harmonic flux produces 30% magnitude of 3rd harmonic voltage. These effects get even more pronounced for higher order harmonics. As these harmonic voltages get short circuited through the low impedance of the supply they produce harmonic currents. These currents produce effects according to Lenz's law and tend to neutralize the harmonic flux and bring the flux wave to a sinusoid. Normally third harmonic is the largest in its magnitude and hence the discussion is based on it. The same can be told of other harmonics also. In the case of a single phase transformer the harmonics are confined mostly to the primary side as the source impedance is much smaller compared to the load impedance. The understanding of the phenomenon becomes more clear if the transformer is supplied with a sinusoidal current source. In this case current has to be sinusoidal and the harmonic currents cannot be supplied by the source and hence the induced emf will be peaky containing harmonic voltages. When the load is connected on the secondary side the harmonic currents flow through the load and voltage tends to become sinusoidal. The harmonic voltages induce electric stress on dielectrics and increased electro static interference. The harmonic currents produce losses and electro magnetic interference as already noted above.

Three Phase Transformer

Introduction

The generation of an electrical power is usually three phase and at higher voltages like 13.2 KV, 22 KV or some what higher, Similarly transmission of an electrical power is also at very high voltages like 110 KV, 132 KV, 400 KV. To step up the generated voltages for transmission purposes it is necessary to have three phase transformers.

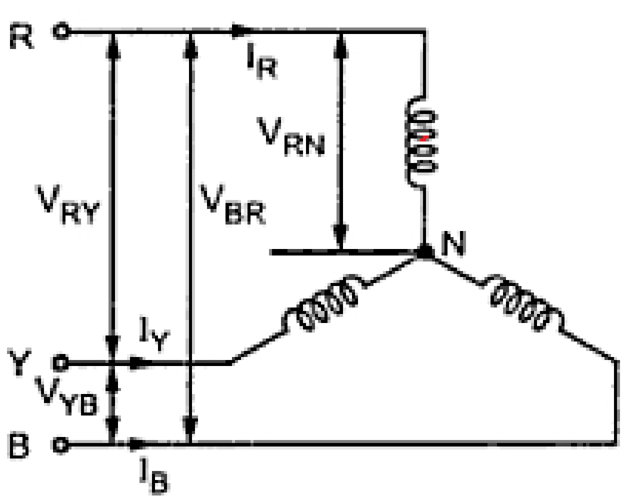
Advantages

* Less space
* Weight Less
* Cost is Less
* Transported easily
* Core will be smaller size
* More efficient
* Structure, switchgear and installation of single three phase unit is simpler

Line voltage VL= voltage between lines

Phase voltage Vph= voltage between a line and neutral

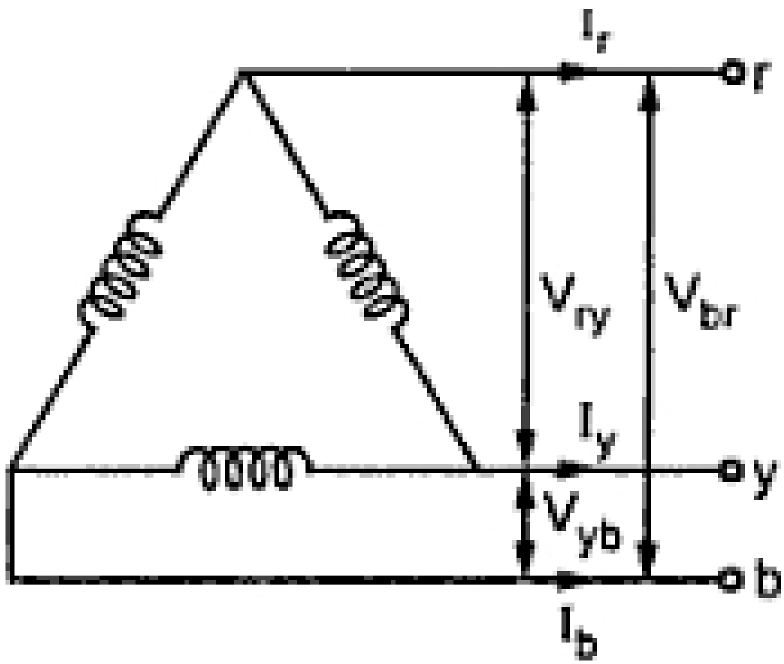
BALANCED STAR



Line Voltage VL= √3 Vph

Line current IL = Iph

BALANCED DELTA



Line Voltage VL= Vph

Line current IL = √3 Iph

Almost all major generation & Distribution Systems in the world are three phase ac systems Three phase transformers play an important role in these systems

3 phase transformers can be constructed from

a) 3 single phase transformers

(b) 2 single phase transformers

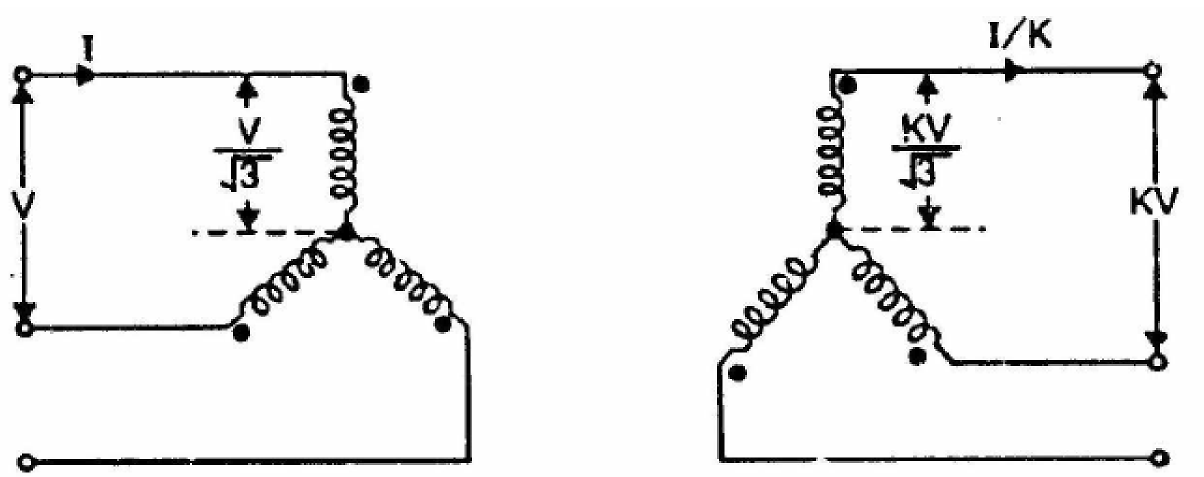
(c) using a common core for three phase windings

By connecting three single phase transformers

1. Star- Star connection
2. Delta- Delta connection
3. Star – Delta connection
4. Delta – Star connection

$$\text{Phase transformation ratio, } K = \frac{\text{Secondary phase voltage}}{\text{Primary phase voltage}} = \frac{N_2}{N_1}$$

Star- Star connection



Y – Y Connection

This connection satisfactory only in balanced load otherwise neutral point will be shifted.

Advantages

1.Requires less turns per winding ie cheaper

Phase voltage is 1/√3 times of line voltage

2.Cross section of winding is large ie stronger to bear stress during short circuit

Line current is equal to phase current

3. Less dielectric strength in insulating materials

phase voltage is less

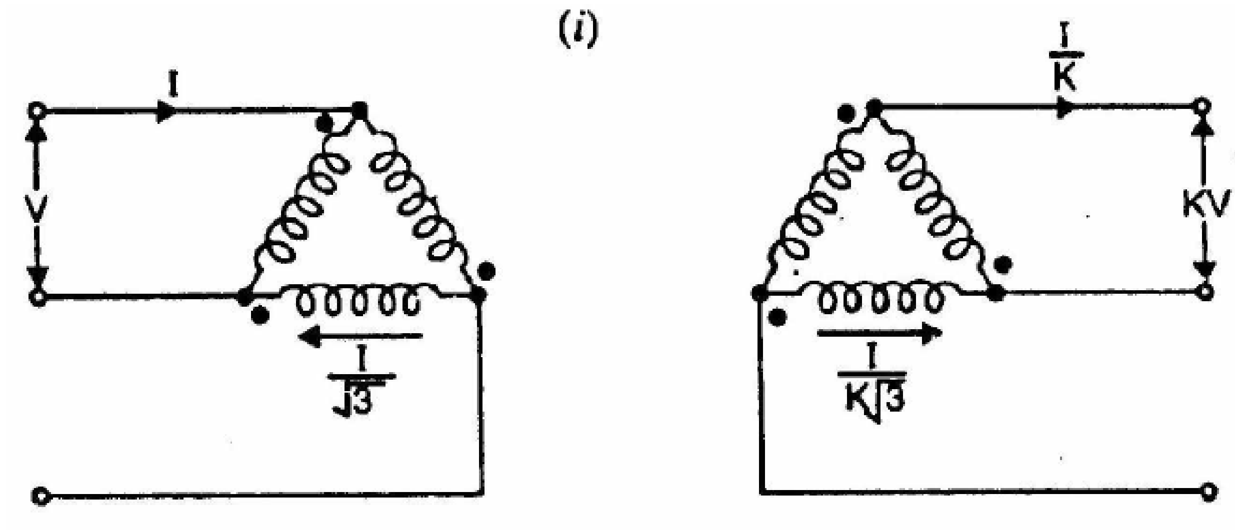
Disadvantages

1.If the load on the secondary side unbalanced then the shifting of neutral point is possible

2.The third harmonic present in the alternator voltage may appear on the secondary side. This causes distortion in the secondary phase voltages

3. Magnetizing current of transformer has 3rd harmonic component

Delta - Delta connection



Δ – Δ Connection

- **This connection is used for moderate voltages**

Advantages

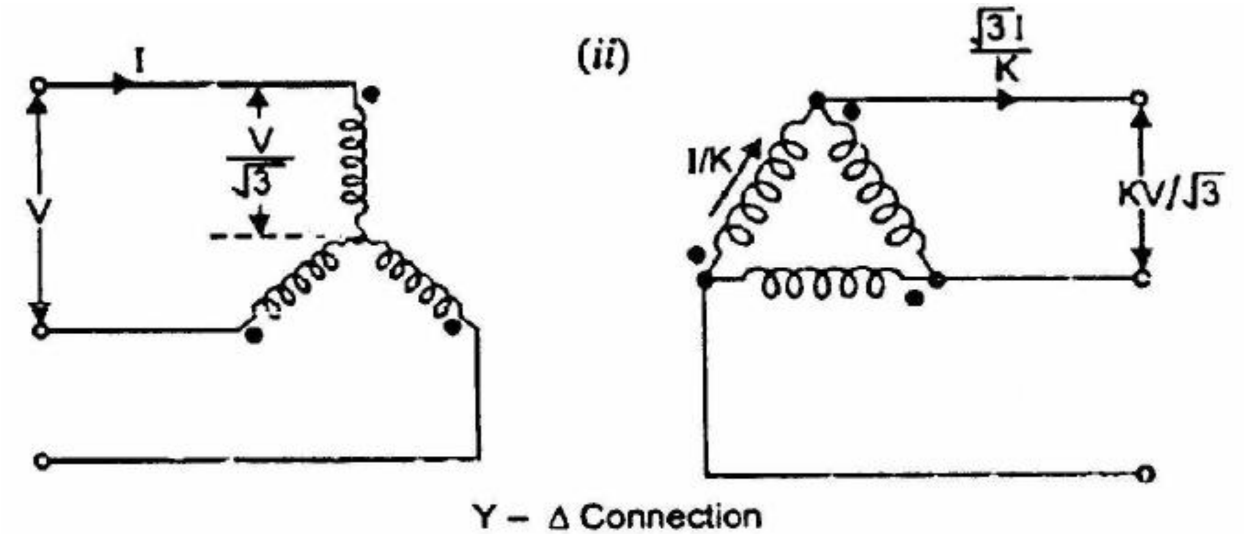
1. System voltages are more stable in relation to unbalanced load
2. If one t/f is failed it may be used for low power level ie V-V connection
3. No distortion of flux ie 3rd harmonic current not flowing to the line wire

Disadvantages

1.Compare to Y-Y require more insulation

2. Absence of star point ie fault may severe

Star- Delta connection



- **Used to step down voltage ie end of transmission line**

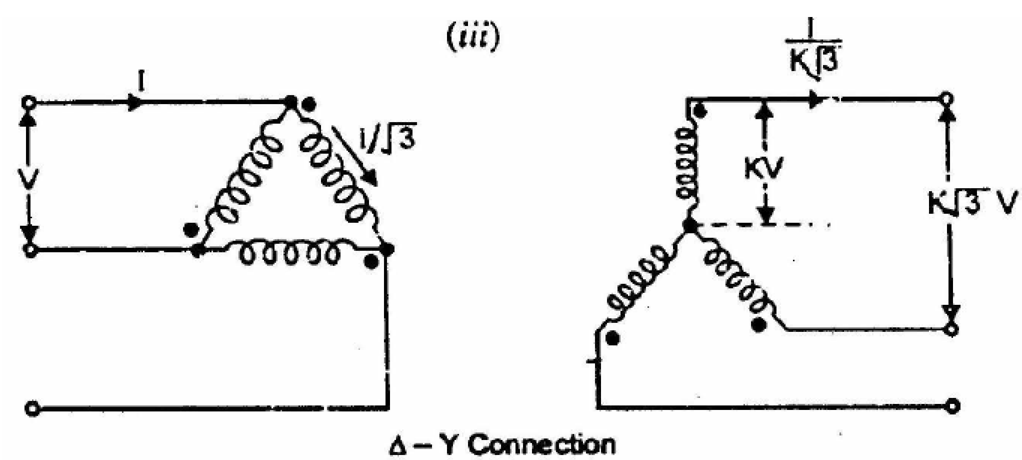
Advantages

1. The primary side is star connected. Hence fewer number of turns are required. This makes the connection economical
2. The neutral available on the primary can be earthed to avoid distortion.
3. Large unbalanced loads can be handled satisfactory.

Disadvantages

1. The secondary voltage is not in phase with the primary. (30 ^{0} phase difference)
2. Hence it is not possible to operate this connection in parallel with star-star or delta-delta connected transformer.

Delta - Star connection



- **This connection is used to step up voltage ie. Beginning of high tension line**

Features

secondary Phase voltage is 1/√3 times of line voltage

- **neutral in secondary can be grounded for 3 phase 4 wire system**
- **Neutral shifting and 3rd harmonics are there**
- **Phase shift of 30° between secondary and primary currents and voltages**

V-V Connection

If one of the transformers of a − is removed and 3-phase supply is connected to the primaries , then three equal 3-phase voltages will be available at the secondary terminals on noload.

This method of transforming 3-phase power by means of only two transformers is called the open − or $V - V$ connection.

It is employed :

1. when the three-phase load is too small to warrant the installation of full three-phase transformer bank.

2. when one of the transformers in a − bank is disabled, so that service is continued although at reduced capacity, till the faulty transformer is repaired or a new one is substituted.

3. when it is anticipated that in future the load will increase necessitating the closing of open delta.

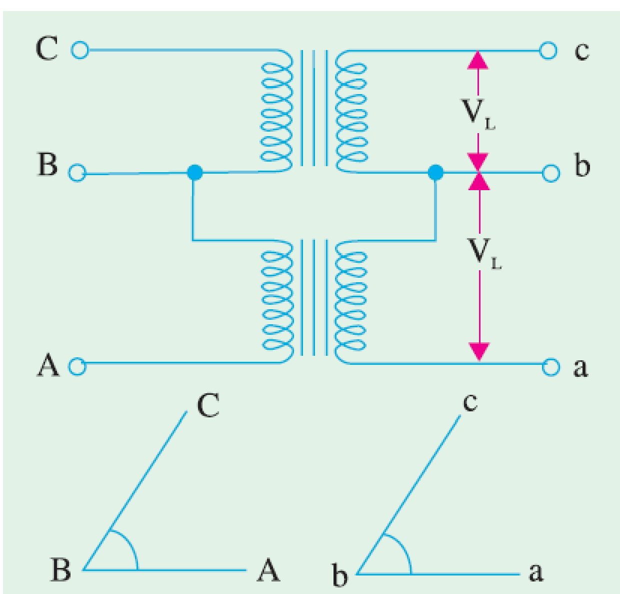


Fig. 33.11

One important point to note is that the total load that can be carried by a $V - V$ bank is *not* two-third of the capacity of a − bank but it is only 57.7% of it. That is a reduction of 15% (strictly, 15.5%) from its normal rating.

Suppose there is − bank of three 10-kVA transformers. When one transformer is removed, then it runs in $V - V$. The total rating of the two transformers is 20 kVA. But the capacity of the $V - V$ bank is not the sum of the transformer kVA ratings but only 0.866 of it *i.e.* 20 × 0.866 = 17.32 (or 30 × 0.57 = 17.3 kVA).

The fact that the ratio of V-capacity to -capacity is 1/ 3 = 57.7% (or nearly 58%) instead of 66 per cent can be proved as follows :

As seen from Fig. 33.12 (*a*)

$\Delta - \Delta$ capacity = $\sqrt{3} \,.\, V_L \,.\, I_L = \sqrt{3} \,.\, V_L\,(\sqrt{3} \,.\, I_S) = 3V_L I_S$

In Fig. 33.12 (*b*), it is obvious that when $\Delta - \Delta$ bank becomes $V - V$ bank, the secondary line current I_L becomes equal to the secondary phase current I_S.

$$\therefore \qquad V - V \text{ capacity} = \sqrt{3} \,.\, V_L I_L = \sqrt{3}\, V_L \,.\, I_S$$

$$\therefore \qquad \frac{V - V \text{ capacity}}{\Delta - \Delta \text{ capacity}} = \frac{\sqrt{3} \,.\, V_L I_S}{3 V_L\, I_S} = \frac{1}{\sqrt{3}} = 0.577 \text{ or } 58 \text{ per cent}$$

It means that the 3-phase load which can be carried ***without exceeding the ratings*** of the transformers is 57.7 per cent of the original load rather than the expected 66.7%.

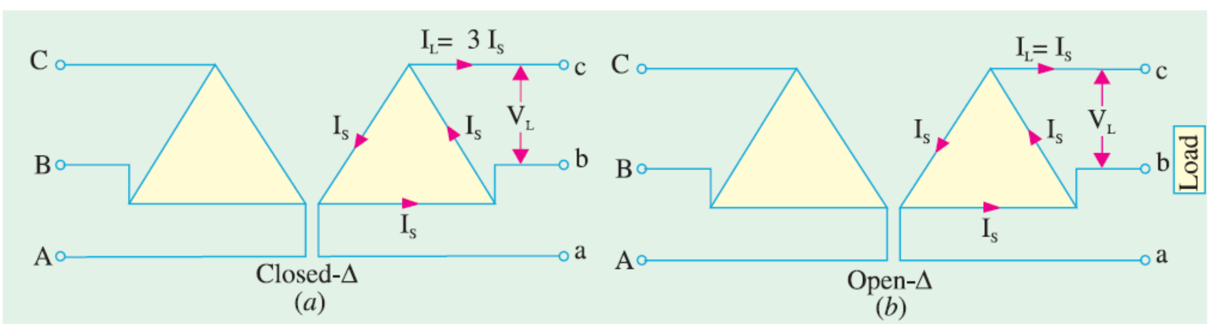


Fig. 33.12

It is obvious from above that when one transformer is removed from a $\Delta - \Delta$ bank.

1. the bank capacity is reduced from 30 kVA to $30 \times 0.577 = 17.3$ kVA and not to 20 kVA as might be thought off-hand.

2. only 86.6% of the rated capacity of the two remaining transformers is available (*i.e.* $20 \times 0.866 = 17.3$ kVA). In other words, ratio of *operating* capacity to *available* capacity of an open-Δ is 0.866. This factor of 0.866 is sometimes called the ***utility factor***.

3. each transformer will supply 57.7% of load and not 50% when operating in $V - V$ (Ex. 33.13).

However, it is worth noting that if three transformers in a $\Delta - \Delta$ bank are delivering their *rated load** and one transformer is removed, the overload on *each* of the two remaining transformers is 73.2% because

$$\frac{\text{total load in } V - V}{VA/\text{transformer}} = \frac{\sqrt{3}\,.V_L I_S}{V_L I_S} = \sqrt{3} = 1.732$$

This over-load may be carried temporarily but some provision must be made to reduce the load if overheating and consequent breakdown of the remaining two transformers is to be avoided.

The disadvantages of this connection are :

1. The average power factor at which the *V*-bank operates is less than that of the load. ***This power factor is actually 86.6% of the balanced load power factor.*** Another significant point to note is that, except for a balanced unity power factor load, the two transformers in the $V - V$ bank operate at different power factors (Art. 33.8).

2. Secondary terminal voltages tend to become unbalanced to a great extent when the load is increased, this happens even when the load is perfectly balanced.

It may, however, be noted that if two transformers are operating in $V - V$ and loaded to rated capacity (in the above example, to 17.3 kVA), the addition of a third transformer increases the total capacity by $\sqrt{3}$ or 173.2% (*i.e.* to 30 kVA). It means that for an increase in cost of 50% for the third transformer, the increase in capacity is 73.2% when converting from a $V - V$ system to a $\Delta - \Delta$ system.

33.8. Power Supplied by $V - V$ Bank

When a $V - V$ bank of two transformers supplies a balanced 3-phase load of power factor $\cos \phi$, then one transformer operates at a p.f. of $\cos (30° - \phi)$ and the other at $\cos (30° + \phi)$. Consequently, the two transformers will not have the same voltage regulation.

$$\therefore \quad P_1 = \text{kVA} \cos (30° - \phi) \text{ and } P_2 = \text{kVA} \cos (30° + \phi)$$

(*i*) When $\phi = 0$ *i.e.* load p.f. = 1

Each transformer will have a p.f. $= \cos 30° = 0.866$

(*ii*) When $\phi = 30°$ *i.e.* load p.f. = 0.866.

In this case, one transformer has a p.f. of $\cos (30° - 30°) = 1$ and the other of $\cos (30° + 30°) = 0.866$.

(*iii*) When $\phi = 60°$ *i.e.* load p.f. = 0.5

In this case, one transformer will have a p.f. $= \cos (30 - 60°) = \cos (-30°) = 0.866$ and the other of $\cos (30° + 60°) = 0$. It means that one of the transformers will not supply any load whereas the other having a p.f. = 0.866 will supply the entire load.

Example 33.13. *A $\Delta - \Delta$ bank consisting of three 20-kVA, 2300/230-V transformers supplies a load of 40 kVA. If one transformer is removed, find for the resulting V – V connection*

(*i*) *kVA load carried by each transformer*

(*ii*) *per cent of rated load carried by each transformer*

(*iii*) *total kVA rating of the V-V bank*

(*iv*) *ratio of the V-V bank to $\Delta - \Delta$ bank transformer ratings.*

(*v*) *per cent increase in load on each transformer when bank is converted into V-V bank.*

Solution. (*i*) As explained earlier in Art. 33.7, $\frac{\text{total kVA load in } V - V \text{ bank}}{VA/\text{transformer}} = \sqrt{3}$

$\therefore$ kVA load supplied by *each* of the two transformers = $40/\sqrt{3}$ = **23.1 kVA**

Obviously, each transformer in *V* - *V* bank does not carry 50% of the original load but 57.7%.

(*ii*) per cent of rated load = $\frac{\text{kVA load/transformer}}{\text{kVA rating/transformer}} = \frac{23.1}{20}$ = **115.5 %**

carried by each transformer.

Obviously, in this case, each transformer is overloaded to the extent of 15.5 per cent.*

(*iii*) kVA *rating* of the *V* - *V* bank = $(2 \times 20) \times 0.866$ = **34.64 kVA**

(*iv*) $\frac{V - V \text{ rating}}{\Delta - \Delta \text{ rating}} = \frac{34.64}{60} = 0.577$ or **57.7%**

As seen, the rating is reduced to 57.7% of the original rating.

(*v*) Load supplied by each transformer in $\Delta - \Delta$ bank = 40/3 = 13.33 kVA

$\therefore$ Percentage increase in load supplied by each transformer

$$= \frac{\text{kVA load/transformer in } V - V \text{ bank}}{\text{kVA load/transformer in } \Delta - \Delta \text{ bank}} = \frac{23.1}{13.3} = 1.732 = \mathbf{173.2\ \%}$$

It is obvious that each transformer in the $\Delta - \Delta$ bank supplying 40 kVA was running underloaded (13.33 *vs* 20 kVA) but runs overloaded (23.1 *vs* 20 kVA) in *V* – *V* connection.

T-T Connection

This conversion is required to supply two-phase furnaces, to link two-phase circuit with 3-phase system and also to supply a 3-phase apparatus from a 2-phase supply source. For this purpose, Scott connection as shown in Fig. 33.17 is employed. This connection requires two transformers of different ratings although for interchangeability and provision of spares, both transformers may be identical but having suitable tappings.

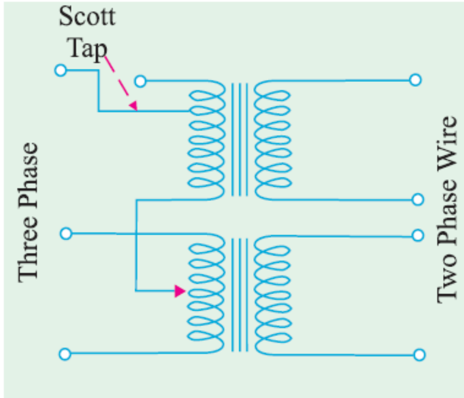


Fig. 33.17

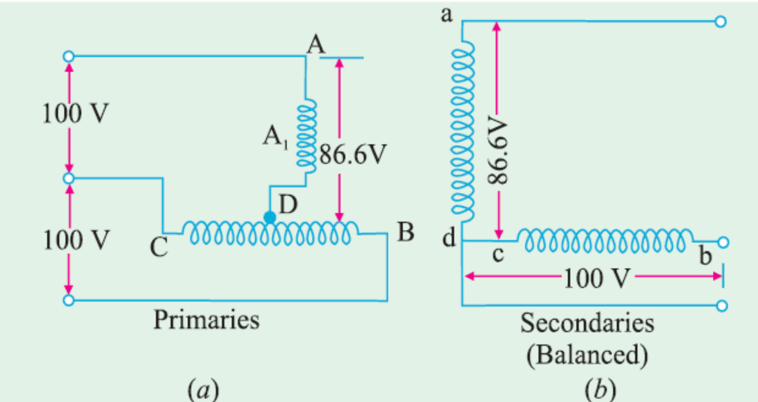
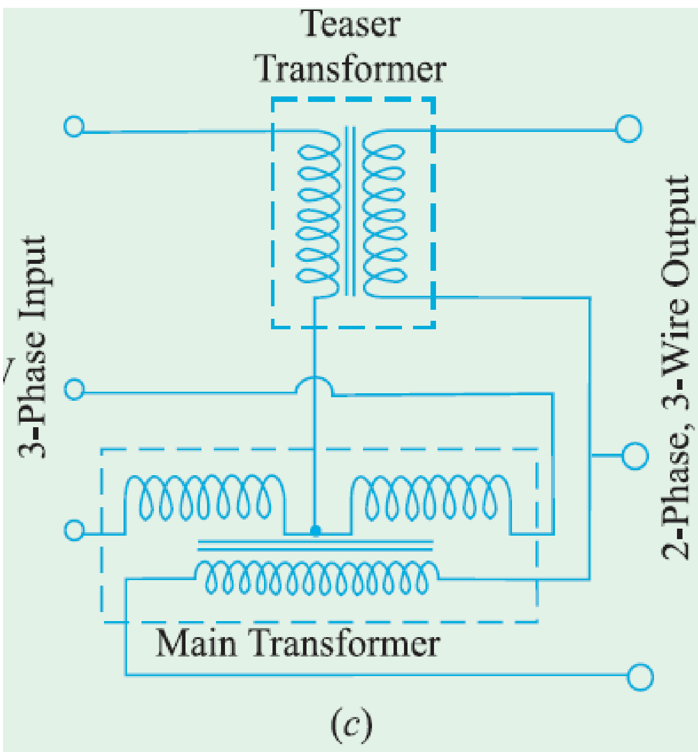


Fig. 33.18

- If, in the secondaries of Fig. 33.14 (*b*), points *c* and *d* are connected as shown in Fig. 33.18 (*b*), then a 2-phase, 3-wire system is obtained.
- The voltage *Edc is 86.6 V but* ECb = 100 V, hence the resulting 2-phase voltages will be unequal.



- Consider the same connection drawn slightly differently as in Fig. 33.20.
- The primary of the main transformer having *N*1 turns is connected between terminals *CB* of a 3-phase supply.

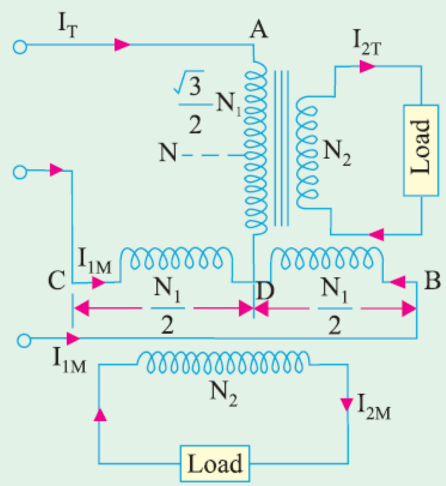


Fig. 33.20

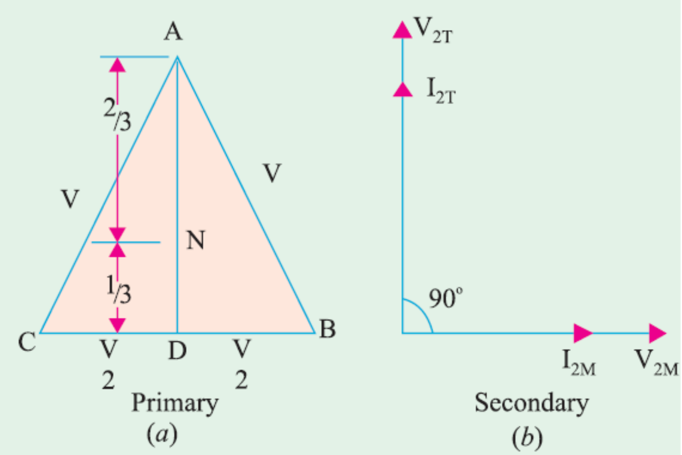


Fig. 33.21

- If supply line voltage is *V*, then obviously *VAB* = *VBC* = *VCA* = *V* but voltage between *A* and *D* is *V* × root 3 / 2.
- As said above, the number of turns between *A* and *D* should be also root(3/2) *N*1 for making volt/turn the same in both primaries.
- If so, then for secondaries having equal turns, the secondary terminal voltages will be equal in magnitude although in phase quadrature.
- It is to be noted that point *D* is not the neutral point of the primary supply because its voltage with respect to any line is not *V* / root 3. Let *N* be the neutral point. Its position can be determined as follows.
- Voltage of *N* with respect to *A* must be *V* / root 3 and since *D* to *A* voltage is *V* × root 3 / 2, hence *N* will be (root 3*V* / 2 −*V* /root 3)= 0.288 V or 0.29 V from *D*.
- Hence, *N* is above *D* by a number of turns equal to 29% of *N*1. Since 0.288
- is one-third of 0.866, hence *N* divides the teaser winding *AD* in the
- ratio 2 : 1.
- Let the teaser secondary supply a current *I*2*T* at unity power factor. If we neglect the magnetizing current *I*0, then teaser primary current is *I*1*T* = *I*2*T* × transformation ratio.
- where *K* = *N*2/*N*1 = transformation ratio of *main* transformer. The current is in phase with star voltage of the primary supply (Fig. 33.21).

$$\therefore \quad I_{1T} = I_{2T} \times N_2/(\sqrt{3}N_1/2) = (2/\sqrt{3}) \times (N_2/N_1) \times I_{2T} = 1.15\ (N_2/N_1)\ I_{2T} = 1.15\ KI_{2T}$$

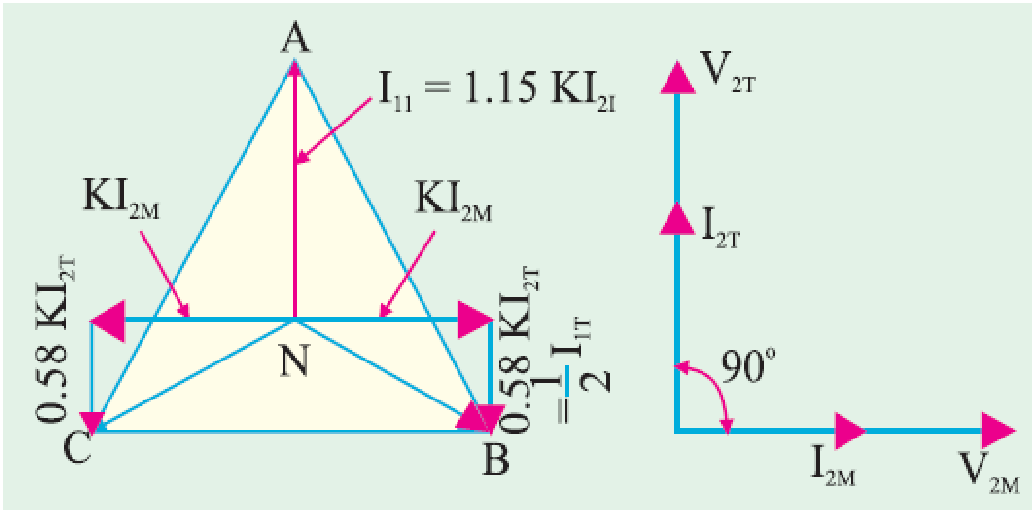


Fig. 33.22

- Poly

  The total current *I*1*M* in each half of the primary of the *main* transformer consists of two parts :

  (*i*) One part is that which is necessary to balance the main secondary current I_{2M}. Its value is

  $$= I_{2M} \times \frac{N_2}{N_1} = KI_{2M}$$

  (*ii*) The second part is equal to one-half of

-

the teaser primary current *i.e.* $\frac{1}{2} I_{1T}$. This is so because the main transformer primary forms a return path for the teaser primary current which divides itself into two halves at mid-point *D* in either direction. The value of each half is $= I_{1T}/2 = 1.15\ KI_{2T}/2 = 0.58\ KI_{2T}$.

Hence, the currents in the lines *B* and *C* are obtained vectorially as shown in Fig. 33.22. It should be noted that as the two halves of the teaser primary current flow in opposite directions from point *D*, they have no magnetic effect on the core and play no part at all in balancing the secondary ampere-turns of the main transformer.

The line currents thus have rectangular components of *KI*2*M* and 0.58,*KI*2*T* and, as shown in Fig. 33.22, are in phase with the primary star voltages *VNB* and *VNC* and are equal to the teaser primary current. Hence, the three-phase side is balanced when the two-phase load of unity power factor is balanced.

- Fig. 33.23 (*a*) illustrates the condition corresponding to a balanced two-phase load at a lagging power factor of 0.866. The construction is the same as in Fig. 33.22. It will be seen that the 3-phase side is again balanced. But under these conditions, the main transformer rating is 15% greater than that of the teaser, because its voltage is 15% greater although its current is the same.
- Hence, we conclude *that if the load is balanced on one side, it would always be balanced on the other side.*
- The conditions corresponding to an unbalanced two-phase load having different currents and power factors are shown in Fig. 33.23 (*b*). The geometrical construction is similar to those explained in Fig. 33.22 and 33.23 (*a*).

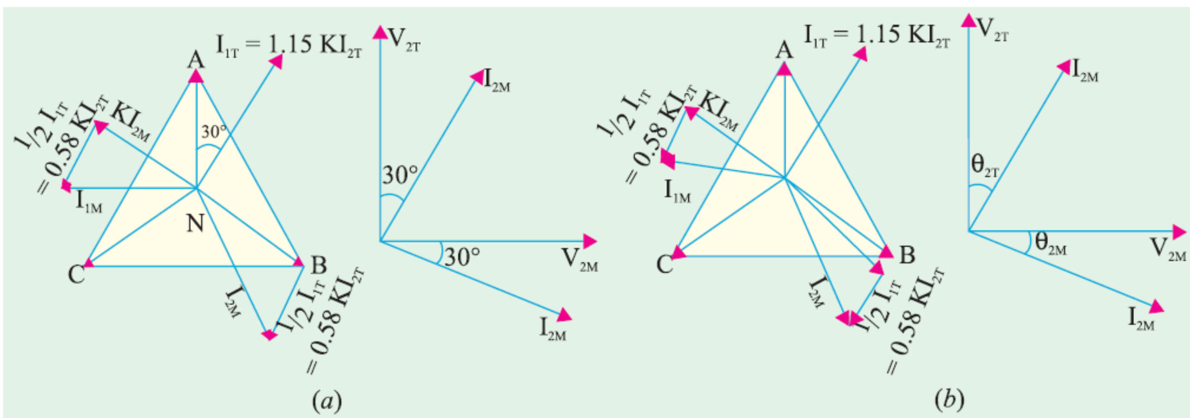


Fig. 33.23

Summarizing the above we have :

1. Teaser transformer primary has $\sqrt{3}/2$ times the turns of main primary. But volt/turn is the same. Their secondaries have the same turns which results in equal secondary terminal voltages.

2. If main primary has N_1 turns and main secondary has N_2 turns, then main transformation ratio is N_2/N_1. However, the transformation ratio of teaser is

$$N_2/(\sqrt{3}N_1/2) = 1.15\ N_2/N_1 = 1.15\ K$$

3. If the load is balanced on one side, it is balanced on the other side as well.

4. Under balanced load conditions, main transformer rating is 15% greater than that of the teaser.

5. The currents in either of the two halves of main primary are the vector sum of KI_{2M} and $0.58\ KI_{2T}$ (or $\frac{1}{2}I_{1T}$).

Example 33.20. *In a Scott-connection, calculate the values of line currents on the 3-phase side if the loads on the 2-phase side are 300 kW and 450 kW both at 100 V and 0.707 p.f. (lag) and the 3-phase line voltage is 3,300 V. The 300-kW load is on the leading phase on the 2-phase side. Neglect transformer losses.* **(Elect. Technology, Allahabad Univ. 1991)**

Solution. Connections are shown in Fig. 33.25 (*a*) and phasor diagram in Fig. 33.25 (*b*).

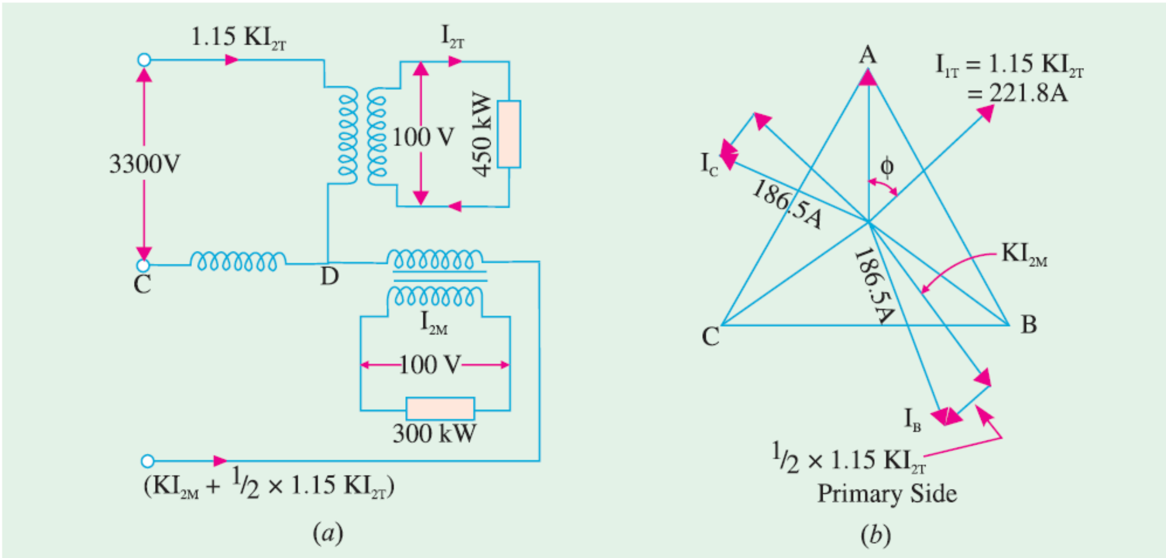


Fig. 33.25

Here, $K = 100/3{,}300 = 1/33$

Teaser secondary current is $I_{2T} = 450{,}000/100 \times 0.707 = 6360$ A

Teaser primary current is $I_{1T} = 1.15\,KI_{2T} = 1.5 \times (1/33) \times 6360 = 221.8$ A

Example 33.22. *Two furnaces are supplied with 1-phase current at 50 V from a 3-phase, 4.6 kV system by means of two 1-phase, Scott-connected transformers with similar secondary windings. When the load on the main transformer is 350 kW and that on the other transformer is 200 kW at 0.8 p.f. lagging, what will be the current in each 3-phase line ? Neglect phase displacement and losses in transformers.* **(Electrical Machinery-II, Bangalore Univ. 1991)**

Solution. Connections and vector diagrams are shown in Fig. 33.28.

$$K = 50/4{,}600 = 1/92; I_{2T} = 200{,}000/50 \times 0.8 = 5{,}000 \text{ A}$$

$$I_{1T} = 1.15\, KI_{2T} = 1.1 \times (1/92) \times 5{,}000 = 62.5 \text{ A}$$

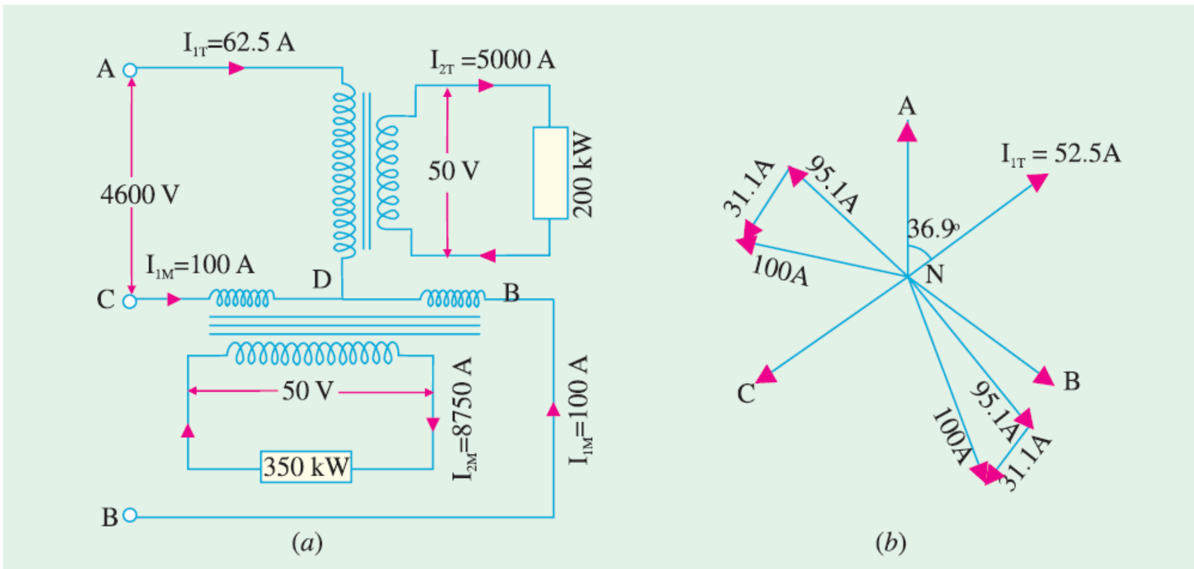


Fig. 33.28

As shown in Fig. 33.28 (*b*), main primary current I_{1M} has two rectangular components.

(*i*) KI_{2M} where $I_{2M} = 350{,}000/50 \times 0.8 = 8{,}750$ A $\therefore KI_{2M} = 8{,}750/92 = 95.1$ A

(*ii*) $(1/2)\, I_{1T} = 62.5/2 = 31.3$ A $\quad \therefore \quad I_{1M} = \sqrt{95.1^2 + 31.3^2} = 100$ A

$\therefore$ Current in line A = **62.5 A;** Current in line B = **100 A**; Current in line C = **100 A.**

As shown in Fig. 33.25 (*b*), main primary current I_{1M} has two rectangular components.

(*i*) KI_{2M} where I_{2M} is the secondary current of the main transformer and

(*ii*) Half of the teaser primary current $\frac{1}{2} I_{1T} = \frac{1}{2} \times 1.15\, KI_{2T} = 0.577\, KI_{2T}$

Now $KI_{2M} = \frac{1}{33} \times \frac{300{,}000}{100 \times 0.707} = 128.58$ A ; Also $\frac{1}{2} I_{1T} = \frac{1}{2} \times 221.8 = 110.9$A

Main Primary current $= \sqrt{128.58^2 + 110.9^2} = 169.79$A

Hence, the 3-phase line currents are **221.8 A** in one line and **169.79 A** in each of the other two.

Poly phase Transformers

The individual transformers are connected in a variety of ways in a power system. Due to the advantages of polyphase power during generation, transmission and utilization polyphase power handling is very important. As an engineering application is driven by techno-economic considerations, no single connection or setup is satisfactory for all applications. Thus transformers are deployed in many forms and connections. Star and mesh connections are very commonly used. Apart from these, vee or open delta connections, zigzag connections , T connections, auto transformer connections, multi winding transformers etc. are a few of the many possibilities. A few of the common connections and the technical and economic considerations that govern their usage are discussed here. Literature abounds in the description of many other. Apart from the characteristics and advantages of these, one must also know their limitations and problems, to facilitate proper selection of a configuration for an application.

Many polyphase connections can be formed using single phase transformers. In some cases it may be preferable to design, develop and deploy a polyphase transformer itself. In a balanced two phase system we encounter two voltages that are equal in magnitude differing in phase by 90◦. Similarly, in a three phase system there are three equal voltages differing in phase 120 electrical degrees. Further there is an order in which they reach a particular voltage magnitude. This is called the phase sequence. In some applications like a.c. to d.c. conversion, six phases or more may be encountered. Transformers used in all these applications must be connected properly for proper functioning. The basic relationship between the primary and secondary voltages (brought about by a common mutual flux and the number of turns), the polarity of the induced emf (decided by polarity test and used with dot convention) and some understanding of the magnetic circuit are all necessary for the same. To facilitate the manufacturer and users, international standards are also available. Each winding has two ends designated as 1 and 2. The HV winding is indicated by capital letters and the LV winding by small letters. If more terminals are brought out from a winding by way of taps there are numbered in the increasing numbers in accordance to their distance from 1 (eg A1,A2,A3...). If the induced emf at an instant is from A1 to A2 on the HV winding it will rise from a1 to a2 on the LV winding.

Out of the different polyphase connections three phase connections are mostly encountered due to the wide spread use of three phase systems for generation, transmission and utilization. Three balanced 3-phase voltages can be connected in star or mesh fashion to yield a balanced 3-phase 3-wire system. The transformers that work on the 3-phase supply have star, mesh or zig-zag connected windings on either primary secondary or both. In addition to giving different voltage ratios, they introduce phase shifts between input and output sides. These connections are broadly classified into 4 popular vector groups.

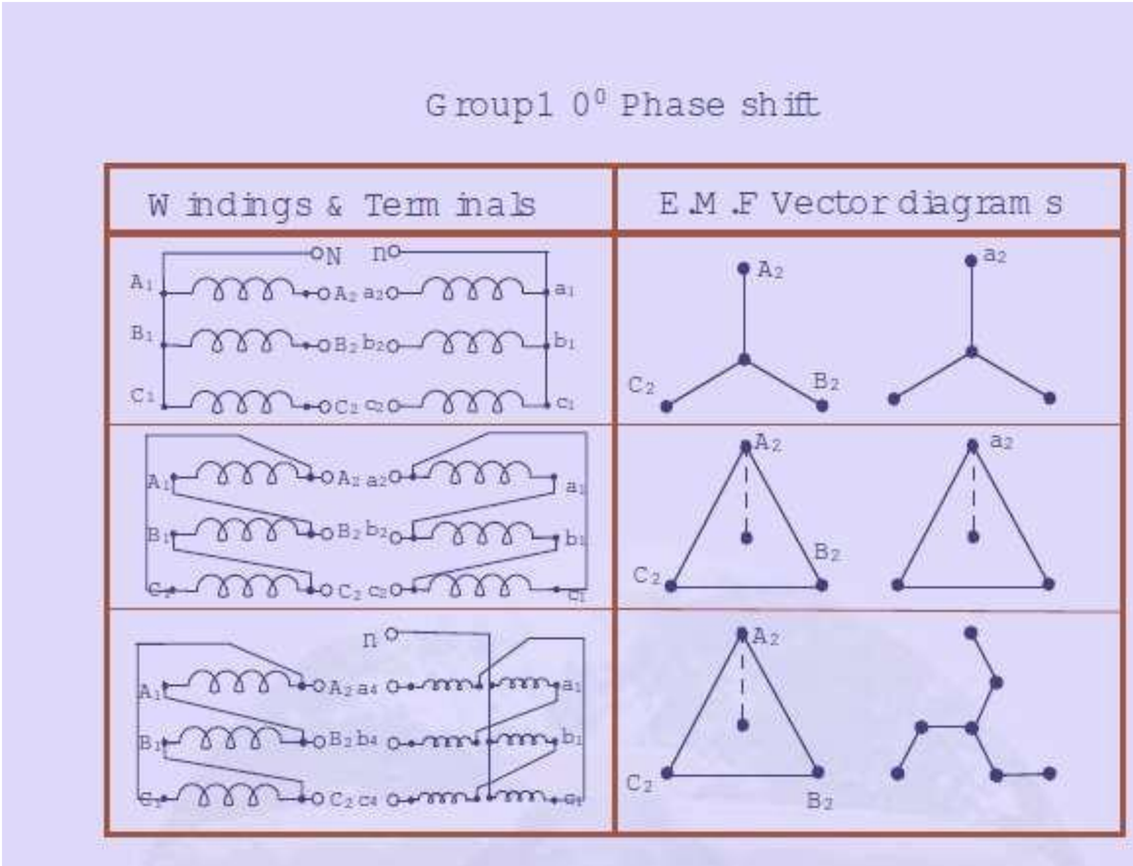
1. Group I: zero phase displacement between the primary and the secondary.

2. Group II: 180◦ phase displacement.

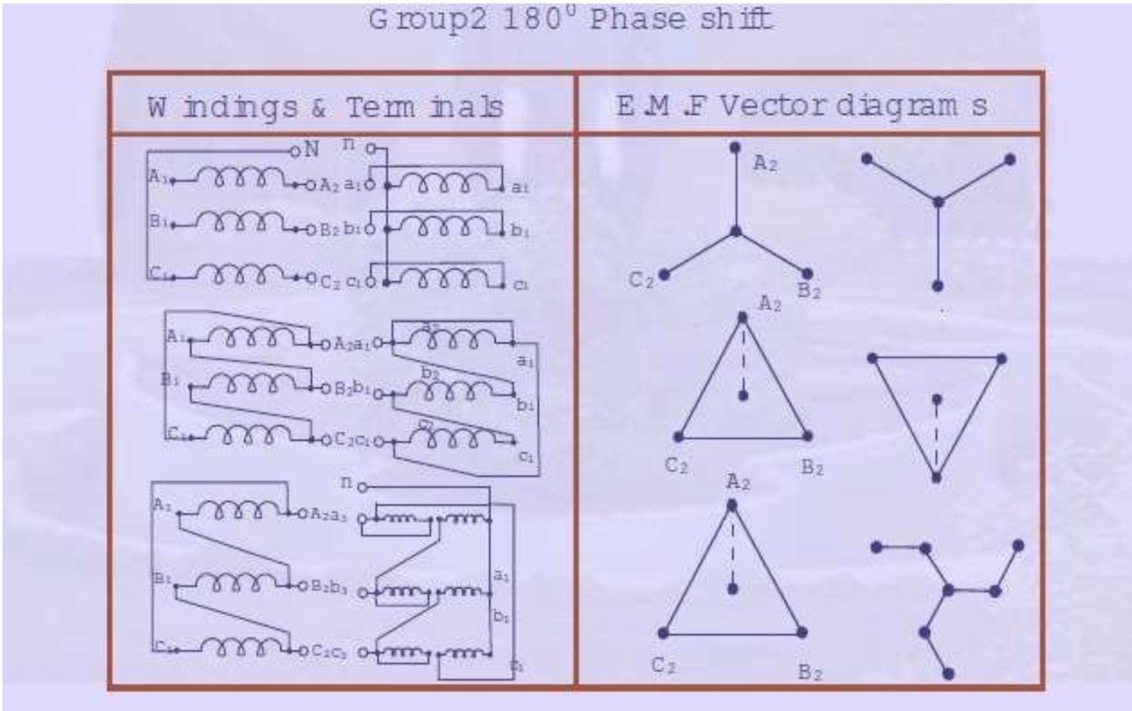
3. Group III: 30◦ lag phase displacement of the secondary with respect to the primary.

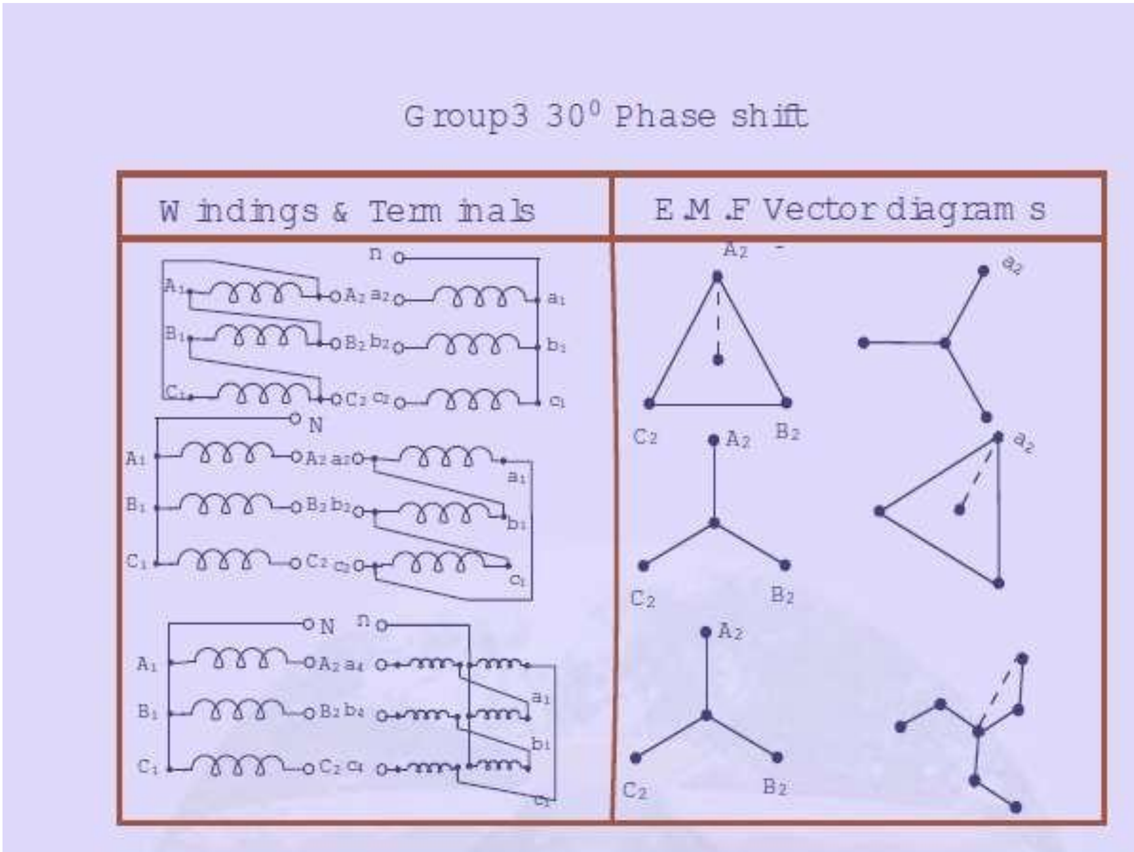
4. Group IV: 30◦ lead phase displacement of the secondary with respect to the primary.

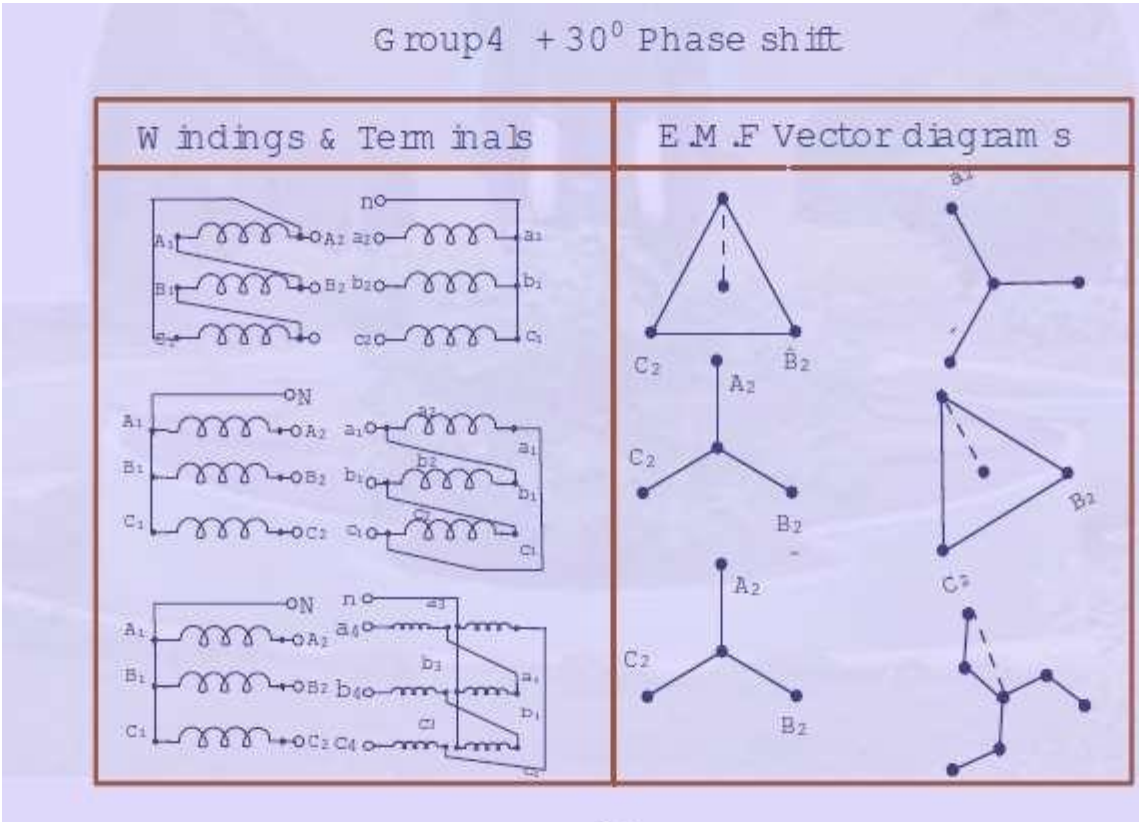
A few examples of the physical connections and phasor diagrams are shown in Fig. 35 and Fig. 36 corresponding to each group. The capital letters indicates primary and the small letters the secondary. D/d stand for mesh, Y/y - for star, Z/z for zig-zag. The angular displacement of secondary with respect to the primary are shown as clock position, 0^0


Group1 0⁰ Phase shift
Windings & Terminals
E.M.F Vector diagrams
A1
B1
C1
N
n
A2
B2
C2
a1
b1
c1
a2
b2
c2
a4
b4
c4

(a)


Group2 180° Phase shift
Windings & Terminals
E.M.F Vector diagrams
A2
B2
C2


Group3 30⁰ Phase shift
Windings & Terminals
E.M.F Vector diagrams
A2
a2
C2
B2
N
n
A1
B1
C1
a1
b1
c1



(b)

referring to 12 o'clock position. These vector groups are especially important when two or more transformers are to be connected in parallel.

Star connection is normally cheaper as there are fewer turns and lesser cost of insulation. The advantage becomes more with increase in voltage above 11kv. In a star connected winding with earthed-neutral the maximum voltage to the earth is (1√3)of the line voltage.

Also star connection permits mixed loading due to the presence of the neutral. Mesh connections are advantageous in low voltage transformers as insulation costs are insignificant and the conductor size becomes (1√3) of that of star connection and permits ease of winding. The common polyphase connections are briefly discussed now.

Star/star (Yy0, Yy6) connection This is the most economical one for small high voltage transformers. Insulation cost is highly reduced. Neutral wire can permit mixed loading. Triplen harmonics are absent in the lines. These triplen harmonic currents cannot flow, unless there is a neutral wire. This connection produces oscillating neutral. Three phase shell type units have large triplen harmonic phase voltage. However three phase core type transformers work satisfactorily. A tertiary mesh connected winding may be required to stabilize the oscillating neutral due to third harmonics in three phase banks.

Mesh/mesh (Dd0, Dd6) This is an economical configuration for large low voltage transformers. Large amount of unbalanced load can be met with ease. Mesh permits a circulating path for triplen harmonics thus attenuates the same. It is possible to operate with one transformer removed in open delta or Vee connection meeting 58 percent of the balanced load. Three phase units cannot have this facility. Mixed single phase loading is not possible due to the absence of neutral.

Star/mesh(Dy or Yd) This arrangement is very common for power supply transformers. The delta winding permits triplen harmonic currents to circulate in the closed path and attenuates them.

Zig zag/ star (ZY1 or Zy11) Zigzag connection is obtained by inter connection of phases. 4-wire system is possible on both sides. Unbalanced loading is also possible. Oscillating neutral problem is absent in this connection. This connection requires 15% more turns for the same voltage on the zigzag side and hence costs more.

Generally speaking a bank of three single phase transformers cost about 15% more than their 3-phase counter part. Also, they occupy more space. But the spare capacity cost will be less and single phase units are easier to transport.

Mesh connected three phase transformers resemble 3- single phase units but kept in a common tank. In view of this single tank, the space occupied is less. Other than that there is no big difference. The 3-phase core type transformer on the other hand has a simple core arrangement. The three limbs are equal in cross section. Primary and secondary of each phase are housed on the same limb. The flux setup in any limb will return through the other two limbs as the mmf of those limbs are in the directions so as to aid the same. Even though magnetically this is not a symmetrical arrangement, as the reluctance to the flux setup by side limbs is different from that of the central limb, it does not adversely affect the performance. This is due to the fact that the magnetizing current itself forms a small fraction of the total phase current drawn on load. The added advantage of 3-phase core is that it can tolerate substantially large value of 3rd harmonic mmf without affecting the performance. The 3rd harmonic mmf of the three phases will be in phase and hence rise in all the limbs together.

The 3rd harmonic flux must therefore find its path through the air. Due to the high reluctance of the air path even a substantially large value of third harmonic mmf produces negligible value of third harmonic flux. Similarly unbalanced operation of the transformer with large zero sequence fundamental mmf content also does not affect its performance. Even with Yy type of poly phase connection without neutral connection the oscillating neutral does not occur with these cores. Finally, three phase cores themselves cost less than three single phase units due to compactness.

MODULE - 2

Tests,Parallel Operation of Transformers: polarity test, Sumpner's test ,separation of core loss, Necessity of Parallel operation, conditions for parallel operation – Single phase and three phase. Load sharing in case of similar and dissimilar transformers.

Auto transformers and Tap changing transformers: Introduction to auto transformer - copper economy, equivalent circuit, three phase auto connection and voltage regulation. Voltage regulation by tap changing – off circuit and on load.

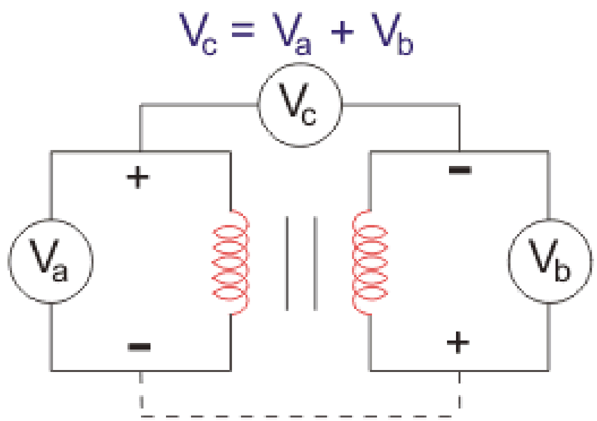
Polarity test

We use dot convention to identify the voltage polarity of the mutual inductance of two windings. The two used conventions are:

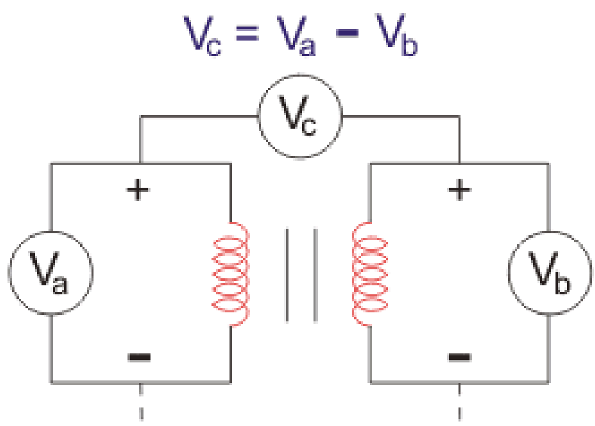
- If a current enters the dotted terminal of one winding, then the voltage induced on the other winding will be positive at the dotted terminal of the second winding.
- If a current leaves the dotted terminal of one winding, then the polarity of the voltage induced in the other winding will be negative at the dotted terminal of the second winding.

We can categorise the polarity of the transformer to two types,

- Additive Polarity
- Subtractive Polarity



Additive Polarity



Subtractor Polarity

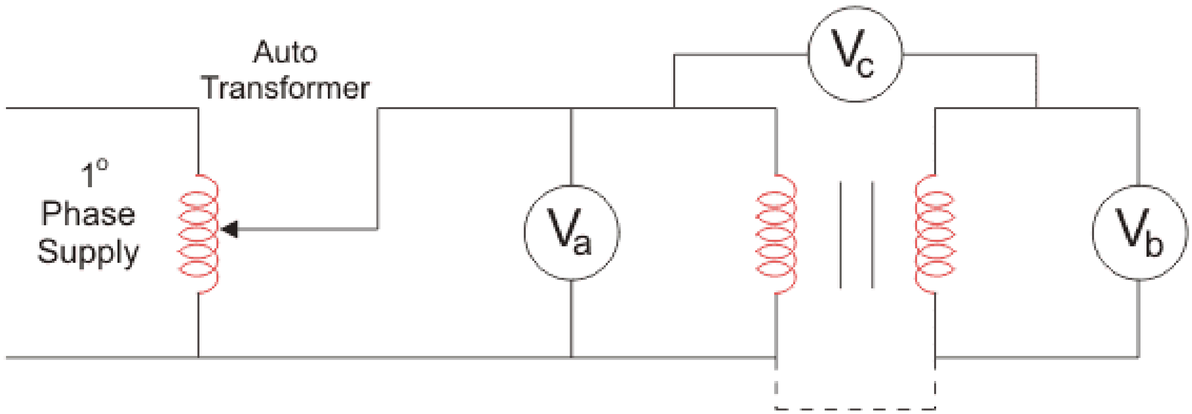
Additive Polarity

- In additive polarity, the voltage (V_c) between the primary side (V_a) and the secondary side (V_b) will be the sum of both high voltage and the low voltage, i.e. we will get $V_c = V_a + V_b$

Subtractive Polarity

- In subtractive polarity, the voltage (V_c) between the primary side (V_a) and the secondary side (V_b) will be the difference of both high voltage and the low voltage, i.e. we will get $V_c = V_a – V_b$
- In subtractive polarity, if $V_c = V_a – V_b$, it is a step-down transformer and if $V_c = V_b – V_a$, it is a step-up transformer.
- We use additive polarity for small-scale distribution transformers and subtractive polarity for large-scale transformers.

Procedure of Polarity Test of Transformer



Transformer Circuit Diagram for Test

- Connect the circuit as shown above with a voltmeter (V_a) across primary winding and another voltmeter (V_b) across the secondary winding.
- If available, take down the ratings of the transformer and the turn ratio.
- We connect a voltmeter (V_c) between primary and secondary windings.
- We apply some voltage to the primary side.
- By checking the value in the voltmeter (V_c), we can find whether it is additive or subtractive polarity.

If additive polarity – V_c should be showing the sum of V_a and V_b.
If subtractive polarity – V_c should be showing the difference between V_a and V_b.

Sumpner test

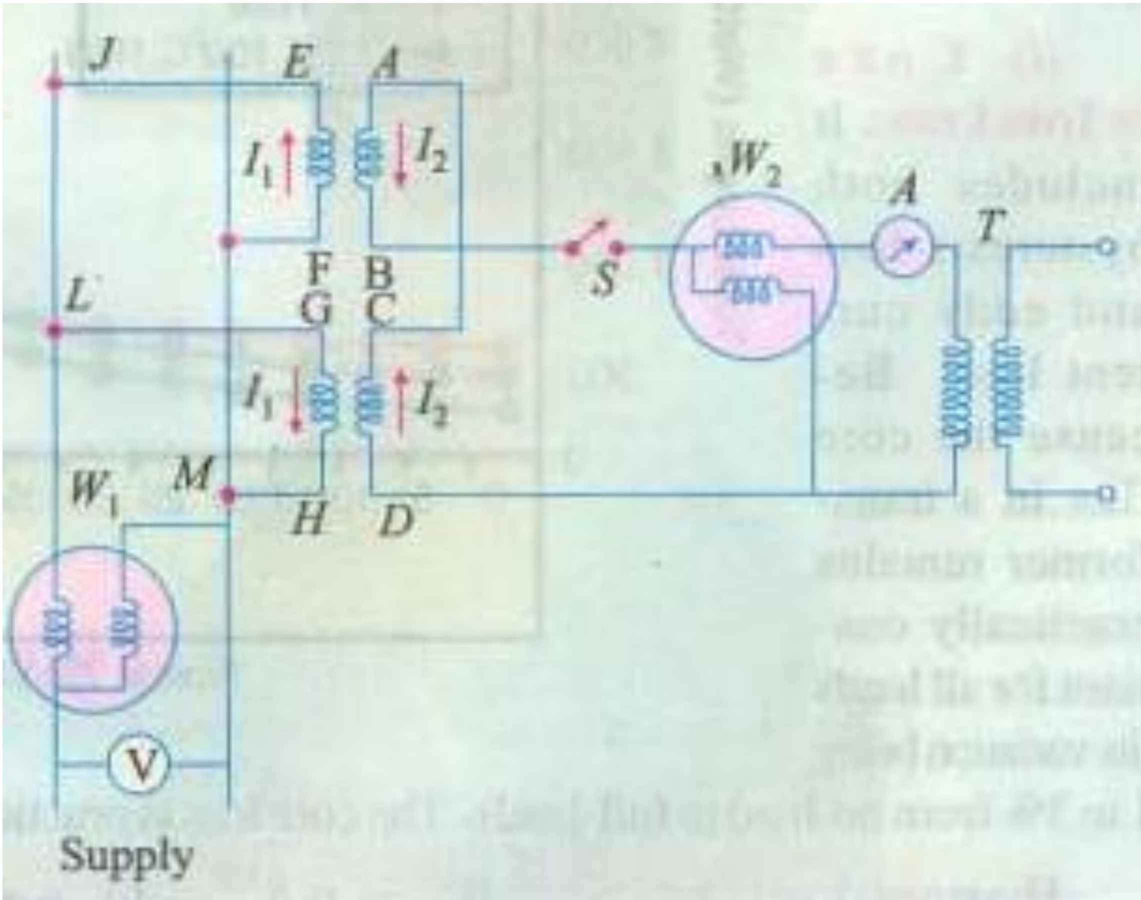


Fig. 32.55

This test provides data for finding the regulation, efficiency and heating under load conditions and is employed only when two similar transformers are available. One transformer is loaded on the other and both are connected to supply. The power taken from the supply is that necessary for supplying the losses of both transformers and the negligibly small loss in the control circuit.

As shown in Fig. 32.55, primaries of the two transformers are connected in parallel across the same a.c. supply. With switch S open, the wattmeter W_1 reads the core loss for the two transformers.

The secondaries are so connected that their potentials are in opposition to each other. This would so if $V_{AB} = V_{CD}$ and A is joined to C whilst B is joined to D. In that case, there would be no secondary current flowing around the loop formed by the two secondaries. T is an auxiliary low-voltage transformer which can be adjusted to give a variable voltage and hence current in the secondary loop circuit. By proper adjustment of T, full-load secondary current I_2 can be made to flow as shown. It is seen, that I_2 flows from D to C and then from A to B. Flow of I_1 is confined to the loop $FEJLGHMF$ and it does not pass through W_1. Hence, W_1 continues to read the core loss and W_2 measures full-load Cu loss (or at any other load current value I_2). Obviously, the power taken in is twice the losses of a single transformer.

Example 32.58. *Two similar 250-kVA, single-phase transformers gave the following results when tested by back-to-back method :*

Mains wattmeter, $W_1 = 5.0$ *kW*

Primary series circuit wattmeter, $W_2 = 7.5$ *kW (at full-load current).*

Find out the individual transformer efficiencies at 75% full-load and 0.8 p.f. lead.

(Electrical Machines-III, Gujarat Univ. 1986)

Solution. Total losses for both transformers = 5 + 7.5 = 12.5 kW

F.L. loss for each transformer = 12.5/2 = 6.25 kW

$$\text{Copper-loss at 75\% load} = \left(\frac{3}{4}\right)^2 \times \frac{7.5}{2} \text{ kW} = 2.11 \text{ kW}$$

Output of each transformer at 75% F.L. and 0.8 p.f. = $(250 \times 0.75) \times 0.8 = 150$ kW

$$\eta = \frac{150}{150 + 2.5 + 2.11} = 97\%$$

Seperation of Core loss

The core loss of a transformer depends upon the frequency and the maximum flux density when the volume and the thickness of the core laminations are given. The core loss is made up of two parts (*i*) hysteresis loss $W_h = PB_{max}^{1.6} f$ as given by Steinmetz's empirical relation and (*ii*) eddy current loss $W_e = QB_{max}^2 f^2$ where Q is a constant. The total core-loss is given by

$$W_i = W_h + W_e = PB_{max}^{1.6} f^2 + QB_{max}^2 f^2$$

If we carry out two experiments using two different frequencies but the same maximum flux density, we should be able to find the constants P and Q and hence calculate hysteresis and eddy current losses separately.

Example 32.29. *In a transformer, the core loss is found to be 52 W at 40 Hz and 90 W at 60 Hz measured at same peak flux density. Compute the hysteresis and eddy current losses at 50 Hz.*

(Elect. Machines, Nagpur Univ. 1993)

Solution. Since the flux density is the same in both cases, we can use the relation

Total core loss $W_i = Af + Bf^2$ or $W_i/f = A + Bf$

$\therefore$ $52/40 = A + 40B$ and $90/60 = A + 60B$; $\therefore$ $A = 0.9$ and $B = 0.01$

At 50 Hz, the two losses are

$W_h = A_f = 0.9 \times 50 = 45$ W ; $W_e = Bf^2 = 0.01 \times 50^2 = 25$ W

Example 32.30. *In a power loss test on a 10 kg specimen of sheet steel laminations, the maximum flux density and waveform factor are maintained constant and the following results were obtained:*

Frequency (Hz)	*25*	*40*	*50*	*60*	*80*
Total loss (watt)	*18.5*	*36*	*50*	*66*	*104*

Calculate the eddy current loss per kg at a frequency of 50 Hz.

(Elect. Measur. A.M.I.E. Sec B, 1991)

Solution. When flux density and wave form factor remain constant, the expression for iron loss can be written as

$$W_i = Af + Bf^2 \quad \text{or} \quad W_i/f = A + Bf$$

The values of W_i/f for different frequencies are as under :

f	25	40	50	60	80
W_i/f	0.74	0.9	1.0	1.1	1.3

The graph between f and W_i/f has been plotted in Fig. 32.44. As seen from it, $A = 0.5$ and $B = 0.01$

$\therefore$ Eddy current loss at 50 Hz $= Bf^2 = 0.01 \times 50^2 = 25$ W

$\therefore$ Eddy current loss/kg $= 25/10 = 2.5$ W

Parallel operation of one phase and two-phase transformers

By parallel operation we mean two or more transformers are connected to the same supply bus bars on the primary side and to a common bus bar/load on the secondary side.

Such requirement is frequently encountered in practice. The reasons that necessitate parallel operation are as follows.

1. Non-availability of a single large transformer to meet the total load requirement.

2. The power demand might have increased over a time necessitating augmentation of the capacity. More transformers connected in parallel will then be pressed into service.

3. To ensure improved reliability. Even if one of the transformers gets into a fault or is taken out for maintenance/repair the load can continued to be serviced.

4. To reduce the spare capacity. If many smaller size transformers are used one machine can be used as spare. If only one large machine is feeding the load, a spare of similar rating has

Fig. 37 shows the physical arrangement of two single phase transformers working in parallel on the primary side. Transformer A and Transformer B are connected to input voltage bus bars. After ascertaining the polarities they are connected to output/load bus

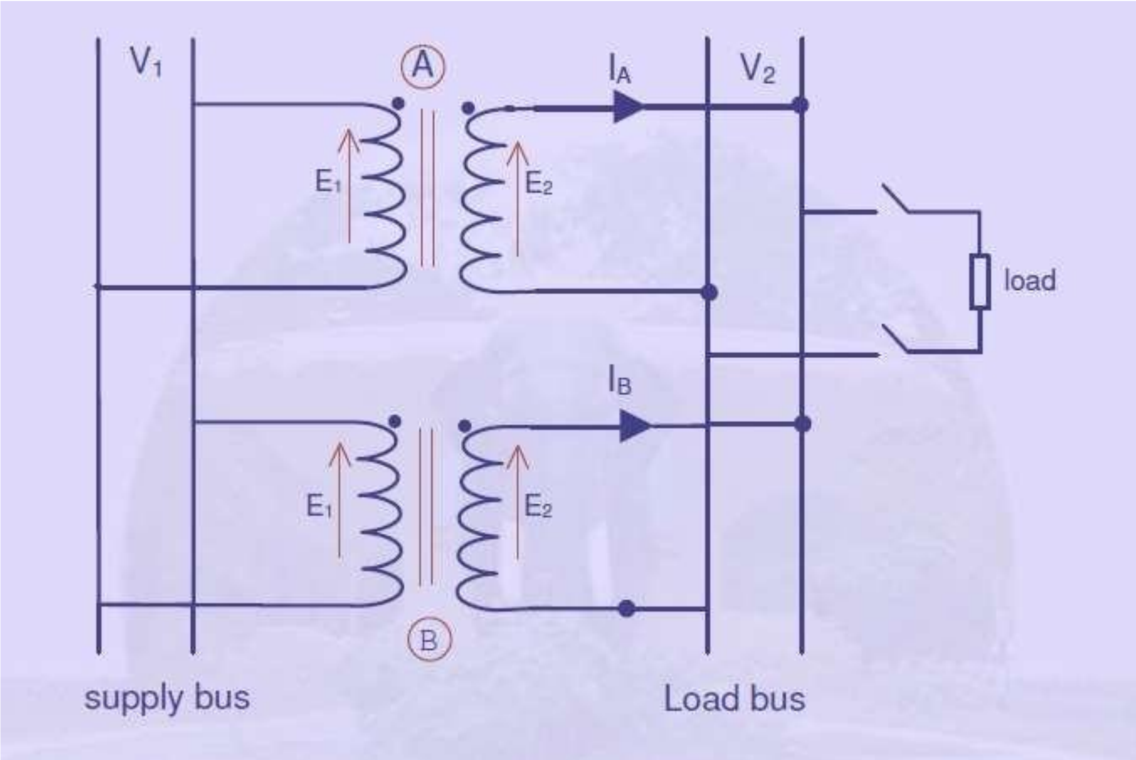


Figure 37: Parallel Operation of Two Single Phase Transformers - Physical

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

1. The voltage ratio must be the same.

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

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

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

These conditions are examined first with reference to single phase transformers and then the three phase cases are discussed.

Same voltage ratio Generally the turns ratio and voltage ratio are taken to be the same. If the ratio is large there can be considerable error in the voltages even if the turns ratios are the same. When the primaries are connected to same bus bars, if the secondaries do not show the same voltage, paralleling them would result in a circulating current between the secondaries. Reflected circulating current will be there on the primary side also. Thus even without connecting a load considerable current can be drawn by the transformers and they produce copper losses. In two identical transformers with percentage impedance of 5 percent, a no-load voltage difference of one percent will result in a circulating current of 10 percent of full load current. This circulating current gets added to the load current when the load is connected resulting in unequal sharing of the load. In such cases the combined full load of the two transformers can never be met without one transformer getting overloaded.

Per unit impedance

Transformers of different ratings may be required to operate in parallel. If they have to share the total load in proportion to their ratings the larger machine has to draw more current. The voltage drop across each machine has to be the same by virtue of their connection at the input and the output ends. Thus the larger machines have smaller impedance and smaller machines must have larger ohmic impedance. Thus the impedances must be in the inverse ratios of the ratings. As the voltage drops must be the same the per unit impedance of each transformer on its own base, must be equal. In addition if active and reactive power are required to be shared in proportion to the ratings the impedance angles also must be the same. Thus we have the requirement that per unit resistance and per unit reactance of both the transformers must be the same for proper load sharing.

Polarity of connection

The polarity of connection in the case of single phase transformers can be either same or opposite. Inside the loop formed by the two secondaries the resulting voltage must be zero. If wrong polarity is chosen the two voltages get added and short circuit results. In the case of polyphase banks it is possible to have permanent phase error between the phases with substantial circulating current. Such transformer banks must not be connected in parallel. The turns ratios in such groups can be adjusted to give very close voltage ratios but phase errors cannot be compensated. Phase error of 0.6 degree gives rise to one percent difference in voltage. Hence poly phase transformers belonging to the same vector group alone must be taken for paralleling.

Transformers having -30° angle can be paralleled to that having $+30^\circ$ angle by reversing the phase sequence of both primary and secondary terminals of one of the transformers. This way one can overcome the problem of the phase angle error.

Phase sequence

The phase sequence of operation becomes relevant only in the case of poly phase systems. The poly phase banks belonging to same vector group can be connected in parallel. A transformer with $+30^\circ$ phase angle however can be paralleled with the one with -30° phase angle, the phase sequence is reversed for one of them both at primary and secondary terminals. If the phase sequences are not the same then the two transformers cannot be connected in parallel even if they belong to same vector group. The phase sequence can be found out by the use of a phase sequence indicator.

Performance of two or more single phase transformers working in parallel can be computed using their equivalent circuit. In the case of poly phase banks also the approach is identical and the single phase equivalent circuit of the same can be used. Basically two cases arise in these problems. Case A: when the voltage ratio of the two transformers is the same and Case B: when the voltage ratios are not the same. These are discussed now in sequence.

Case A: Equal voltage ratios

Always two transformers of equal voltage ratios are selected for working in parallel. This way one can avoid a circulating current between the transformers. Load can be switched on subsequently to these bus bars. Neglecting the parallel branch of the equivalent circuit the above connection can be shown as in Fig. 38(a),(b). The equivalent circuit is drawn in terms of the secondary parameters. This may be further simplified as shown under Fig. 38(c). The voltage drop across the two transformers must be the same by virtue of common connection at input as well as output ends. By inspection the voltage equation for the drop can be

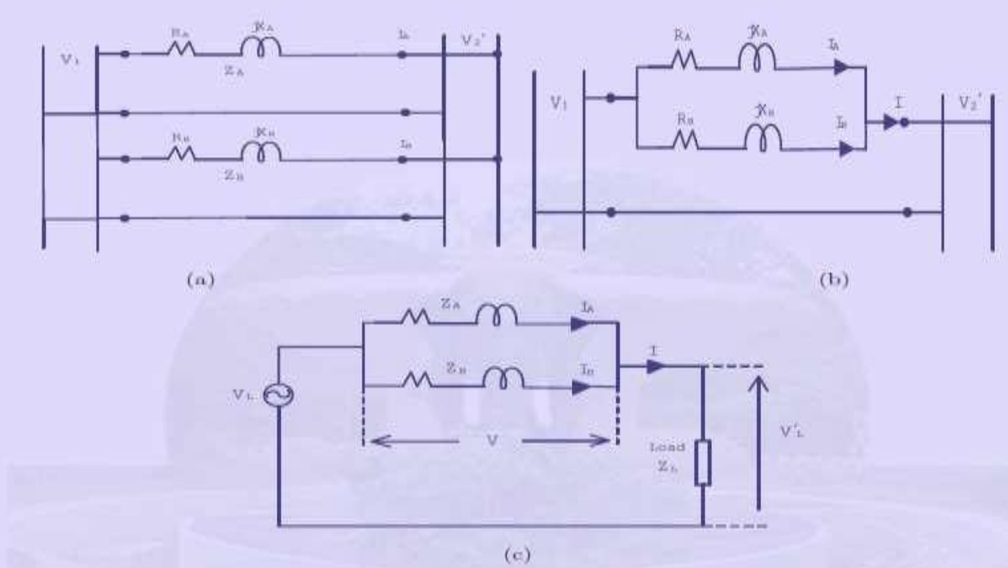


Figure 38: Equivalent Circuit for Transformers working in Parallel -Simplified circuit and Further simplification for identical voltage ratio

written as

$$I_A Z_A = I_B Z_B = IZ = v \quad (say)$$

$$\text{Here} I = I_A + I_B$$

And Z is the equivalent impedance of the two transformers given by,

$$Z = \frac{Z_A Z_B}{Z_A + Z_B}$$

$$\text{Thus} \quad I_A = \frac{v}{Z_A} = \frac{IZ}{Z_A} = I.\frac{Z_B}{Z_A + Z_B}$$

$$\text{and } I_B = \frac{v}{Z_B} = \frac{IZ}{Z_B} = I.\frac{Z_A}{Z_A + Z_B}$$

If the terminal voltage is V = IZL then the active and reactive power supplied by each of the two transformers is given by

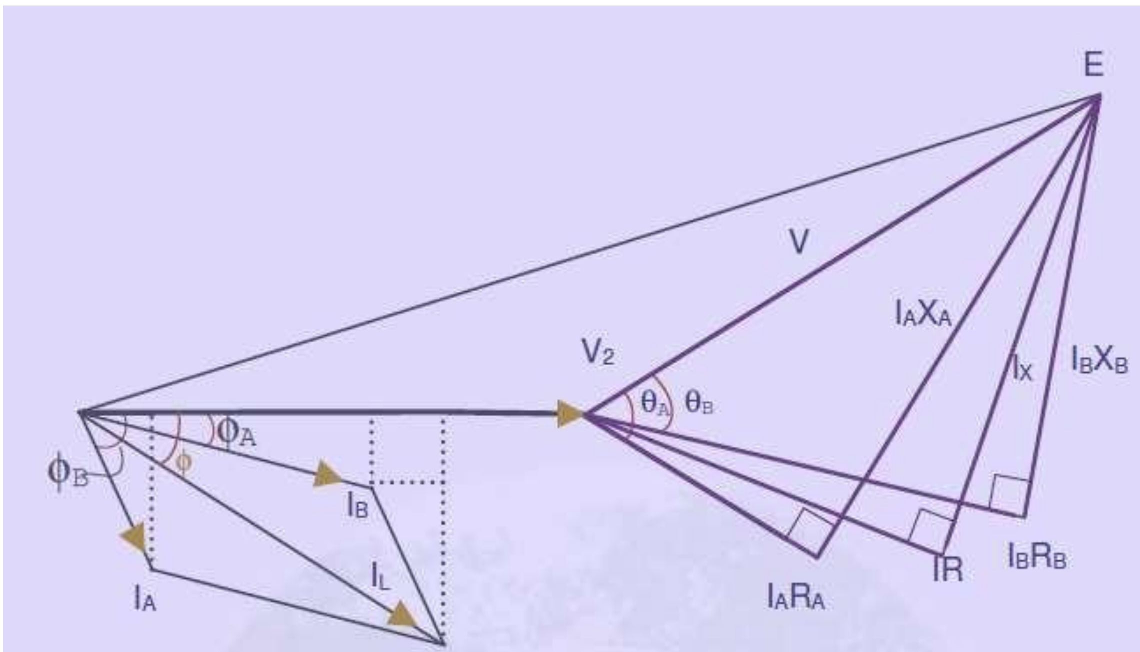
$$P_A = Real(VI_A^*) \text{ and } Q_A = Imag(VI_A^*) \text{ and}$$

$$P_B = Real(VI_B^*) \text{ and } Q_B = Imag(VI_B^*)$$

From the above it is seen that the transformer with higher impedance supplies lesser load current and vice versa. If transformers of dissimilar ratings are paralleled the trans former with larger rating shall have smaller impedance as it has to produce the same drop as the other transformer, at a larger current the ohmic values of the impedances must be in the inverse ratio of the ratings of the transformers. IAZA = IBZB, therefore IA/IB= ZB/ZA.

Expressing the voltage drops in p.u basis, we aim at the same per unit drops at any load for the transformers. The per unit impedances must therefore be the same on their respective bases.

Fig shows the phasor diagram of operation for these conditions. The drops are magnified and shown to improve clarity. It is seen that the total voltage drop inside the



transformers is v but the currents IA and IB are forced to have a different phase angle due to the difference in the internal power factor angles _A and _B. This forces the active and reactive components of the currents drawn by each transformer to be different (even in the case when current in each transformer is the same). If we want them to share the load current in proportion to their ratings, their percentage (or p.u) impedances must be the same. In order to avoid any divergence and to share active and reactive powers also properly, ϴA = ϴB. Thus the condition for satisfactory parallel operation is that the p.u resistances and p.u reactance must be the same on their respective bases for the two transformers. To determine the sharing of currents and power either p.u parameters or ohmic values can be used.

Example 32.96. *Two 1-phase transformers with equal turns have impedances of (0.5 + j3) ohm and (0.6 + j10) ohm with respect to the secondary. If they operate in parallel, determine how they will share a total load of 100 kW at p.f. 0.8 lagging ?* **(Electrical Technology, Madras Univ. 1987)**

Solution. $\mathbf{Z_A} = 0.5 + j3 = 3.04\angle 80.6°$ $\mathbf{Z_B} = 0.6 + j10 = 10.02\angle 86.6°$

$$\mathbf{Z_A} + \mathbf{Z_B} = 1.1 + j13 = 13.05\angle 85.2°$$

Now, a load of 100 kW at 0.8 p.f. means a kVA of 100/0.8 = 125. Hence,

$$\mathbf{S} = 125\angle -36.9°$$

$$\mathbf{S_A} = \mathbf{S}\frac{\mathbf{Z_A}}{\mathbf{Z_A}+\mathbf{Z_B}} = \frac{125\angle -36.9° \times 10.02\angle 86.6°}{13.05\angle 85.2°} = 96\angle -35.5°$$

$$= \text{a load of } 96 \times \cos 35.5° = 78.2 \text{ kW}$$

$$\mathbf{S_B} = \mathbf{S}\frac{\mathbf{Z_A}}{\mathbf{Z_A}+\mathbf{Z_B}} = \frac{125\angle -36.9° \times 3.04\angle 80.6°}{13.05\angle 85.2°} = 29.1\angle -41.5°$$

$$= \text{a load of } 29.1 \times \cos 41.5° = \mathbf{21.8\ kW}$$

Note. Obviously, transformer *A* is carrying more than its due share of the common load.

Example 32.99. *Two 100-kW, single-phase transformers are connected in parallel both on the primary and secondary. One transformer has an ohmic drop of 0.5% at full-load and an inductive drop of 8% at full-load current. The other has an ohmic drop of 0.75% and inductive drop of 2%. Show how will they share a load of 180 kW at 0.9 power factor.*

(Elect. Machines-I, Calcutta Univ. 1988)

Solution. A load of 180 kW at 0.9 p.f. means a kVA of 180/0.9 = 200

∴ Load $\mathbf{S} = 200 - 25.8°$

$$\frac{\mathbf{Z_1}}{\mathbf{Z_1}+\mathbf{Z_2}} = \frac{(0.5 + j\,8)}{(1.25 + j\,12)} = \frac{(0.5 + j\,8)(1.25 - j\,12)}{1.25^2 + 12^2}$$

$$= \frac{96.63 + j\,4}{145.6} = \frac{96.65\angle 2.4°}{145.6} = 0.664\angle 2.4°$$

$$\frac{\mathbf{Z}_2}{\mathbf{Z}_1+\mathbf{Z}_2} = \frac{(0.75+j4)(1.25-j12)}{145.6}$$

$$= \frac{48.94-j4}{145.6} = \frac{49.1\angle-5^\circ}{145.6}$$

$$= 0.337\angle-5^\circ$$

$$\mathbf{S}_1 = \mathbf{S}\frac{\mathbf{Z}_2}{\mathbf{Z}_1+\mathbf{Z}_2} = 200\angle-25.8^\circ \times 0.337\angle-5^\circ = 67.4\angle-30.8^\circ$$

$$\therefore \quad kW_1 = 67.4 \times \cos 30.8^\circ = 67.4 \times 0.859 = 57.9 \text{ kW}$$

$$\mathbf{S}_2 = 200\angle-25.8^\circ \times 0.664\angle 2.4^\circ = 132.8\angle-23.4$$

$$kW_2 = 132.8 \times \cos 23.4^\circ = 132.8 \times 0.915 = 121.5 \text{ kW}$$

Note. Second transformer is working 21.5% over-load. Also, it shares 65.7% of the total load.

Case B :Unequal voltage ratios

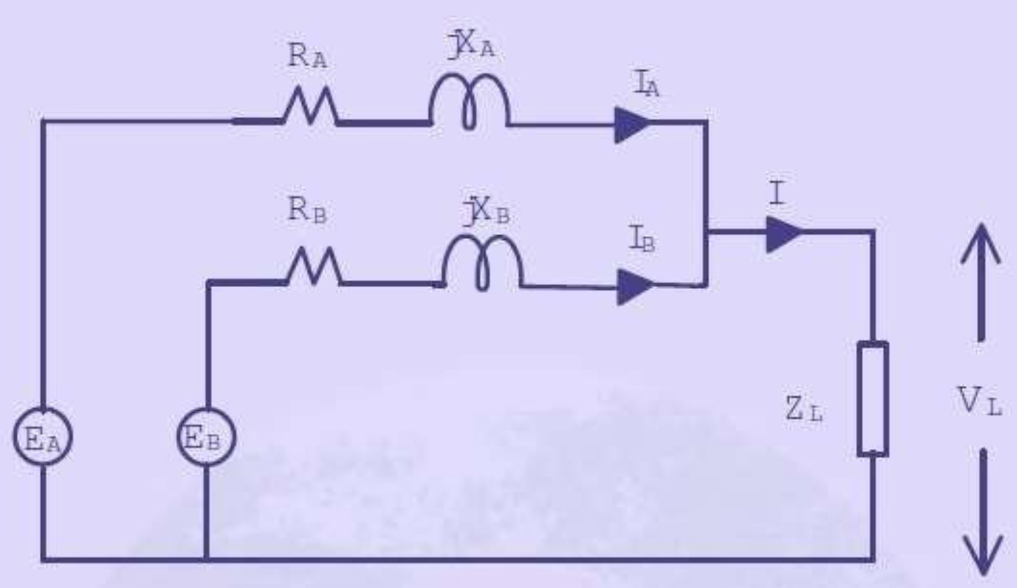


Figure 40: Equivalent Circuit for unequal Voltage Ratio

One may not be able to get two transformers of identical voltage ratio inspite of ones best efforts. Due to manufacturing differences, even in transformers built as per the same design, the voltage ratios may not be the same. In such cases the circuit representation for parallel operation will be different as shown in Fig. 40. In this case the two input voltages cannot be merged to one, as they are different. The load brings about a common connection at the output side. EA and EB are the no-load secondary emf. ZL is the load impedance at the secondary terminals. By inspection the voltage equation can be written as below:

$$E_A = I_A Z_A + (I_A + I_B) Z_L = V + I_A Z_A \cdot$$
$$E_B = I_B Z_B + (I_A + I_B) Z_L = V + I_B Z_B \cdot$$

Solving the two equations the expression for IA and IB can be obtained as

$$I_A = \frac{E_A Z_B + (E_A - E_B) Z_L}{Z_A Z_B + Z_L (Z_A + Z_B)} \quad \text{and}$$
$$I_B = \frac{E_B Z_A + (E_B - E_A) Z_L}{Z_A Z_B + Z_L (Z_A + Z_B)}$$

ZA and ZB are phasors and hence there can be angular difference also in addition to the difference in magnitude. When load is not connected there will be a circulating current between the transformers. The currents in that case can be obtained by putting ZL = 1 (after dividing the numerator and the denominator by ZL). Then,

$$I_A = -I_B = \frac{(E_A - E_B)}{(Z_A + Z_B)}$$

If the load impedance becomes zero as in the case of a short circuit, we have,

$$I_A = \frac{E_A}{Z_A} \quad \text{and} \quad I_B = \frac{E_B}{Z_B}$$

Instead of the value of ZL if the value of V is known , the currents can be easily determined

$$I_A = \frac{E_A - V}{Z_A} \quad \text{and} \quad I_B = \frac{E_B - V}{Z_B}$$

Example 32.106. *Two transformers A and B are joined in parallel to the same load. Determine the current delivered by each transformer having given : open-circuit e.m.f. 6600 V for A and 6,400 V for B. Equivalent leakage impedance in terms of the secondary = 0.3 + j3 for A and 0.2 + j1 for B. The load impedance is 8 + j6.* **(Elect. Machines-I, Indore Univ. 1987)**

Solution.

$$\mathbf{I_A} = \frac{\mathbf{E_A Z_B} + (\mathbf{E_A} - \mathbf{E_B})\mathbf{Z_L}}{\mathbf{Z_A Z_B} + \mathbf{Z_L}(\mathbf{Z_A} + \mathbf{Z_B})}$$

Here $\mathbf{E_A} = 6{,}600 \text{ V}$; $\mathbf{E_B} = 6{,}400 \text{ V}$; $\mathbf{Z_L} = 8 + j\,6$; $\mathbf{Z_A} = 0.3 + j\,3$; $\mathbf{Z_B} = 0.2 + j\,1$

$$\mathbf{I_A} = \frac{6600(0.2 + j1) + (6600 - 6400)(8 + j6)}{(0.3 + j3)(0.2 + j1) + (8 + j6)(0.3 + j3 + 0.2 + j1)}$$

$$117 - j\,156 = 195\text{A in magnitude}$$

Similarly,

$$\mathbf{I_B} = \frac{\mathbf{E_B Z_A} - (\mathbf{E_A} - \mathbf{E_B})\mathbf{Z_L}}{\mathbf{Z_A Z_B} + \mathbf{Z_L}(\mathbf{Z_A} + \mathbf{Z_B})}$$

$$= \frac{6400\,(0.3 + j3) - (6600 - 6400)\,(8 + j6)}{(0.3 + j3) + (0.2 + j1)\,(8 + j6) + (0.5 + j4)}$$

$$= 349 - j\,231 = 421 \text{ A (in magnitude)}$$

If more than two transformers are connected across a load then the calculation of load currents following the method suggested above involves considerable amount of computational labor. A simpler and more elegant method for the case depicted in Fig. 41 is given below. It is known by the name parallel generator theorem.

$$I_L = I_A + I_B + I_C + \ldots\ldots$$

$$\text{But} \quad I_A = \frac{E_A - V}{Z_A}, \quad I_B = \frac{E_B - V}{Z_B}, \quad I_C = \frac{E_C - V}{Z_C}$$

$$V = I_L.Z_L$$

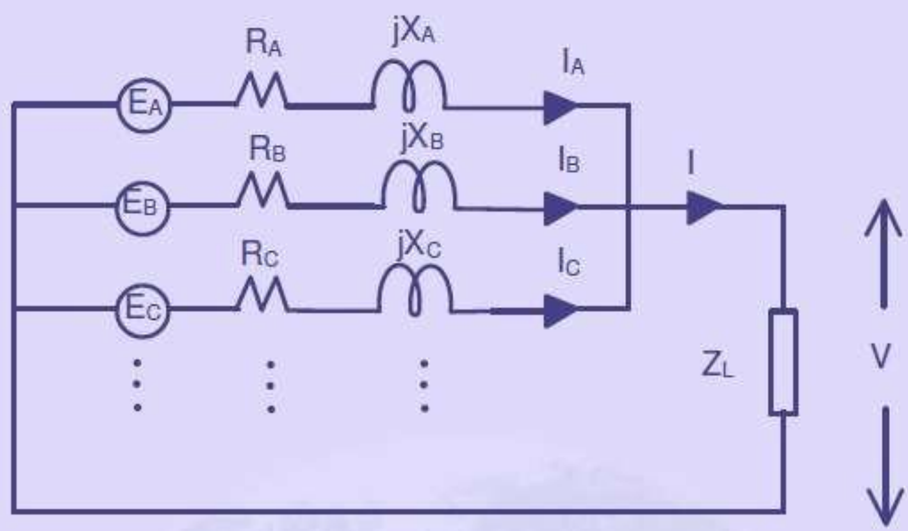


Figure 41: Parallel Generator Theorem

Combining these equations

$$\frac{V}{Z_L} = \frac{E_A - V}{Z_A} + \frac{E_B - V}{Z_B} + \frac{E_C - V}{Z_C} + \ldots$$

Grouping the terms together

$$V(\frac{1}{Z_L} + \frac{1}{Z_A} + \frac{1}{Z_B} + \frac{1}{Z_C} + ...) = \frac{E_A}{Z_A} + \frac{E_B}{Z_B} + \frac{E_C}{Z_C} + ...$$
$$= I_{SCA} + I_{SCB} + I_{SCC} + ...$$
$$(\frac{1}{Z_L} + \frac{1}{Z_A} + \frac{1}{Z_B} + \frac{1}{Z_C} + ...) = \frac{1}{Z}$$
$$V = Z(I_{SCA} + I_{SCB} + I_{SCC} + ...)$$

From this V can be obtained. Substituting V in Eqn. 98, IA, IB etc can be obtained. Knowing the individual current phasor, the load shared by each transformer can be computed.

Auto transformer

- Transformer having only one winding such that part of winding common to both primary and secondary
- In the fig 1 the auto transformer is step down because N1>N2 and here N1 is common to both sides
- In the fig2 the autotransformer is step down because N1<N2 and here N2 is common to both
- It works on the principle of both induction and conduction
- Power transfer also takes by both induction and conduction.
- Weight of copper in autotransformer can be reduced

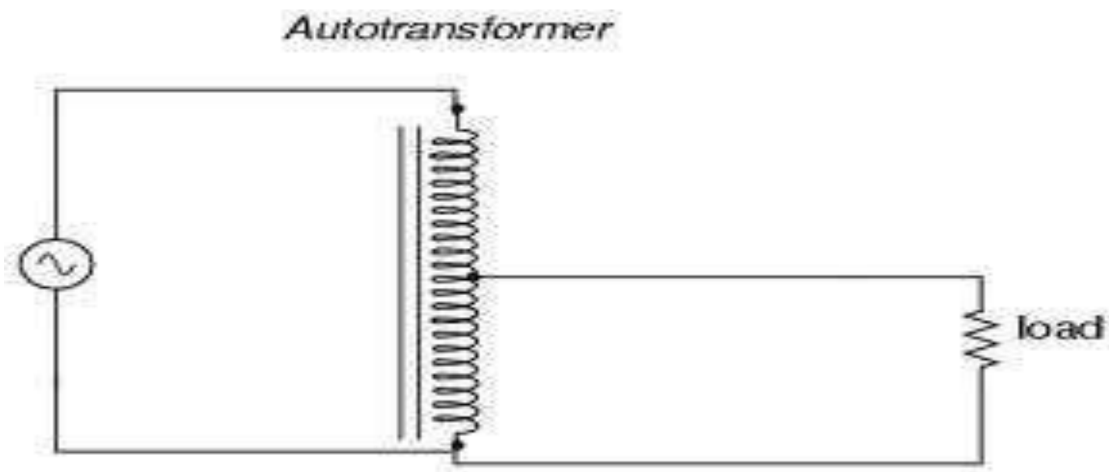
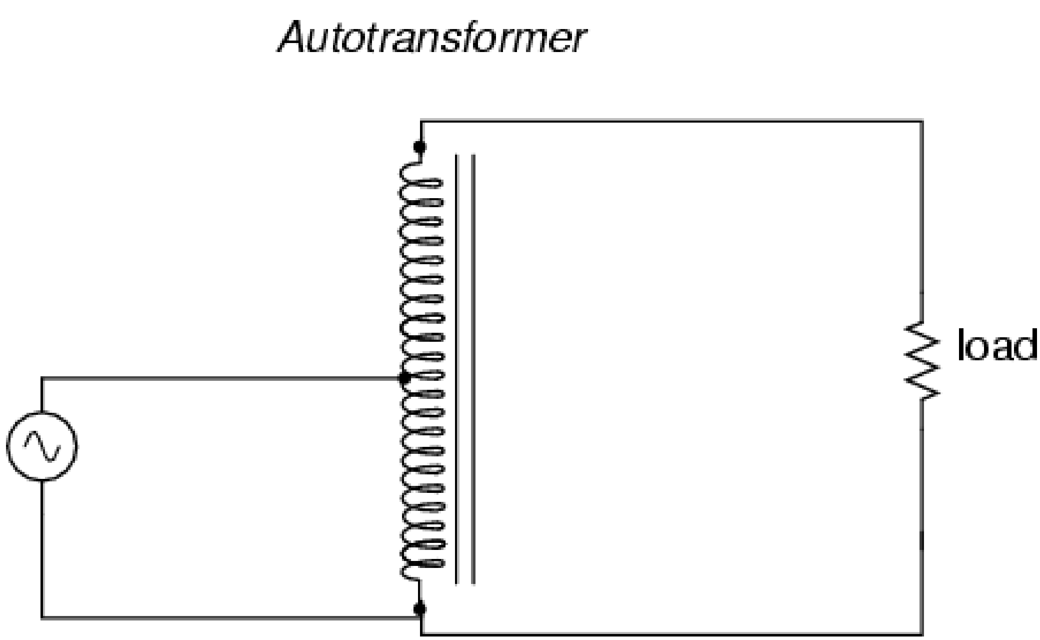


Fig 1



- Transformer having only one winding such that part of winding common to both primary and secondary
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- It works on the principle of both induction and conduction

- Power transfer also takes by both induction and conduction.
- Weight of copper in autotransormer can be reduced

Advantages of Autotransformer

- Copper required is very less and hence copper loss is reduced.
- Efficiency is higher compared to two winding transformer
- The power rating is m ore compared to two winding transformer
- The size and cost is less compared to two winding transformer

Applications of Autotransformer

- It is used as variac for starting of machines like Induction machines, Synchronous machines.
- The voltage drop is compensated and acts as booster.
- It used as furnace transformer at the required supply.
- It can be connected between two systems operating at same voltage level.

Copper Savings in Auto Transformer

Now we will discuss the savings of copper in auto transformer compared to conventional two winding transformer.

We know that weight of copper of any winding depends upon its length and cross-sectional area. Again length of conductor in winding is proportional to its number of turns and cross-sectional area varies with rated current.

So weight of copper in winding is directly proportional to product of number of turns and rated current of the winding.

Therefore, weight of copper in the section AC proportional to,

$$(N_1 - N_2)I_1$$

and similarly, weight of copper in the section BC proportional to,

$$N_2(I_2 - I_1)$$

Hence, total weight of copper in the winding of auto transformer proportional to,

$$(N_1 - N_2)I_1 + N_2(I_2 - I_1)$$

$$\Rightarrow N_1I_1 - N_2I_1 + N_2I_2 - N_2I_1$$

$$\Rightarrow N_1I_1 + N_2I_2 - 2N_2I_1$$

$$\Rightarrow 2N_1I_1 - 2N_2I_1 (Since,\ N_1I_1 = N_2I_2)$$

$$\Rightarrow 2(N_1I_1 - N_2I_1)$$

In similar way it can be proved, the weight of copper in two winding transformer is proportional to,

$$N_1I_1 - N_2I_2$$

$$\Rightarrow 2N_1I_1 \qquad (Since,\ in\ a\ transformer\ N_1I_1 = N_2I_2)$$

$N_1I_1 + N_2I_2$

$2N_1I_1$ (Since, in a transformer $N_1I_1 = N_2I_2$)

Let's assume, W_a and W_{tw} are weight of copper in auto transformer and two winding transformer respectively,

$$Hence,\ \frac{W_a}{W_{tw}} = \frac{2(N_1I_1 - N_2I_1)}{2(N_1I_1)}$$

$$= \frac{N_1I_1 - N_2I_1}{N_1I_1} = 1 - \frac{N_2I_1}{N_1I_1}$$

$$= 1 - \frac{N_2}{N_1} = 1 - k$$

$$\therefore W_a = W_{tw}(1 - k)$$

$$\Rightarrow W_a = W_{tw} - kW_{tw}$$

$$\Rightarrow W_{tw} - W_a = kW_{tw}$$

Example 32.87. *An auto-transformer supplies a load of 3 kW at 115 volts at a unity power factor. If the applied primary voltage is 230 volts, calculate the power transferred to the load (a) inductively and (b) conductively.* **(Basic Elect. Machines, Nagpur Univ, 1991)**

Solution. As seen from Art 32.33

Power transferred inductively = Input $(1 - K)$

Power transferred conductively = Input $\times K$

Now, $K = 115/230 = 1/2$, input $\cong$ output = 3 kW

$\therefore$ Inductively transferred power = 3 (1 − 1/2) = **1.5 kW**

Conductivley transferred power = (1/2) × 3 = **1.5 kW**

Example 32.88. *The primary and secondary voltages of an auto-transformer are 500 V and 400 V respectively. Show with the aid of diagram, the current distribution in the winding when the secondary current is 100 A and calculate the economy of Cu in this particular case.*

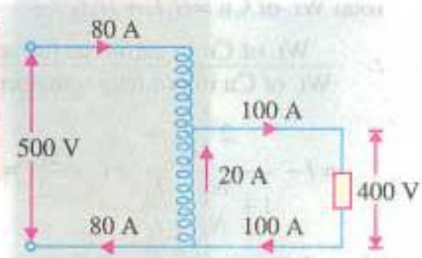


Fig. 32.61

Solution. The circuit is shown in Fig, 30.61.

$K = V_2/V_1 = 400/500 = 0.8$

$\therefore \quad I_1 = KI_2 = 0.8 \times 100 = 80$ A

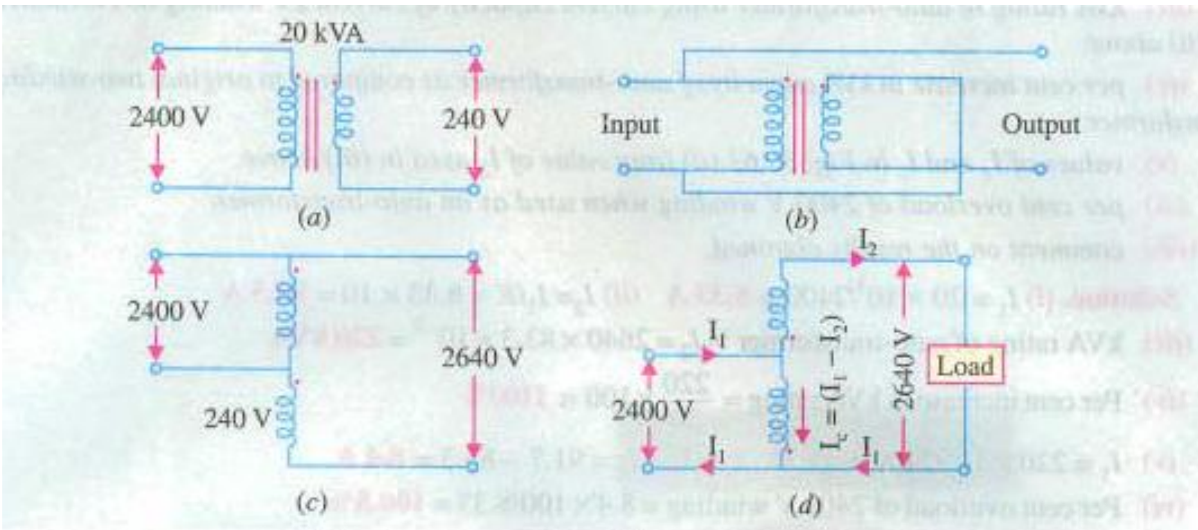
The current distribution is shown in Fig. 32.61.

Saving = $KW_0 = 0.8\ W_0$ - Art 32.33

$\therefore$ Percentage saving = 0.8 × 100 = **80**

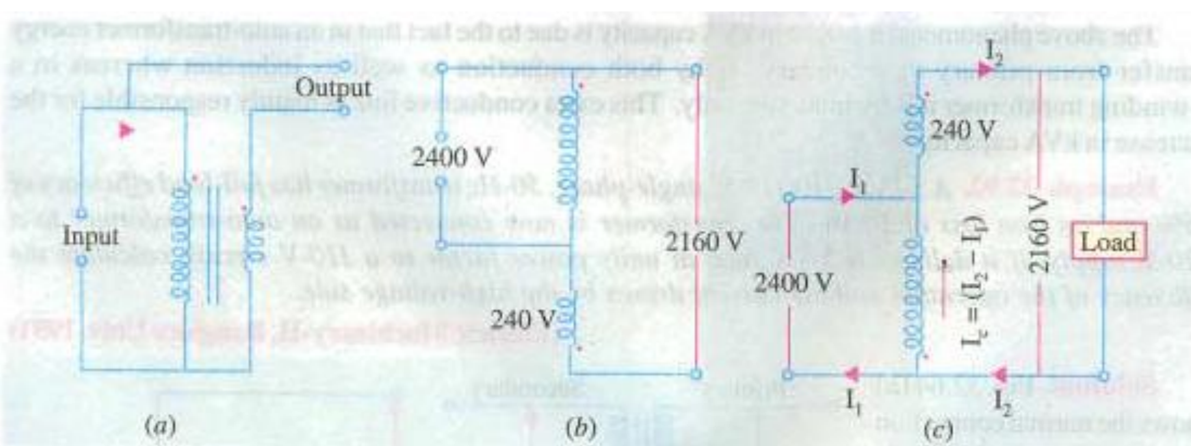
(a) Additive Polarity

Connections for such a polarity are shown in Fig. 32.62 (*b*). The circuit is re-drawn in Fig. 32.62 (*c*) showing common terminal of the transformer at the top whereas Fig. 32.62 (*d*) shows the same circuit with common terminal at the bottom. Because of additive polarity, $V_2 = 2400 + 240 = 2640$ V and V_1 is 2400 V. There is a marked increase in the kVA of the auto-transformer (Ex. 32.90). As shown in Fig. 32.62 (*d*), common current flows *towards* the common terminal. The transformer acts as a step-up transformer.



(b) Subtractive Polarity

Such a connection is shown in Fig. 32.63 (*a*). The circuit has been re-drawn with common polarity at top in Fig. 32.63 (*b*) and at bottom in Fig. 32.63 (*c*). In this case, the transformer acts as a step-down auto-transformer.



The common current flows *away* from the common terminal. As will be shown in Example 32.91, in this case also, there is a very large increase in kVA rating of the auto-transformer though not as marked as in the previous case. Here, $V_2 = 2400 - 240 = 2160$ V.

Example 32.94. *An 11500/2300 V transformer is rated at 100 kVA as a 2 winding transformer. If the two windings are connected in series to form an auto-transformer, what will be the possible voltage ratios ?* **(Manonmaniam Sundaranar Univ. April 1998)**

Solution. Fig. 32.66 (*a*) shows this 2-winding transformer with rated winding currents marked .

Rated current of 11.5 kV winding = 100 × 100/11500 = 8.7 Amp

Rated current of 2300 V winding = 43.5 Amp

Fig. 32.66 (*a*). 2 winding transformer

Fig. 32.66 (*b*) and Fig. 32.66 (*c*) show autotransformer connections. On H.V. side, they have a rating of 13.8 kV. On L.V. side, with connection as in Fig. 32.66 (*b*), the rating is 2300 V. On L.V. side of Fig. 32.66 (*c*), the output is at 11.5 kV.

Thus, possible voltage ratios are : 13800/2300 V and 13800/11500 V.

With both the connections, step-up or step-down versions are possible.

Extension of Question : Calculate kVA ratings in the two cases.

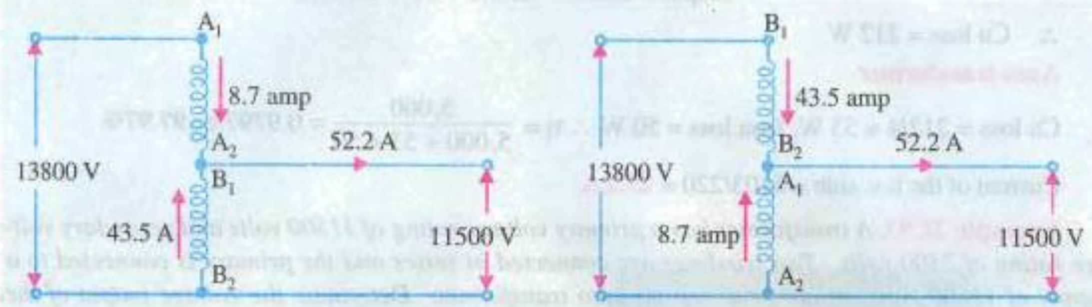


Fig. 32.66

Windings will carry the rated currents, while working out kVA outputs.

In Fig. 32.66 (*b*), Input current (into terminal A_1 of windings A_1-A_2) can be 8.7 Amp with H.V.-side-voltage ratings as 13.8 kV. Transformation ratio = 13800/2300 = 6

Hence, kVA rating = $13.8 \times 8.7 = 120$

Output current = $120 \times 1000/2300 = 52.2$ Amp

Current in the winding B_1-B_2

= Difference of Output current and Input current

$= 52.2 - 8.7 = 43.5$ A, which is the rated current of the winding B_1-B_2.

In Fig. 32.66 (*c*). Similarly, transformation ratio = 13800/11500 = 1.2

kVA rating = $13800 \times 43.5 \times 10^{-3} = 600$

Output current = $600 \times 1000/11500 = 52.2$ Amp

Current carried by common winding = $52.2 - 43.5 = 8.7$ A, which is rated current for the winding A_1-A_2. Thus, with the same two windings give, a transformation ratio closer to unity gives higher kVA rating as an auto transformer.

Thus, a 100 kVA two winding transformer is reconnected as an autotransformer of 120 kVA with transformation ratio as 6, and becomes a 600 kVA autotransformer with transformation ratio as 1.2.

Tap Changing Transformer

The transformer voltage at the load side desired to be constant or as close to the design value. But the load voltage may vary according to current drawn by the load or supply voltage.

Secondary voltage = (supply voltage or primary voltage) / Turns ratio.

Based on the above equation to maintain constant secondary voltage/load voltage or as close to the desired value it is needed to change the turn's ratio. The tap changer of the transformer performs this task to change the turn's ratio.

The tap changer basic function is that it removes or connects some portion of the winding to the load side or source side. Tap changer can be located on primary side or secondary side. However it will be placed on high voltage winding side.

Why tap changer is placed on high voltage side?

The tap changer is placed on high voltage side because:

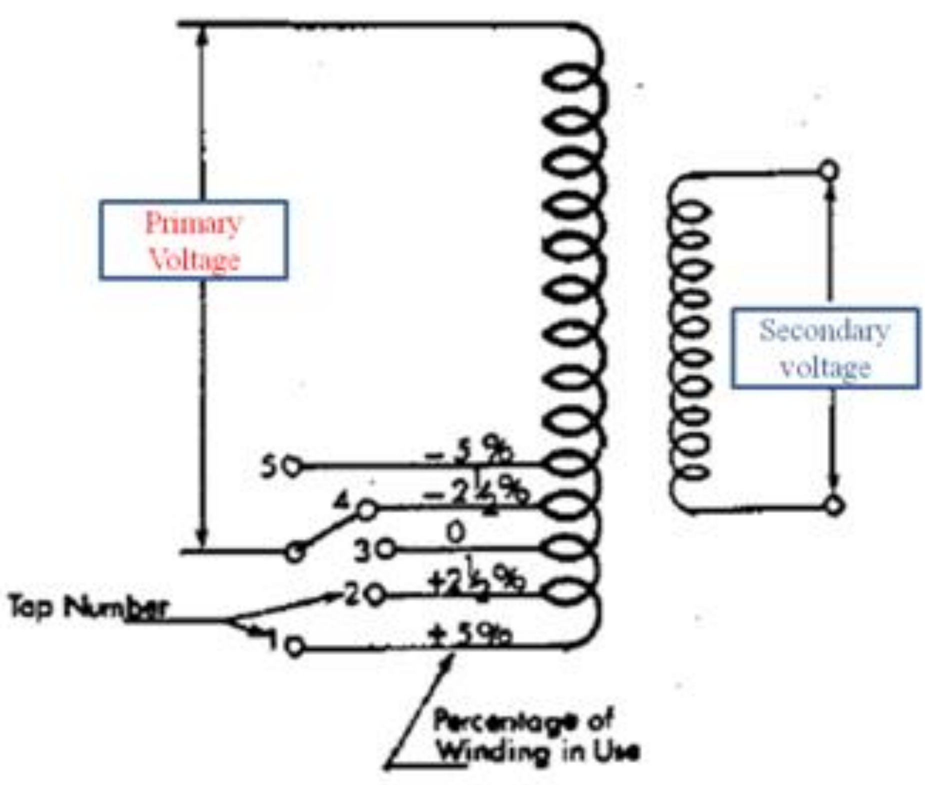
1) The HV winding generally wound over LV winding hence it is easier to access the HV winding turns instead of LV winding.
2) Because of high voltage the current through the HV winding is less compared to LV windings, hence there is less "wear" on the tap changer contacts. Due this low current, in on load tap changer the change over spark will be less.

Tap changer Primary side:
In this type the tap changer circuit is placed in primary side or supply side. As we know;

Turns ratio = secondary winding turns (Ns)/ primary winding turns (Np).

Secondary voltage = (supply voltage or primary voltage) / Turns ratio.

By the above formulas it is stated that if the primary turns decreases the turn's ratio increases hence then secondary voltage decreases. Opposite for the reverse case i.e. primary turns increase leads to turns ratio decrease which increases the voltage in secondary .
Figure shows the tap changer on primary winding with tap changing interval of 2.5 % per tap. With this we can understand three conditions**:**



In normal operation the tap changer will be at 0% position to provide required designed secondary voltage.

2) If the supply voltage increases or load current decreases there will be an increase in supply voltage which is not desirable. At this case the tap position in the primary winding will rise

towards positive direction i.e. +2.5%, and hence decreases the Np. This will increases the turns ratio (Ns/Np) further decreases the secondary voltage.

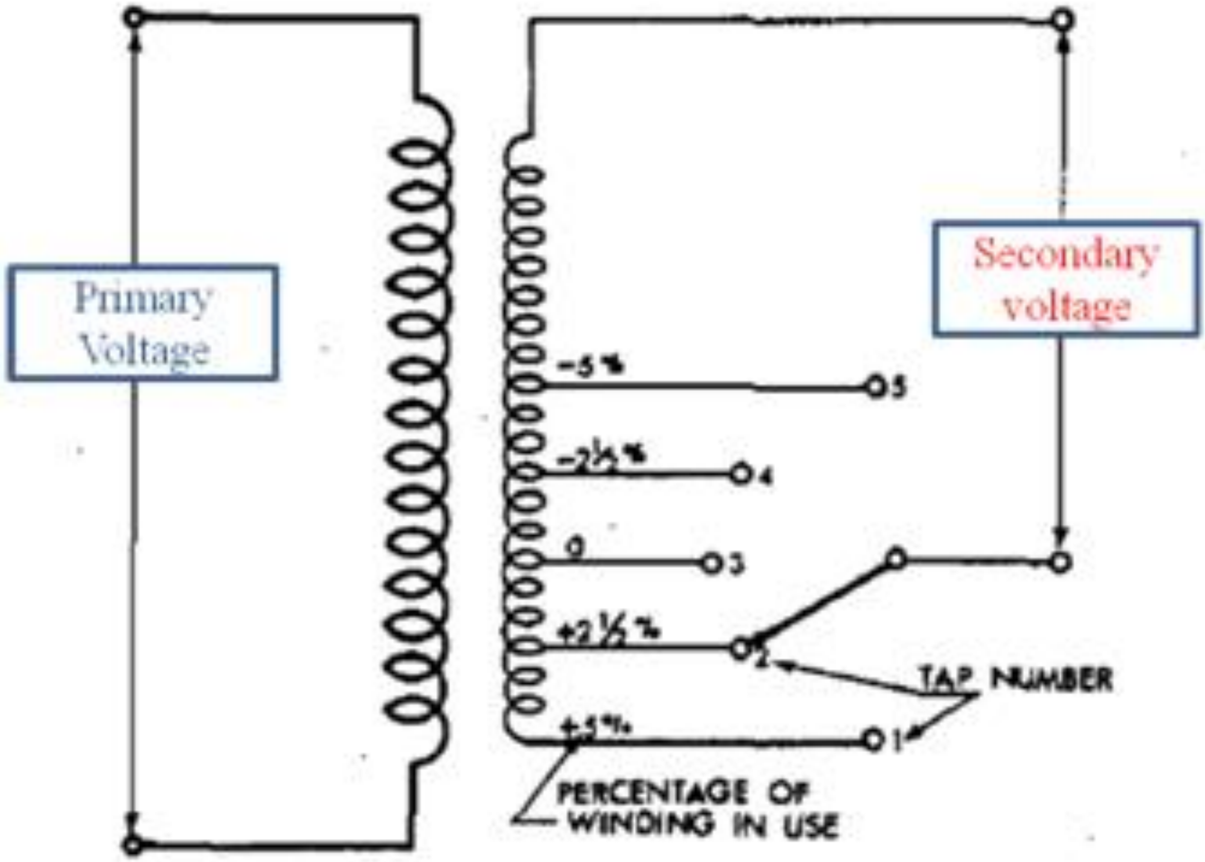
Consider the load voltage decreased then the tap changer shift towards negative side to increase the primary turns and hence decreases the turn's ratio. The secondary voltage will increase to compensate the change.

Tap changer Secondary side:

In this the tap changer is placed in secondary side of the transformer. This type of taping is used in step-up transformer where low voltage winding is in primary side and high voltage winding is in secondary side.

Figure shows the tap changer circuit on secondary side with tap interval of 2.5 %. In some distribution transformers the tap changer resolution can be up to 1% for fine adjustments.

In this the case is reverse compared to primary tap changer. To increase the secondary voltage the tap changer will move towards positive direction and it moves in negative direction to decrease the secondary voltage.



No-load tap changer

No-load tap changer (NLTC), also known as Off-circuit tap changer (OCTC) or De-energized tap changer (DETC), is a tap changer utilized in situations in which a transformer's turn ratio does not require frequent changing and it is permissible to de-energize the transformer system.

This type of transformer is frequently employed in low power, low voltage transformers in which the tap point often may take the form of a transformer connection terminal, requiring the input line to be disconnected by hand and connected to the new terminal.

Alternatively, in some systems, the process of tap changing may be assisted by means of a rotary or slider switch.

No load tap changers are also employed in high voltage distribution-type transformers in which the system includes a no load tap changer on the primary winding to accommodate transmission system variations within a narrow band around the nominal rating.

In such systems, the tap changer will often be set just once, at the time of installation, although it may be changed later to accommodate a long-term change in the system voltage profile.

On-load tap changer

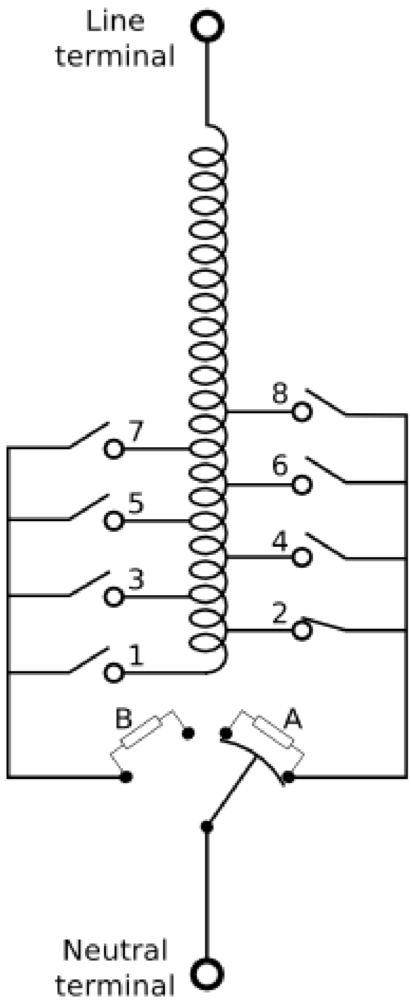
On-load tap changer (OLTC), also known as On-circuit tap changer (OCTC), is a tap changer in applications where a supply interruption during a tap change is unacceptable, the transformer is often fitted with a more expensive and complex on load tap changing mechanism. On load tap changers may be generally classified as either mechanical, electronically assisted, or fully electronic.

On-load tap changer

These systems usually possess 33 taps (one at centre "Rated" tap and sixteen to increase and decrease the turn ratio) and allow for ±10% variation[3] (each step providing 0.625% variation) from the nominal transformer rating which, in turn, allows for stepped voltage regulation of the output.

Tap changers typically use numerous tap selector switches which may not be switched under load, broken into even and odd banks, and switch between the banks with a heavy-duty diverter switch which can switch between them under load.

The result operates like a dual-clutch transmission, with the tap selector switches taking the place of the gearbox and the diverter switch taking the place of the clutch.



A mechanical tap changer physically makes the new connection before releasing the old using multiple tap selector switches but avoids creating high circulating currents by using a diverter switch to temporarily place a large diverter impedance in series with the short-circuited turns.

This technique overcomes the problems with open or short circuit taps. In a resistance type tap changer, the changeover must be made rapidly to avoid overheating of the diverter.

A reactance type tap changer uses a dedicated preventive autotransformer winding to function as the diverter impedance, and a reactance type tap changer is usually designed to sustain off-tap loading indefinitely.

In a typical diverter switch, powerful springs are tensioned by a low power motor (motor drive unit, MDU), and then rapidly released to effect the tap changing operation.

To reduce arcing at the contacts, the tap changer operates in a chamber filled with insulating transformer oil, or inside a vessel filled with pressurized SF_6 gas. Reactance-type tap changers, when operating in oil, must allow for the additional inductive transients generated by the autotransformer and commonly include a vacuum bottle contact in parallel with the diverter switch.

During a tap change operation, the potential rapidly increases between the two electrodes in the bottle, and some of the energy is dissipated in an arc discharge through the bottle instead of flashing across the diverter switch contacts.

Some arcing is unavoidable, and both the tap changer oil and the switch contacts will slowly deteriorate with use.

To prevent contamination of the tank oil and facilitate maintenance operations, the diverter switch usually operates in a separate compartment from the main transformer tank, and often the tap selector switches will be located in the compartment as well. All of the winding taps will then be routed into the tap changer compartment through a terminal array.

One possible design (flag type) of on load mechanical tap changer is shown to the right. It commences operation at tap position 2, with load supplied directly via the right hand connection. Diverter resistor A is short-circuited; diverter B is unused. In moving to tap 3, the following sequence occurs:

1. Switch 3 closes, an off-load operation.
2. Rotary switch turns, breaking one connection and supplying load current through diverter resistor A.
3. Rotary switch continues to turn, connecting between contacts A and B. Load now supplied via diverter resistors A and B, winding turns bridged via A and B.
4. Rotary switch continues to turn, breaking contact with diverter A. Load now supplied via diverter B alone, winding turns no longer bridged.
5. Rotary switch continues to turn, shorting diverter B. Load now supplied directly via left hand connection. Diverter A is unused.
6. Switch 2 opens, an off-load operation.

The sequence is then carried out in reverse to return to tap position 2.

Solid-state tap changer

This is a relatively recent development which uses thyristors both to switch the transformer winding taps and to pass the load current in the steady state.

The disadvantage is that all non-conducting thyristors connected to the unselected taps still dissipate power due to their leakage currents and they have limited short circuit tolerance. This power consumption can add up to a few kilowatts which appears as heat and causes a reduction in overall efficiency of the transformer; however, it results in a more compact design that reduces the size and weight of the tap changer device.

Solid state tap changers are typically employed only on smaller power transformers.

Off Load Tap Changer:

The cheapest method of changing the turn ratio of a transformer is the use of Off Load Tap Changer. As the name indicates, it is required to deenergize the transformer before changing the tap. A simple Off Load Tap Changer is shown in Fig. 3.68. It has eight studs marked one to eight. The winding is tapped at eight points. The face plate carrying the suitable studs can be mounted at a convenient place on the transformer such as upper yoke or located near the tapped positions on the windings. The movable contact arm A may be rotated by handwheel mounted externally on the tank.

If the winding is tapped at 2% intervals, then as the rotatable arm A is moved over to studs 1, 2; 2, 3; . . . 6, 7; 7, 8 the winding in circuit reduces progressively by it from 100% with arm at studs (1, 2) to 88% at studs (7, 8).

The stop F which fixes the final position of the arm A prevents further anticlockwise rotation so that stud 1 and 8 cannot be bridged by the arm. Adjustment of tap setting is carried out with transformer deenergized. For example, for 94% tap the arm is brought in position to bridge studs 4 and 5. The transformer can then be switched on.

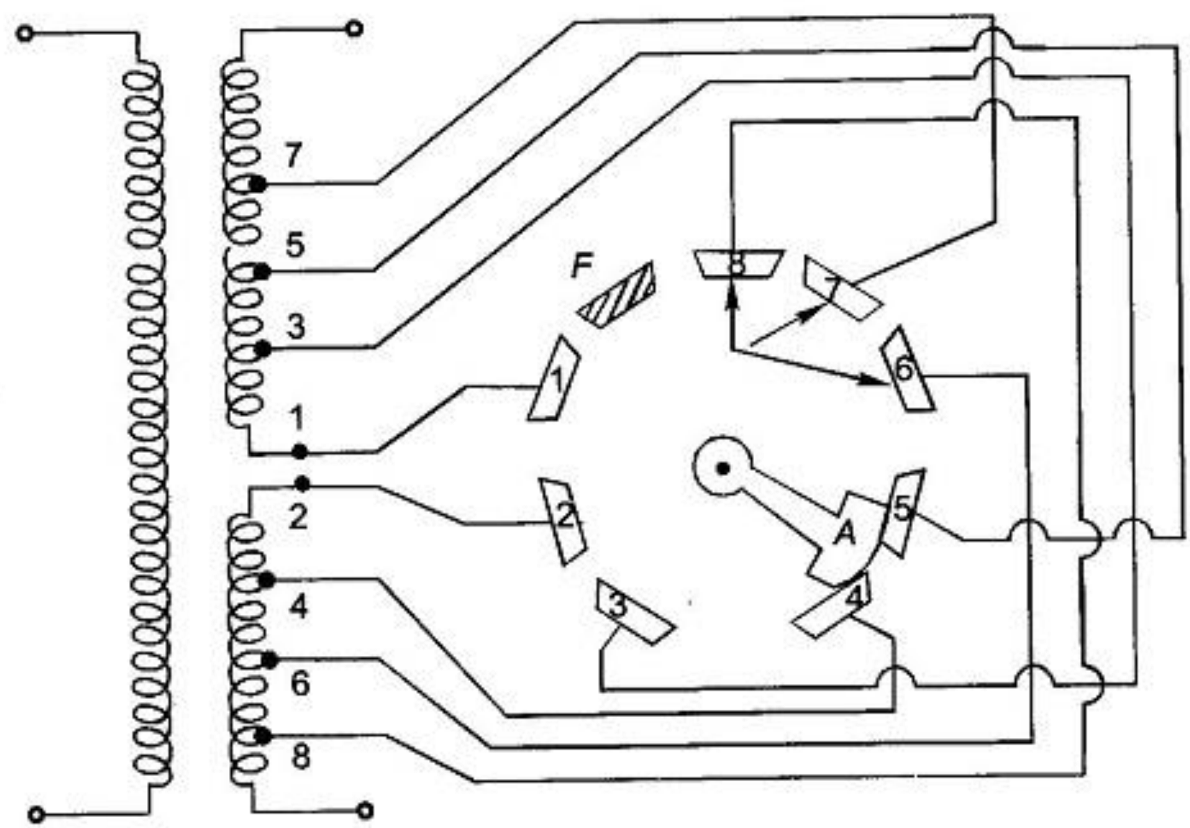


Fig. 3.68 *No-load tap changer*

To prevent unauthorized operation of an off-circuit tap changer, a mechanical lock is provided. Further, to prevent inadvertent operation, an electromagnetic latching device or microswitch is provided to open the circuit breaker so as to deenergize the transformer as soon as the tap changer handle is moved; well before the contact of the arm with the stud (with which it was in contact)

MODULE – 3

Transformers (continuation): Tertiary winding and cooling

Direct current Generator – Review of construction, types, armature windings, relation between no load and terminal voltage (No question shall be set from the review portion).Armature reaction, Commutation and associated problems, no load and full load characteristics. Reasons for reduced dependency on dc generators.

Synchronous generators- Review of construction and operation of salient & non-salient pole synchronous generators (No question shall be set from the review portion). Armature windings, winding factors, emf equation. Harmonics – causes, reduction and elimination. Armature reaction, Synchronous reactance, Equivalent circuit.

Tertiary Winding

In some high rating transformer, one winding in addition to its primary and secondary winding is used. This additional winding, apart from primary and secondary windings, is known as Tertiary winding of transformer. Because of this third winding, the transformer is called three winding transformer or 3 winding transformer.

Advantages of Using Tertiary

It reduces the unbalancing in the primary due to unbalancing in three phase load.

It redistributes the flow of fault current.

Sometime it is required to supply an auxiliary load in different voltage level in addition to its main secondary load. This secondary load can be taken from tertiary winding of three winding transformer.

As the tertiary winding is connected in delta formation in 3 winding transformer, it assists in limitation of fault current in the event of a short circuit from line to neutral.

Stabilization by Tertiary Winding of Transformer

In star-star transformer comprising three single units or a single unit with 5 limb core offers high impedance to the flow of unbalanced load between the line and neutral. This is because, in both of these transformers, there is very low reluctance return path of unbalanced flux. If any transformer has N turns in winding and reluctance of the magnetic path is RL, then,

$$mmf = NI = \phi R_L \cdots\cdots\cdot (1)$$

Where I and Φ are current and flux in the transformer.

$$Again,\ induced\ voltage = 4.44\phi f N$$

$$\Rightarrow V \propto \phi$$

$$\phi = KV\ (Where\ K\ is\ constant).........(2)$$

Now, from equation (1) & (2), it can be rewritten as,

$$NI = KVR_L$$

$$\Rightarrow \frac{V}{I} = \frac{N}{KR_L}$$

$$\Rightarrow Z = \frac{N}{KR_L}$$

$$\Rightarrow Z \propto \frac{1}{R_L}$$

From this above mathematical expression it is found that, impedance is inversely proportional to reluctance. The impedance offered by the return path of unbalanced load current is very high where very low reluctance return path is provided for unbalanced flux.

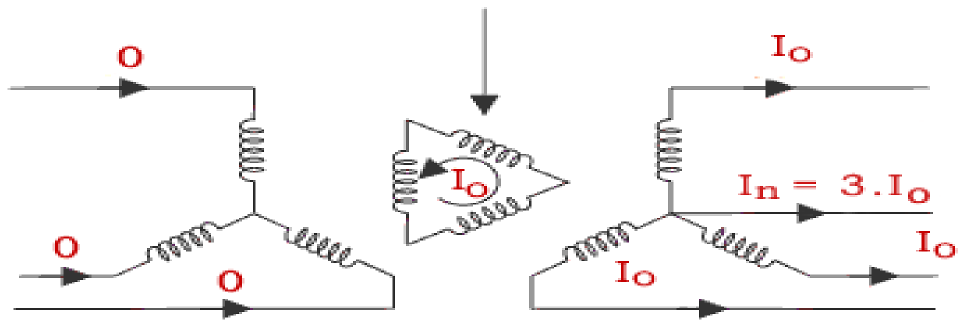


Diagram of Three Winding Transformer

In other words, very high impedance to the flow of unbalanced current in 3 phase system is offered between line and neutral. Any unbalanced current in three phase system can be divided into three sets of components likewise positive sequence, negative sequence and zero sequence components. The zero sequence current is actually co-phasial current in three lines. If value of co-phasial current in each line is Io, then total current flows through the neutral of secondary side of transformer is In = 3.Io. This current cannot be balanced by primary current as the zero sequence current cannot flow through the isolated neutral star connected primary. Hence the said current in the secondary side set up a magnetic flux in the core. As we discussed earlier in this chapter, low reluctance path is available for the zero sequence flux in a bank of single phase units and in the 5 limb core consequently; the impedance offered to the zero sequence current is very high. The delta connected tertiary winding of transformer permits the circulation of zero sequence current in it. This circulating current in this delta winding balances the zero sequence component of unbalance load, hence prevents unnecessary development of unbalance zero sequence flux in the transformer core. In few words it can be said that, placement of tertiary winding in star - star-neutral transformer considerably reduces the zero sequence impedance of transformer.

Rating of Tertiary Winding of Transformer

Rating of tertiary winding of transformer depends upon its use. If it has to supply additional load, its winding cross - section and design philosophy is decided as per load, and three phase dead short circuit on its terminal with power flow from both sides of HV & MV. In case it is to be provided for stabilizing purpose only, its cross - section and design has to be decided from thermal and mechanical consideration for the short duration fault currents during various fault conditions single line -to-ground fault being the most onerous.

Harmonics

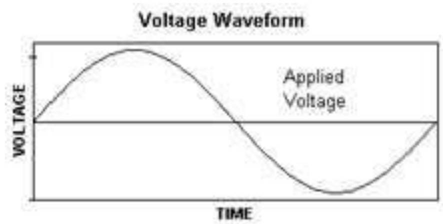
Harmonics are sinusoidal voltages or currents having frequencies that are whole multiples of the frequency at which the supply system is designed to operate (e.g. 50Hz or 60 Hz).

Harmonics are simply a technique to analyze the current drawn by computers, electronic ballasts, variable frequency drives and other equipment which have modem “transformer-less” power supplies.

There are two important concepts to bear in mind with regard to power system harmonics.

The first is the nature of harmonic-current producing loads (non-linear loads) and the second is the way in which harmonic currents flow and how the resulting harmonic voltages develop.

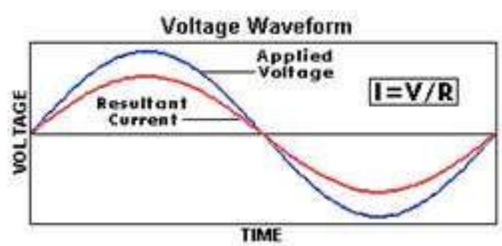
There is a law in electrical engineering called Ohm's Law. This basic law states that when a voltage is applied across a resistance, current will flow. This is how all electrical equipment operates. The voltage we apply across our equipment is a sine wave which operates 60 Hertz (cycles per second).



To generate this voltage sine wave. It has (relatively) constant amplitude and constant frequency.

Once this voltage is applied to a device, Ohm's Law kicks in. Ohm's Law states that current equal's voltage divided by resistance. Expressed mathematically I=V/R

Expressed graphically, the current ends up being another sine wave, since the resistance is a constant number. Ohm's Law dictates that the frequency of the current wave is also 60 Hertz. In the real world, this is true; although the two sine waves may not align perfectly (as a power factor) the current wave will indeed be a 60 Hertz sine wave.



Since an applied voltage sine wave will cause a sinusoidal current to be drawn, systems which exhibit this behaviour are called linear systems. Incandescent lamps, heaters and motors are linear systems.

Some of our modem equipment however does not fit this category. Computers, variable frequency drives, electronic ballasts and uninterruptable power supply systems are non-linear systems. In these systems, the resistance is not a constant and in fact, varies during each sine wave. This occurs because the resistance of the device is not a constant. The resistance in fact, changes during each sine wave

Linear and non-linear loads (motors, heaters and incandescent lamps):

A linear element in a power system is a component in which the current is proportional to the voltage.

In general, this means that the current wave shape will be the same as the voltage (See Figure 1). Typical examples of linear loads include motors, heaters and incandescent lamps.

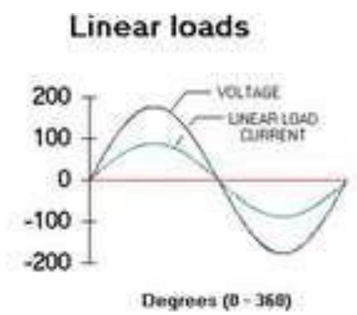


Figure 1. Voltage and current waveforms for linear

Non-Linear System (Computers, VFDS, Electronic Ballasts):

As in Figure As we apply a voltage to a solid state power supply, the current drawn is (approximately) zero until a critical "firing voltage" is reached on the sine wave. At this firing voltage, the transistor (or other device) gates or allows current to be conducted.

This current typically increases over time until the peak of the sine wave and decreases until the critical firing voltage is reached on the "downward side" of the sine wave. The device then shuts off and current goes to zero. The same thing occurs on the negative side of the sine wave with a second negative pulse of current being drawn. The current drawn then is a series of positive and negative pulses, and not the sine wave drawn by linear systems.

Some systems have different shaped waveforms such as square waves. These types of systems are often called non-linear systems. The power supplies which draw this type of current are called switched mode power supplies. Once these pulse currents are formed, we have a difficult time analyzing their effect. Power engineers are taught to analyze the effects of sine waves on power systems. Analyzing the effects of these pulses is much more difficult.

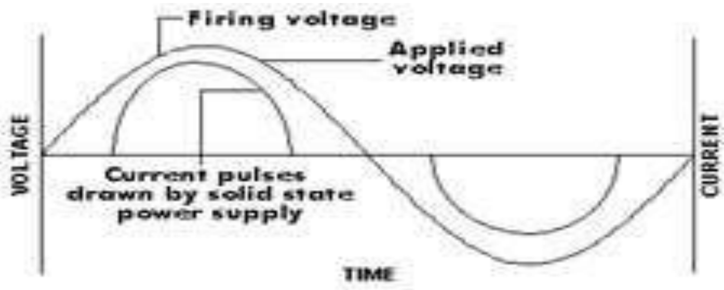


Figure 2. Voltage and current waveforms for linear

The current drawn by non-linear loads is not sinusoidal but it is periodic, meaning that the current wave looks the same from cycle to cycle. Periodic waveforms can be described mathematically as a series of sinusoidal waveforms that have been summed together.

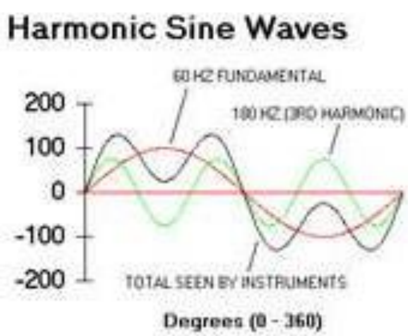


Figure 3. Waveform with symmetrical harmonic components

The sinusoidal components are integer multiples of the fundamental where the fundamental, in the United States, is 60 Hz. The only way to measure a voltage or current that contains harmonics is to use a true-RMS reading meter. If an averaging meter is used, which is the most common type, the error can be Significant.

Each term in the series is referred to as a harmonic of the fundamental. The third harmonic would have a frequency of three times 60 Hz or 180 Hz. Symmetrical waves contain only odd harmonics and un-symmetrical waves contain even and odd harmonics.

A symmetrical wave is one in which the positive portion of the wave is identical to the negative portion of the wave. An un-symmetrical wave contains a DC component (or offset) or the load is such that the positive portion of the wave is different than the negative portion. An example of un-symmetrical wave would be a half wave rectifier.

Most power system elements are symmetrical. They produce only odd harmonics and have no DC offset.

Harmonic current flow

When a non-linear load draws current that current passes through all of the impedance that is between the load and the system source (See Figure 4). As a result of the current flow, harmonic voltages are produced by impedance in the system for each harmonic.

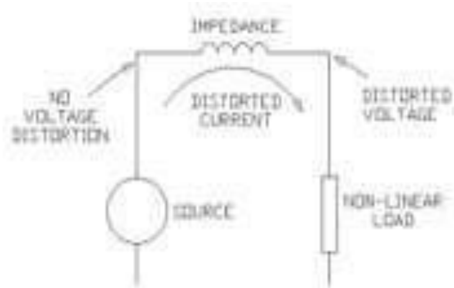


Figure 4 – Distorted-current induced voltage distortion

These voltages sum and when added to the nominal voltage produce voltage distortion. The magnitude of the voltage distortion depends on the source impedance and the harmonic voltages produced.

If the source impedance is low then the voltage distortion will be low. If a significant portion of the load becomes non-linear (harmonic currents increase) and/or when a resonant condition prevails (system impedance increases), the voltage can increase dramatically.

Harmonic currents can produce a number of problems:

Equipment heating

Equipment malfunction

Equipment failure

Communications interference

Fuse and breaker mis-operation

Process problems

Conductor heating.

How harmonics are generated

In an ideal clean power system, the current and voltage waveforms are pure sinusoids. In practice, non-sinusoidal currents are available due to result of the current flowing in the load is not linearly related to the applied voltage.

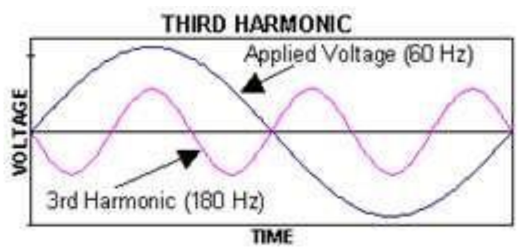
In a simple circuit containing only linear circuit elements resistance, inductance and capacitance. The current which flows is proportional to the applied voltage (at a particular frequency) so that, if a sinusoidal voltage is applied, a sinusoidal current will flow. Note that where there is a reactive element there will be a phase shift between the voltage and current waveforms the power factor is reduced, but the circuit can still be linear.

But in The situation where the load is a simple full-wave rectifier and capacitor, such as the input stage of a typical switched mode power supply (SMPS). In this case, current flows only when the supply voltage exceeds that stored on the reservoir capacitor, i.e. close to the peak of the voltage sine wave, as shown by the shape of the load line.

Any cyclical waveform can be de constructed into a sinusoid at the fundamental frequency plus a number of sinusoids at harmonic frequencies. Thus the distorted current waveform in the figure can be represented by the fundamental plus a percentage of second harmonic plus a percentage of third harmonic and so on, possibly up to the thirtieth harmonic.

For symmetrical waveforms, i.e. where the positive and negative half cycles are the same shape and magnitude, all the even numbered harmonics is zero. Even harmonics are now relatively rare but were common when half wave rectification was widely used.

The frequencies we use are multiples of the fundamental frequency, 60 Hz. We call these multiple frequencies harmonics. The second harmonic is two times 60 Hertz, or 120 Hz. The third harmonic is 180 Hertz and so on. In our three phase power systems, the “even” harmonics (second, fourth, sixth, etc.) cancel, so we only need deal with the “odd” harmonics.



This figure shows the fundamental and the third harmonic. There are three cycles of the third harmonic for each single cycle of the fundamental. If we add these two waveforms, we get a non-sinusoidal waveform.

This resultant now starts to form the peaks that are indicative of the pulses drawn by switch mode power supplies. If we add in other harmonics, we can model any distorted periodic waveform, such as square waves generated by UPS of VFD systems. It is important to remember these harmonics are simply a mathematical model. The pulses or square waves, or other distorted waveforms are what we actually see if we were to put an oscilloscope on the building’s wiring systems.

These current pulses, because of Ohm’s Law, will also begin to distort the voltage waveforms in the building. This voltage distortion can cause premature failure of electronic devices.

On three phase systems, the three phases of the power system are 120’ out of phase. The current on phase B occurs 120 deg (1/3 cycle) after the current on A. Likewise, the current on phase C occurs 120’ after the current on phase B. Because of this, our 60 Hertz (fundamental) currents actually cancel on the neutral. If we have balanced 60 Hertz currents on our three phase conductors, our neutral current will be zero. It can be shown mathematically that the neutral current (assuming only 60 Hertz is present) will never exceed the highest loaded phase conductor. Thus, our over current protection on our phase conductors also protects the neutral conductor, even though we do not put an over current protective device in the neutral conductor. We protect the neutral by the mathematics. When harmonic currents are present, this math breaks down. The third harmonic of each of the three phase conductors is exactly in phase. When these harmonic currents come together on the neutral, rather than cancel, they actually add and we can have more current on the neutral conductor than on phase conductors. Our neutral conductors are no longer protected by mathematics!

These harmonic currents create heat. This heat over a period of time will raise the temperature of the neutral conductor. This rise in temperature can overheat the surrounding conductors and cause insulation failure. These currents also will overheat the transformer sources which supply the power system. This is the most obvious symptom of harmonics problems; overheating neutral conductors and transformers. Other symptoms include:

Nuisance tripping of circuit breakers

Malfunction of UPS systems and generator systems

Metering problems

Computer malfunctions

Over voltage problems

Problems caused by harmonics

Harmonic currents cause problems both on the supply system and within the installation.

The effects and the solutions are very different and need to be addressed separately; the measures that are appropriate to controlling the effects of harmonics within the installation may not necessarily reduce the distortion caused on the supply and vice versa.

Harmonic problems within the installation

Problems caused by harmonic currents:

overloading of neutrals

overheating of transformers

nuisance tripping of circuit breakers

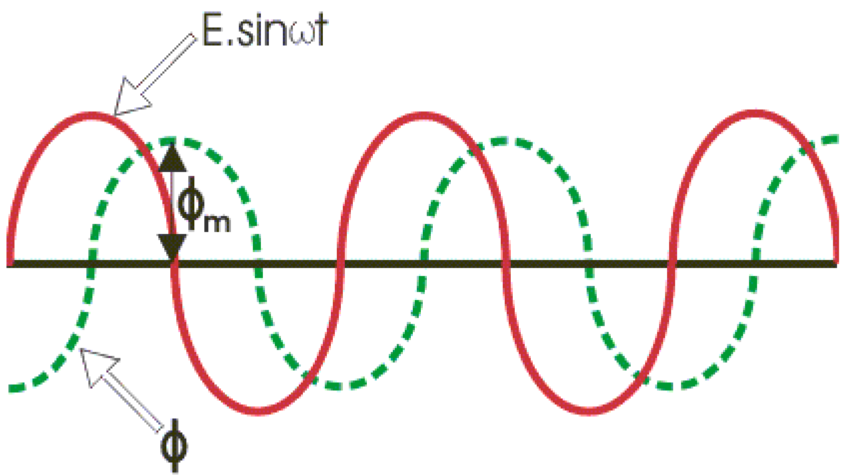
over-stressing of power factor correction capacitors

skin effect

Magnetizing Inrush Current in Power Transformer

When an electrical power transformer is switch on from primary side, with keeping its secondary circuit open, it acts as a simple inductance. When electrical power transformer runs normally, the flux produced in the core is in quadrature with applied voltage as shown in the figure below. That means, flux wave will reach its maximum value, 1/4 cycle or π/2 angle after, reaching maximum value of voltage wave. Hence as per the waves shown in the figure, at the instant when, the voltage is zero, the corresponding steady state value of flux should be negative maximum. But practically it is not possible to have flux at the instant of switching on the supply of transformer. This is because, there will be no flux linked to the core prior to switch on the supply. The steady state value of flux will only reach after a finite time, depending upon how fast the circuit can take energy. This is because the rate of energy transfer to a circuit cannot be infinity. So the flux in the core also will start from its zero value at the time of switching on the transformer.

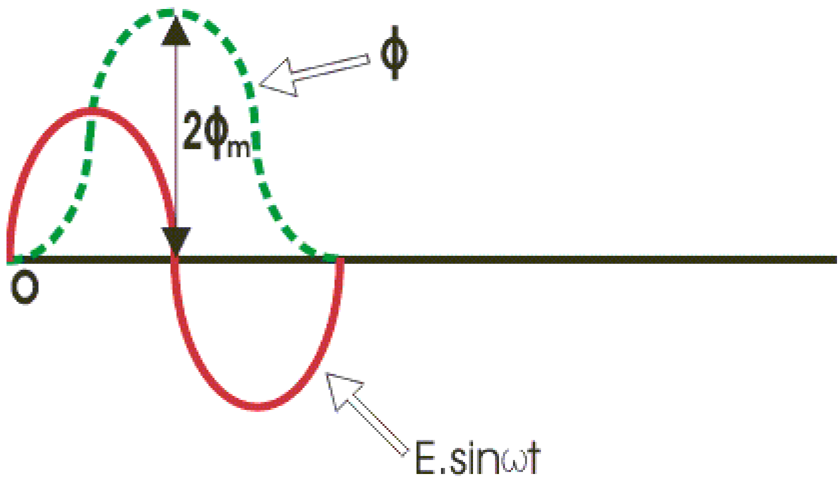
According to Faraday's law of electromagnetic induction the voltage induced across the winding is is given as e = dφ/dt. Where φ is the flux in the core. Hence the flux will bintegral of the voltage wave.



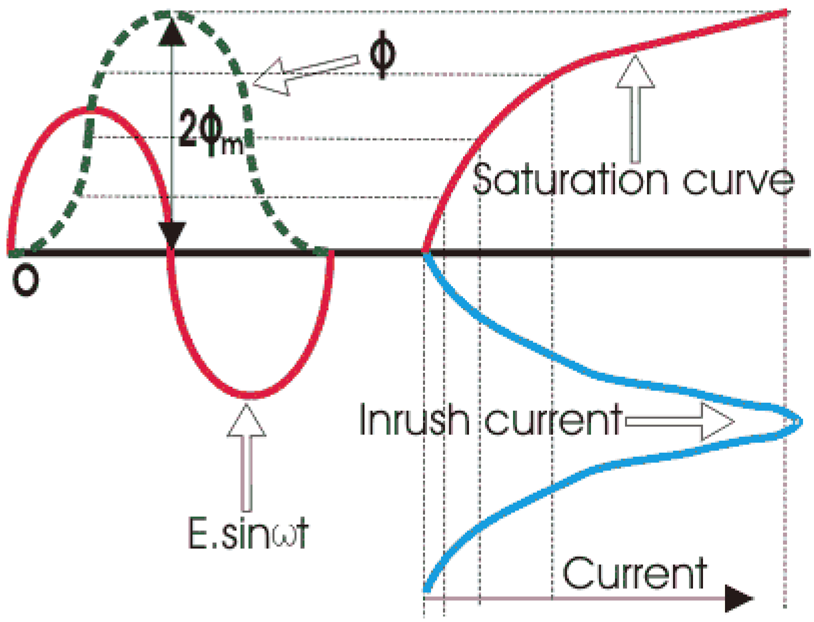
$$e = E.\sin\omega t = d\varphi/dt \Rightarrow \varphi = \int e.dt = E \int \sin\omega t.dt$$

If the transformer is switched on at the instant of voltage zero, the flux wave is initiated from the same origin as voltage waveform, the value of flux at the end of first half cycle of the voltage waveform will be,

$$\varphi_m' = (E/\omega) \int_0^\pi \omega.\sin\omega t.dt = \varphi_m \int_0^\pi \sin\omega t.d(\omega t) = 2\varphi_m$$



Where φm is the maximum value of steady state flux. The transformer core are generally saturated just above the maximum steady state value of flux. But in our example, during switching on the transformer the maximum value of flux will jump to double of its steady state maximum value. As, after steady state maximum value of flux, the core becomes saturated, the current required to produced rest of flux will be very high. So transformer primary will draw a very high peaky current from the source which is called magnetizing inrush current in transformer or simply inrush current in transformer.



Magnetizing inrush current in transformer is the current which is drown by a transformer at the time of energizing the transformer. This current is transient in nature and exists for few milliseconds. The inrush current may be up to 10 times higher than normal rated current of transformer.

Although the magnitude of inrush current is so high but it generally does not create any permanent fault in transformer as it exists for very small time. But still inrush current in power transformer is a problem, because it interferes with the operation of circuits as they have been designed to function. Some effects of high inrush include nuisance fuse or breaker interruptions, as well as arcing and failure of primary circuit components, such as switches. High magnetizing inrush current in transformer also necessitate over-sizing of fuses or breakers. Another side effect of high inrush is the injection of noise and distortion back into the mains.

DC Generator

Introduction:

An Electrical generator is a machine which converts mechanical energy (or power) into electrical energy (or power).

The energy conversion is based on the principal of the production of dynamically (or motionally) induced emf. Whenever a conductor cuts magnetic flux, dynamically induced emf is produced in it according to Faraday's Laws of Electromagnetic Induction. This Emf causes a current to flow if the conductor circuit is closed.

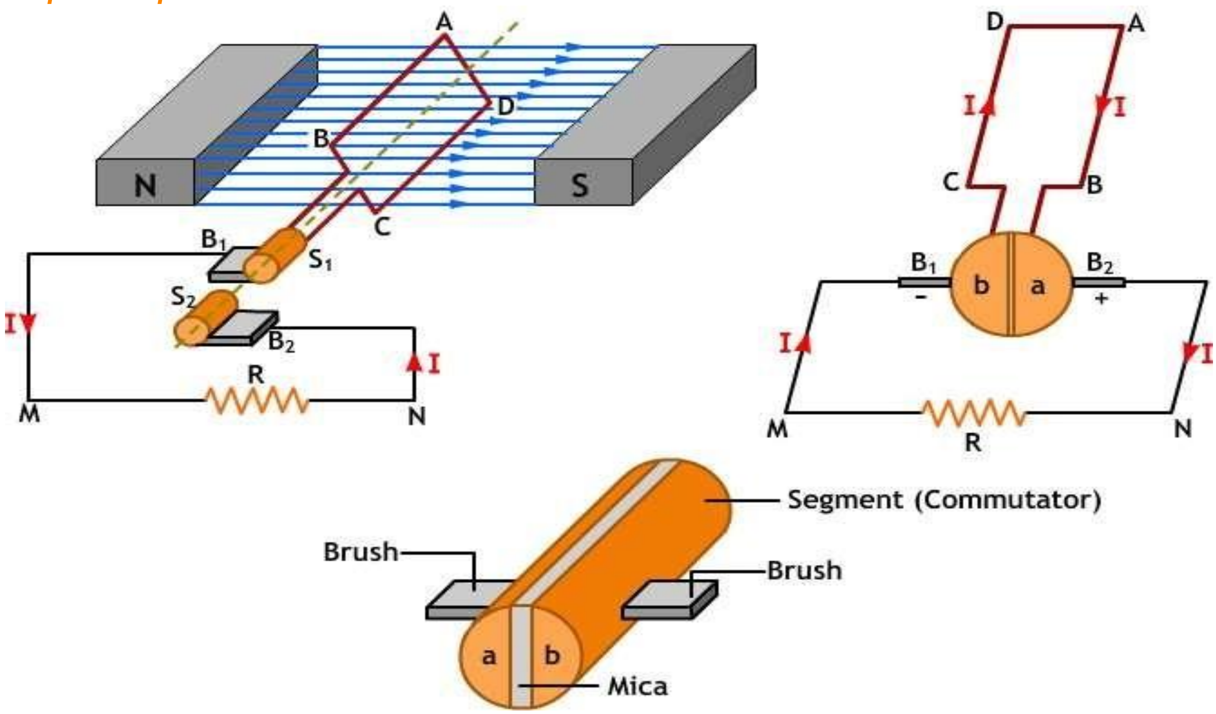
Hence, two basic essential parts of an electrical generator are

i) a magnetic field and
ii) a conductor or conductors which can so move as to cut the flux.

Principle of Operation:

D.C generator is a machine that converts **mechanical energy** into **DC electrical energy**. It works on the principle of dynamically induced emf viz., whenever a conductor cuts flux, an emf is induced in the conductor. The direction of the induced emf is given by Fleming's right hand rule.

Simple Loop Generator:

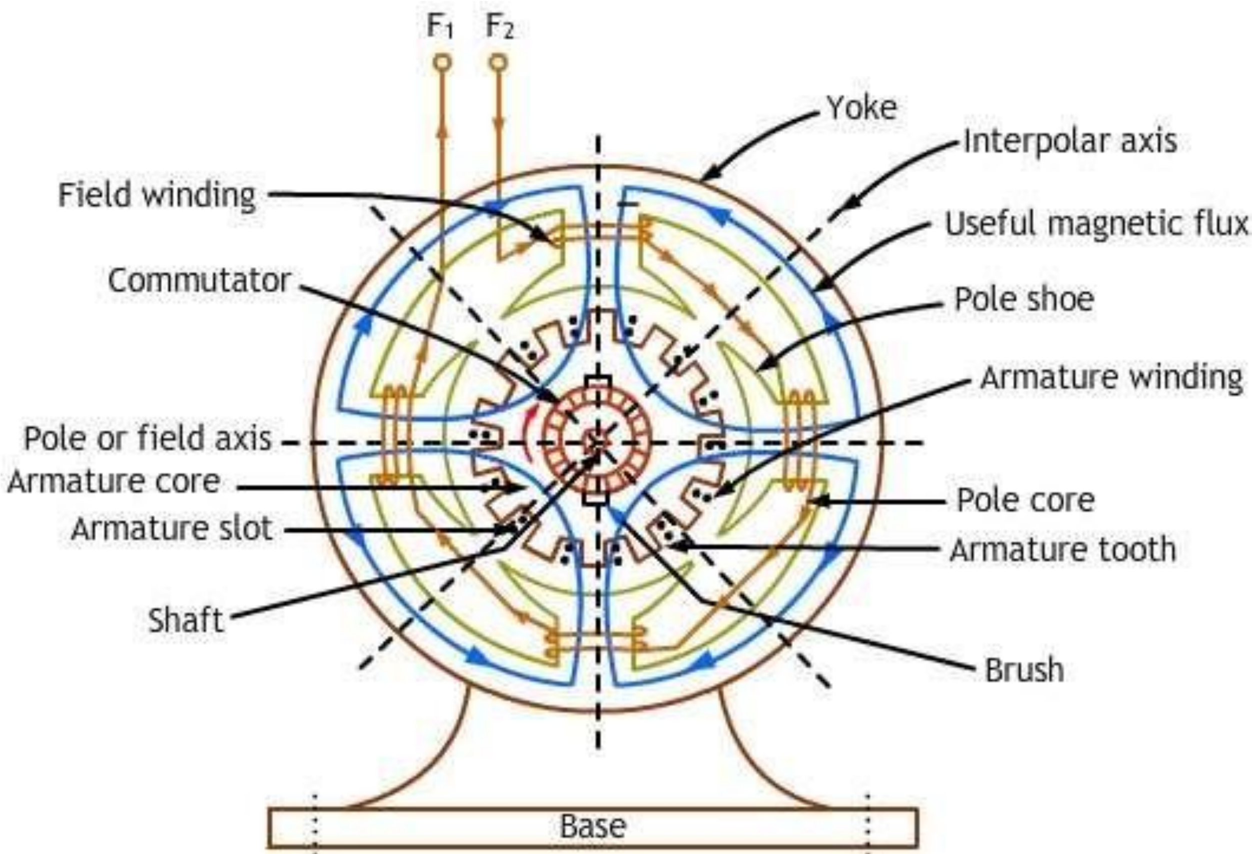


Consider rectangular coil ABCD with coil sides AB and CD being rotated in the magnetic field. The ends of the two coil sides are connected to two slip rings (S_1 and S_2). The two rings rotate along with the conductors. Two brushes (B_1 and B_2) make contact to these two slip rings to collect the current. When the coil starts rotating in anti-clockwise direction, conductor AB is under the influence of North pole and CD is under the influence of South pole. By Fleming's right hand rule, the direction of the current through the load resistance is from M to N.

After the coil rotates through 180^0, the conductor CD comes under the influence of North pole and the conductor AB under the influence of South pole. Hence, again emf is induced in the coil sides. As a result, the current flows through load resistance from N to M (reversed). This is shown in figure.

Note that, e.m.f generated in the loop is an alternating emf hence the current also. The alternating current in the load can be converted into direct current by commutator.

Practical DC Generator:



- The construction of DC generator and motor are same.
- DC generator can be run as a dc motor and vice versa.

A dc generator consists of

i) Field system (stationary)

ii) Armature (rotating)

iii) Armature is having the following parts

a) Armature core

b) Armature winding

c) Commutator

d) Brushes

e) Shaft and bearings

(i) Field system: The main function of the field system is to produce uniform magnetic field within which the armature rotates. It consists of

(a) Yoke (or frame): Yoke forms the outermost cover for the machine. Its functions are:

(i) Giving mechanical protection to the generator and

(ii) to provide path for the flux.

For small generators, yoke is made of cast iron; for large generators, it is made of silicon steel.

(b)Pole core, pole shoes and pole coils: The main poles are made of steel of high relative permeability. The pole core is made of thin laminations to reduce eddy current loss. The poles are fixed to the yoke with bolts and nuts.

The pole shoe performs the following functions.

(i) It supports the field winding.

(ii) It spreads out the flux uniformly in the air gap and also reduces the reluctance of the magnetic path.

The field coils (or field winding) are mounted on the poles and carry the d.c. exciting current.

The field coils are made of copper.

(ii) Armature Core: It is a cylindrical drum like structure made of thin laminations of silicon steel. Each lamination is insulated to reduce the eddy current loss. Silicon steel is used for the core to reduce hysteresis loss. For large machine (length>13cm) ventilating ducts are provided in the core for cooling purpose.

(iii) Armature Winding: The outer periphery of the armature is cut into number of slots to hold insulated conductor called armature winding.

There are two types of windings:

a) Lap winding

b) Wave winding

(iv) Commutator: The function of the commutator is to convert, alternating current to direct current. The commutator is made up of hard drawn copper segments insulated from each other by mica sheets and mounted on the shaft.

(v) Brushes: The function of brushes is to collect the direct current from the commutator segments and supply it to the external circuit. The brushes are made of carbon. Carbon is having negative temperature coefficient and is very soft.

(vi) Shaft and Bearings: For small generators, ball bearings are used. For large rating generators, roller bearings are used.

E.M.F Equation of DC Generator:

Let, ϕ = Flux / pole in webers

$\Rightarrow$ Change in flux $d\phi = \phi P$ webers

Z = Total number armature conductors

= Number of slots x Number of conductors per slot

P = Number of poles

A = Number of parallel paths in the armature.

N = Rotational speed of armature in revolutions per minute (r.p.m)

$\Rightarrow$ Time taken to complete one revolution = 60/N sec.

E = e.m.f induced / parallel path in armature.

Generated e.m.f E_g = e.m.f generated /parallel path

By Faraday's Law ,

$$\text{E.M.F generated per conductor} = \frac{d\phi}{dt} = \frac{\phi PN}{60} \text{ volts}$$

$$\text{Number of armature conductors per parallel path} = \frac{Z}{A}$$

$$E_g = \text{e.m.f generated per conductor} \times \text{Number of conductors in each parallel path}$$

$$E_g = \left(\frac{\phi PN}{60}\right) \times \frac{Z}{A} \text{ volts} \quad \text{........(i)}$$

For a Simplex Wave-Wound Generator

Number of parallel paths A = 2

$$E_g = \frac{\phi PN \cdot \left(\frac{Z}{2}\right)}{60} = \frac{\phi ZPN}{120} \text{ volts}$$

For Simplex Lap-Wound Generator:

Number of parallel paths, A = P

Equation (i) becomes

$$E_g = \frac{\phi PN \cdot \left(\frac{Z}{P}\right)}{60} = \frac{\phi ZN}{60} \text{ volts}$$

Armature Reaction

The current flowing through armature conductors also creates a magnetic flux (called armature flux) that distorts and weakens the flux coming from the poles. This distortion and field weakening takes place in both generators and motors. The action of armature flux on the main flux is known as armature reaction.The phenomenon of armature reaction in a d.c. generator is shown in Fig. Only one pole is shown for clarity. When the generator is on no-load, a smal1 current flowing in the armature does not appreciably affect the main flux 1coming from the pole [See Fig 2.1 (i)]. When the generator is loaded, the current flowing through armature conductors sets up flux 1. Fig. (2.1) (ii) shows flux due to armature current alone. By superimposing 1 and 2, we obtain the resulting flux 3 as shown in Fig. (2.1) (iii). Referring to Fig (2.1) (iii), it is clear that flux density at; the trailing pole tip (point B) is increased while at the leading pole tip (point A) it is decreased. This unequal field distribution produces the following two effects:

(i) The main flux is distorted.

(ii) Due to higher flux density at pole tip B, saturation sets in.

Consequently, the increase in flux at pole tip B is less than the decrease in flux under pole tip A. Flux 3 at full load is, therefore, less than flux 1 at no load. As we shall see, the weakening of flux due to armature reaction depends upon the position of brushes.

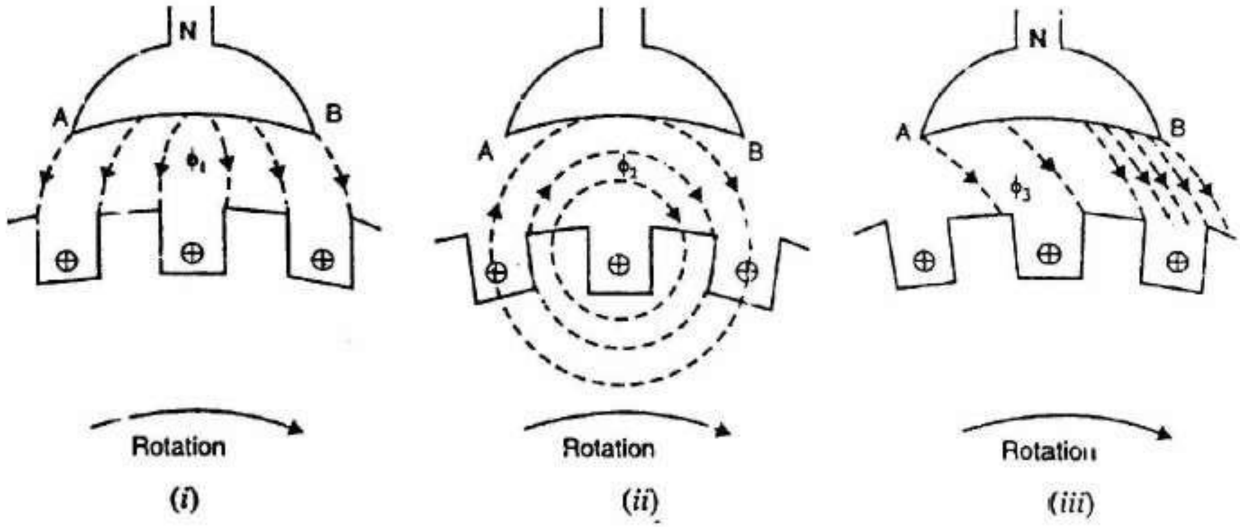


Fig:2.1

Geometrical and Magnetic Neutral Axes

(i) The geometrical neutral axis (G.N.A.) is the axis that bisects the angle between the centre line of adjacent poles [See Fig. 2.2 (i)]. Clearly, it is the axis of symmetry between two adjacent poles.

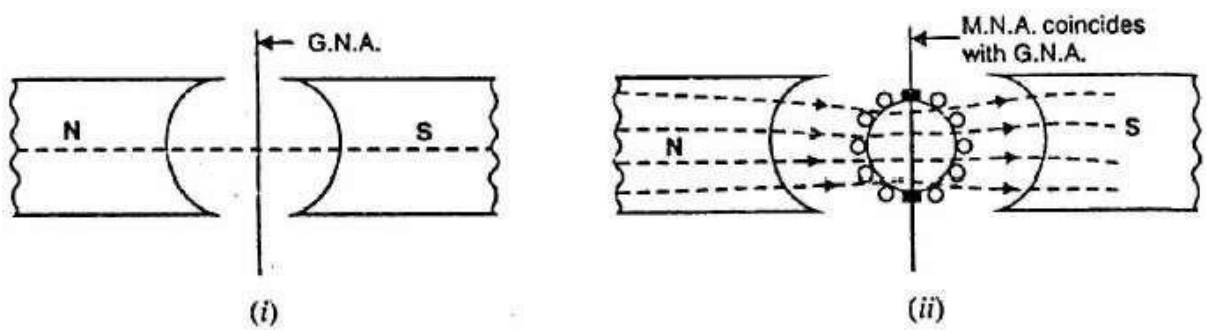


Fig:2.2

(ii) The magnetic neutral axis (M. N. A.) is the axis drawn perpendicular to the mean direction of the flux passing through the centre of the armature. Clearly, no e.m.f. is produced in the armature conductors along this axis because then they cut no flux. With no current in the armature conductors, the M.N.A. coincides with G, N. A. as shown in Fig. (2.2).

(iii). In order to achieve sparkless commutation, the brushes must lie along M.N.A.

Explanation of Armature Reaction

With no current in armature conductors, the M.N.A. coincides with G.N.A. However, when current flows in armature conductors, the combined action of main flux and armature flux shifts the M.N.A. from G.N.A. In case of a generator, the M.N.A. is shifted in the direction of rotation of the machine. In order to achieve sparkless commutation, the brushes have to be moved along the new M.N.A. Under such a condition, the armature reaction produces the following two effects:

1. It demagnetizes or weakens the main flux.

2. It cross-magnetizes or distorts the main flux.

Let us discuss these effects of armature reaction by considering a 2-pole generator (though the following remarks also hold good for a multipolar generator).

i) Fig. (2.3) (i) shows the flux due to main poles (main flux) when the armature conductors carry no current. The flux across the air gap is uniform. The m.m.f. producing the main flux is represented in magnitude and direction by the vector OFm in Fig. (2.3) (i). Note that OFm is perpendicular to G.N.A.

ii) (ii) Fig. (2.3) (ii) shows the flux due to current flowing in armature conductors alone (main poles unexcited). The armature conductors to the left of G.N.A. carry current “in” (´) and those to the right carry current “out” (•). The direction of magnetic lines of force can be found by cork screw rule. It is clear that armature flux is directed downward parallel to the brush axis. The m.m.f. producing the armature flux is represented in magnitude and direction by the vector OFA in Fig. (2.3) (ii).

(iii) Fig. (2.3) (iii) shows the flux due to the main poles and that due to current in armature conductors acting together. The resultant m.m.f. OF is the vector sum of OFm and OFA as shown in Fig. (2.3) (iii). Since M.N.A. is always perpendicular to the resultant m.m.f., the M.N.A. is shifted through an angle q. Note that M.N.A. is shifted in the direction of rotation of the generator.

(iii) In order to achieve sparkless commutation, the brushes must lie along the M.N.A. Consequently, the brushes are shifted through an angle q so as to lie along the new M.N.A. as shown in Fig. (2.3)

(iv) (iv). Due to brush shift, the m.m.f. FA of the armature is also rotated through the same angle q. It is because some of the conductors which were earlier under N-pole now come under S-pole and vice-versa. The result is that armature m.m.f. FA will no longer be vertically downward but will be rotated in the direction of rotation through an angle q as shown in Fig.

(a) The component Fd is in direct opposition to the m.m.f. OFm due to main poles. It has a demagnetizing effect on the flux due to main poles. For this reason, it is called the demagnetizing or weakening component of armature reaction.

(b) The component Fc is at right angles to the m.m.f. OFm due to main poles. It distorts the main field. For this reason, it is called the cross magnetizing or distorting component of armature reaction.

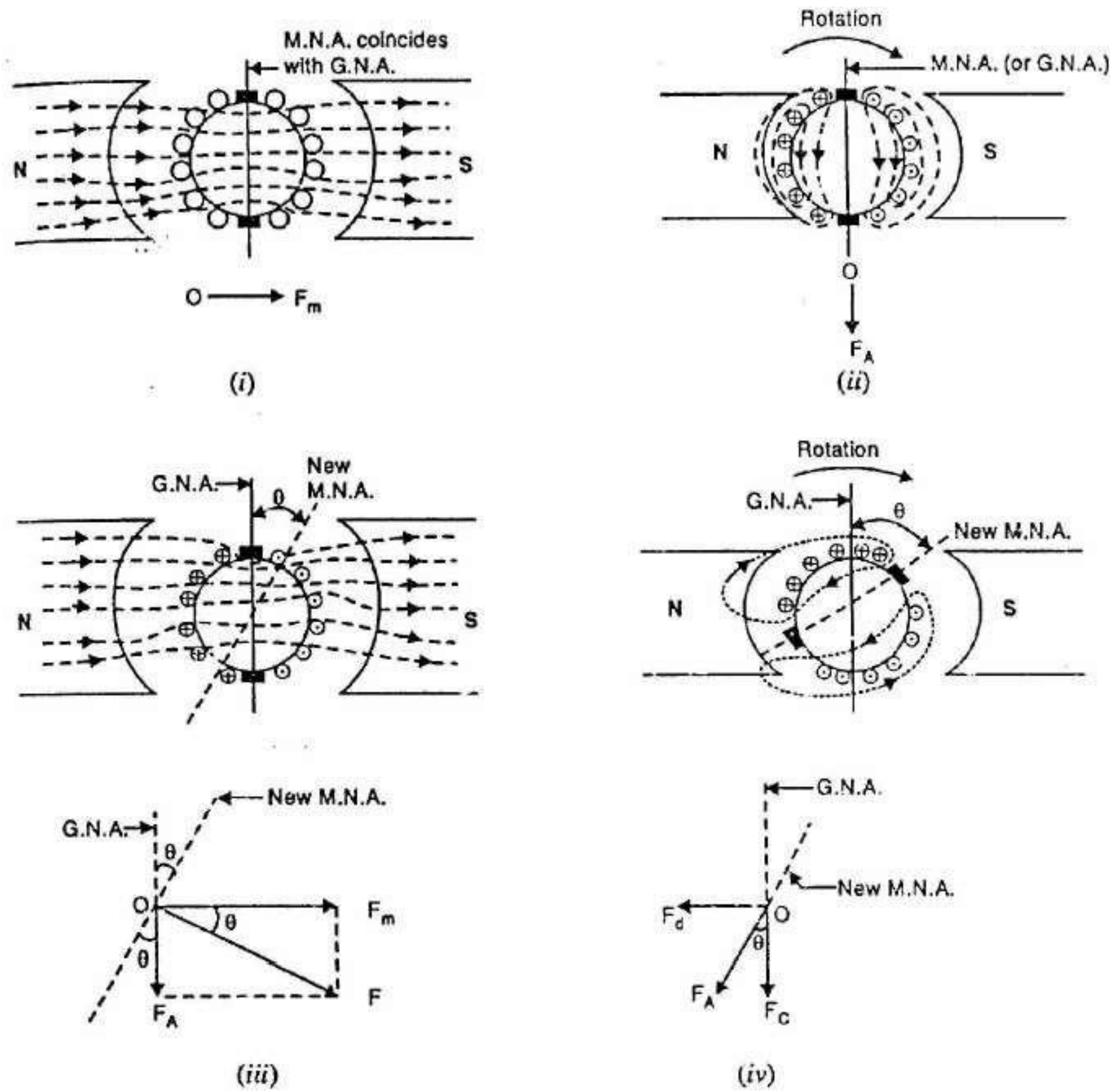


Fig:2.3

Demagnetizing and Cross-Magnetizing Conductors

With the brushes in the G.N.A. position, there is only cross-magnetizing effect of armature reaction. However, when the brushes are shifted from the G.N.A. position, the armature reaction will have both demagnetizing and crossmagnetizing effects. Consider a 2-

pole generator with brushes shifted (lead) qm mechanical degrees from G.N.A. We shall identify the armature conductors that produce demagnetizing effect and those that produce cross-magnetizing effect.

(i) The armature conductors oqm on either side of G.N.A. produce flux in direct opposition to main flux as shown in Fig. (2.4) (i). Thus theconductors lying within angles AOC = BOD = 2qm at the top and bottom ofthe armature produce demagnetizing effect. These are called demagnetizing armature conductors and constitute the demagnetizing ampere-turns of armature reaction (Remember two conductors constitute a turn).

(ii) The axis of magnetization of the remaining armature conductors lying between angles AOD and COB is at right angles to the main flux as shown in Fig. (2.4) (ii). These conductors produce the cross-magnetizing (or distorting) effect i.e., they produce uneven flux distribution on each pole. Therefore, they are called cross-magnetizing conductors and constitute the cross-magnetizing ampere-turns of armature reaction.

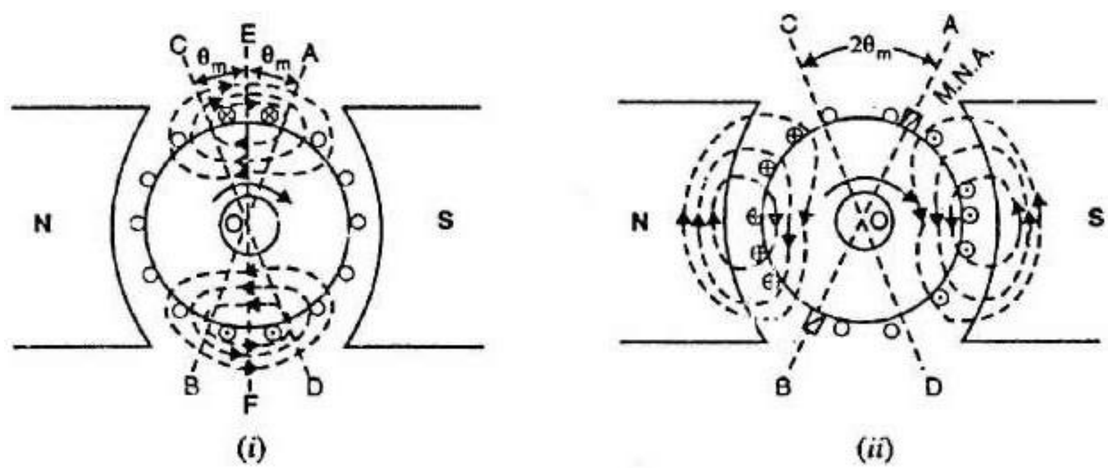


Fig:2.4

Calculation of Demagnetizing Ampere-Turns Per Pole (ATd/Pole)

It is sometimes desirable to neutralize the demagnetizing ampere-turns of armature reaction. This is achieved by adding extra ampere-turns to the main field winding. We shall now calculate the demagnetizing ampere-turns per pole (ATd/pole).

Let Z = total number of armature conductors
I = current in each armature conductor
$= I_a/2$ ... for simplex wave winding
$= I_a/P$ ... for simplex lap winding
θ_m = forward lead in mechanical degrees

Referring to Fig. (2.4) (i) above, we have,
Total demagnetizing armature conductors

$$= \text{Conductors in angles AOC and BOD} = \frac{4\theta_m}{360} \times Z$$

Since two conductors constitute one turn,

$$\therefore \quad \text{Total demagnetizing ampere-turns} = \frac{1}{2}\left[\frac{4\theta_m}{360} \times Z\right] \times I = \frac{2\theta_m}{360} \times ZI$$

These demagnetizing ampere-turns are due to a pair of poles.

$$\therefore \quad \text{Demagnetizing ampere-turns/pole} = \frac{\theta_m}{360} \times ZI$$

i.e.,

$$AT_d\,/\,\text{pole} = \frac{\theta_m}{360} \times ZI$$

As mentioned above, the demagnetizing ampere-turns of armature reaction can be neutralized by putting extra turns on each pole of the generator.

$$\therefore \quad \text{No. of extra turns/pole} = \frac{AT_d}{I_{sh}} \quad \text{for a shunt generator}$$

$$= \frac{AT_d}{I_a} \quad \text{for a series generator}$$

Cross-Magnetizing Ampere-Turns Per Pole (ATc/Pole)

We now calculate the cross-magnetizing ampere-turns per pole (ATc/pole).

Total armature reaction ampere-turns per pole

$$= \frac{Z/2}{P} \times I = \frac{Z}{2P} \times I \qquad (\because \text{ two conductors make one turn})$$

Demagnetizing ampere-turns per pole is given by;

$$AT_d / \text{pole} = \frac{\theta_m}{360} \times ZI$$

□□Cross-magnetizing ampere-turns/pole are

$$AT_d / \text{pole} = \frac{Z}{2P} \times I - \frac{\theta_m}{360} \times ZI = ZI\left(\frac{1}{2P} - \frac{\theta_m}{360}\right)$$

$$\therefore \qquad AT_d / \text{pole} = ZI\left(\frac{1}{2P} - \frac{\theta_m}{360}\right)$$

Commutation:

Fig. (2.5) shows the schematic diagram of 2-pole lap-wound generator. There are two parallel paths between the brushes. Therefore, each coil of the winding carries one half (Ia/2 in this case) of the total current (Ia) entering or leaving the armature.

Note that the currents in the coils connected to a brush are either all towards the brush (positive brush) or all directed away from the brush (negative brush). Therefore, current in a coil will reverse as the coil passes a brush. This reversal of current as the coil passes & brush is called commutation. The reversal of current in a coil as the coil passes the brush axis is called commutation.

When commutation takes place, the coil undergoing commutation is short circuited by the brush. The brief period during which the coil remains short circuited is known as commutation period Tc. If the current reversal is completed by the end of commutation period, it is called ideal commutation. If the current reversal is not completed by that time, then sparking occurs between the brush and the commutator which results in progressive damage to both.

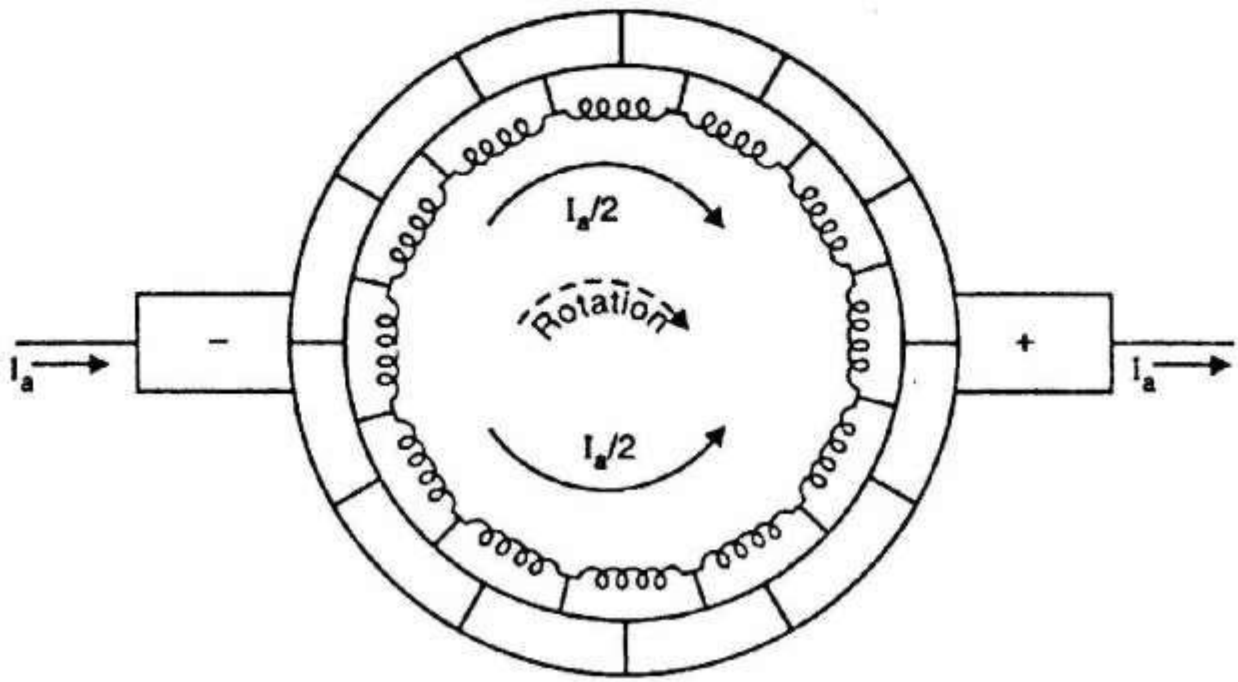


Fig:2.5

Ideal commutation

Let us discuss the phenomenon of ideal commutation (i.e., coil has no inductance) in one coil in the armature winding shown in Fig. (2.6) above. For this purpose, we consider the coil A. The brush width is equal to the width of one commutator segment and one mica insulation. Suppose the total armature current is 40 A. Since there are two parallel paths, each coil carries a current of 20 A.

(i) In Fig. (2.7) (i), the brush is in contact with segment 1 of the commutator. The commutator segment 1 conducts a current of 40 A to the brush; 20 A from coil A and 20 A from the adjacent coil as shown. The coil A has yet to undergo commutation

(ii) As the armature rotates, the brush will make contact with segment 2 and thus short-circuits the coil A as shown in Fig. (2.7) (ii). There are now two parallel paths into the brush as long as the short-circuit of coil A exists. Fig. (2.7) (ii) shows the instant when the brush is one-fourth on segment 2 and three-fourth on segment 1. For this condition, the resistance of the path through segment 2 is three times the resistance of the path through segment 1 (Q contact resistance varies inversely as the area of contact of brush with the segment). The brush again conducts a current of 40 A; 30 A through segment 1 and 10 A through segment 2. Note that current in coil A (the coil undergoing commutation) is reduced from 20 A to 10 A.

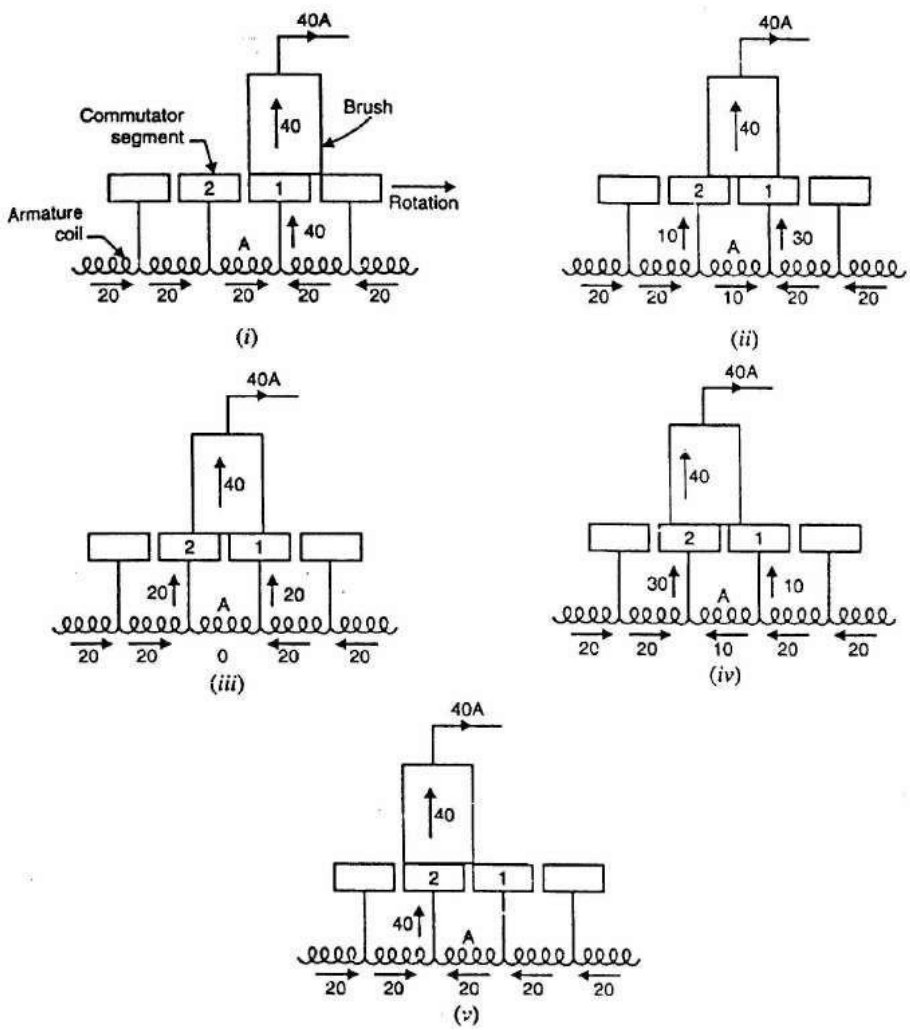


Fig :2.7

(iii) Fig. (2.7) (iii) shows the instant when the brush is one-half on segment 2 and one-half on segment 1. The brush again conducts 40 A; 20 A through segment 1 and 20 A through segment 2 (Q now the resistances of the two parallel paths are equal). Note that now. current in coil A is zero.

(iv) Fig. (2.7) (iv) shows the instant when the brush is three-fourth on segment 2 and one-fourth on segment 1. The brush conducts a current of 40 A; 30 A through segment 2 and 10 A through segment 1. Note that current in coil A is 10 A but in the reverse direction to that before the start of commutation. The reader may see the action of the commutator in reversing the current in a coil as the coil passes the brush axis.

(v) Fig. (2.7) (v) shows the instant when the brush is in contact only with segment 2. The brush again conducts 40 A; 20 A from coil A and 20 A from the adjacent coil to coil A. Note that now current in coil A is 20 A but in the reverse direction. Thus the coil A has undergone commutation. Each coil undergoes commutation in this way as it passes the brush axis. Note that during commutation, the coil under consideration remains short circuited by the brush. Fig. (2.8) shows the current-time graph for the coil A undergoing commutation. The horizontal line AB represents a constant current of 20 A upto the beginning of commutation. From the finish of commutation, it is represented by another horizontal line CD on the opposite side of the zero line and the same distance from it as AB i.e., the current has exactly reversed (- 20 A). The way in which current changes from B to C depends upon the conditions under which the coil undergoes commutation. If the current changes at a uniform rate (i.e., BC is a straight line), then it is called ideal commutation as shown in Fig. (2.8). under such conditions, no sparking will take place between the brush and the commutator

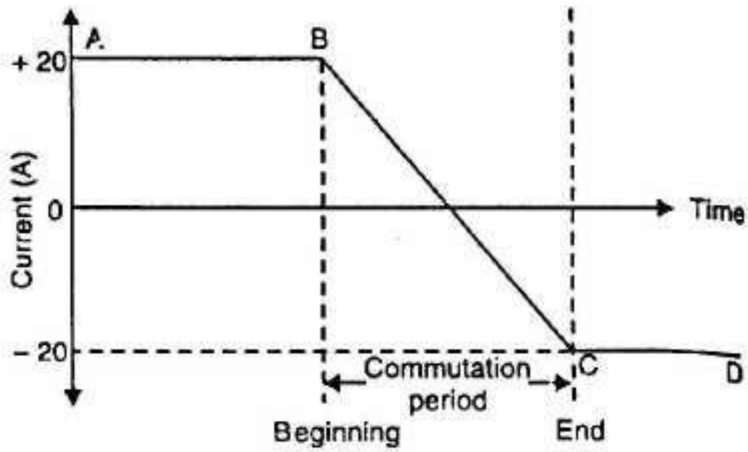


Fig:2.8

Practical difficulties

The ideal commutation (i.e., straight line change of current) cannot be attained in practice. This is mainly due to the fact that the armature coils have appreciable inductance. When the current in the coil undergoing commutation changes, self-induced e.m.f. is produced in the coil. This is generally called reactance voltage. This reactance voltage opposes the change of current in the coil undergoing commutation. The result is that the change of current in the coil undergoing commutation occurs more slowly than it would be under ideal commutation. This is illustrated in Fig. (2.9). The straight line RC represents the ideal commutation whereas the curve BE represents the change in current when self-inductance of the coil is taken into account. Note that current CE (= 8A in Fig. 2.9) is flowing from the commutator segment 1 to the brush at the instant when they part company. This results in sparking just as when any other current carrying circuit is broken. The sparking results in overheating of commutator brush contact and causing damage to both. Fig. (2.10) illustrates how sparking takes place between the commutator segment and the brush. At the end of commutation or short-circuit period, the

current in coil A is reversed to a value of 12 A (instead of 20 A) due to inductance of the coil. When the brush breaks contact with segment 1, the remaining 8 A current jumps from segment 1 to the brush through air causing sparking between segment 1 and the brush.

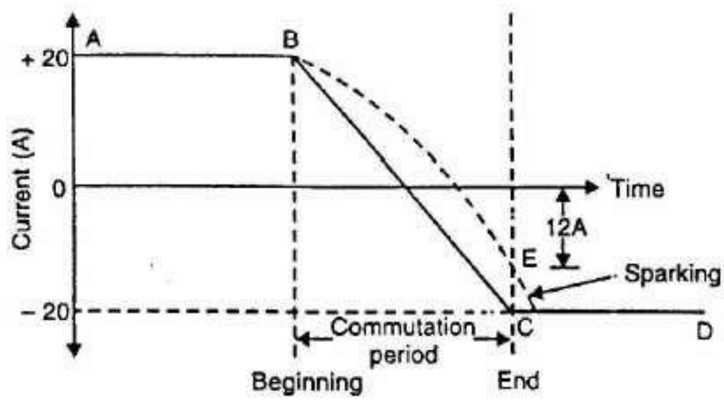


Fig. (2.9)

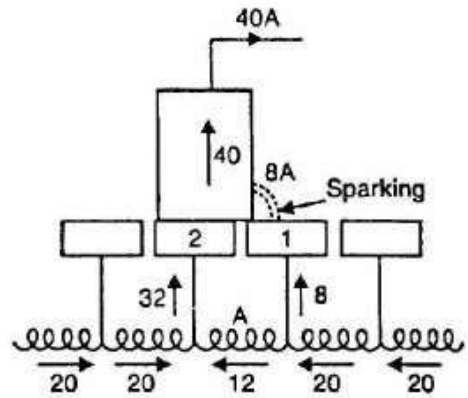


Fig. (2.10)

Methods of Improving Commutation

Improving commutation means to make current reversal in the short-circuited coil as sparkless as possible. The following are the two principal methods of improving commutation:

(i) Resistance commutation

(ii) E.M.F. commutation

Resistance Commutation

The reversal of current in a coil (i.e., commutation) takes place while the coil is short-circuited by the brush. Therefore, there are two parallel paths for the current as long as the short circuit exists. If the contact resistance between the brush and the commutator is made large, then current would divide in the inverse ratio of contact resistances (as for any two resistances in parallel). This is the key point in improving commutation. This is achieved by using carbon brushes (instead of Cu brushes) which have high contact resistance. This method of improving commutation is called resistance commutation. Figs. (2.11) and (2.12) illustrates how high contact resistance of carbon brush improves commutation (i.e., reversal of current) in coil A. In Fig. (2.11) (i), the brush is entirely on segment 1 and, therefore, the current in coil A is 20 A. The coil A is yet to undergo commutation. As the armature rotates, the brush short circuits the coil A and there are two parallel paths for the current into the brush. Fig. (2.11) (ii) shows the instant when the brush is one-fourth on segment 2 and three-fourth on segment 1. The equivalent electric circuit is shown in Fig. (2.11) (iii) where R1 and R2 represent the brush contact resistances on segments 1 and 2. A resistor is not shown for coil A since it is assumed that the coil resistance is negligible as compared to the brush contact resistance. The values of current in the parallel paths of the equivalent circuit are determined by the respective resistances of the paths. For the condition shown in Fig. (2.11) (ii), resistor R2 has three times the resistance of resistor R1. Therefore, the current distribution in the paths will be as shown. Note that current in coil A is reduced from 20 A to 10 A due to division of current in (he inverse ratio of contact resistances. If the Cu brush is used (which has low contact resistance), R1 R2 and the current in coil A would not have reduced to 10 A.

E.M.F. Commutation

In this method, an arrangement is made to neutralize the reactance voltage by producing a reversing voltage in the coil undergoing commutation. The reversing voltage acts in opposition to the reactance voltage and neutralizes it to some extent. If the reversing voltage is equal to the reactance voltage, the effect of the latter is completely wiped out and we get sparkless commutation. The reversing voltage may be produced in the following two ways:

(i) By brush shifting

(ii) By using interpoles or compoles

(i) By brush shifting

In this method, the brushes are given sufficient forward lead (for a generator) to bring the short-circuited coil (i.e., coil undergoing commutation) under the influence of the next pole of opposite polarity. Since the short-circuited coil is now in the reversing field, the reversing voltage produced cancels the reactance voltage. This method suffers from the following drawbacks:

(a) The reactance voltage depends upon armature current. Therefore, the brush shift will depend on the magnitude of armature current which keeps on changing. This necessitates frequent shifting of brushes.

(b) The greater the armature current, the greater must be the forward lead for a generator. This increases the demagnetizing effect of armature reaction and further weakens the main field.

(ii) By using interpoles or compotes

The best method of neutralizing reactance voltage is by, using interpoles or compoles.

Generator types & Characteristics

D.C generators may be classified as

(i) separately excited generator,

(ii) shunt generator,

(iii) series generator and

(iv) compound generator.

In a separately excited generator field winding is energised from a separate voltage source in order to produce flux in the machine. So long the machine operates in unsaturated condition the flux produced will be proportional to the field current. In order to implement shunt connection, the field winding is connected in parallel with the armature. It will be shown that subject to fulfillment of certain conditions, the machine may have sufficient field current developed on its own by virtue of its shunt connection. In series d.c machine, there is one field winding wound over the main poles with fewer turns and large cross sectional area. Series winding is meant to be connected in series with the armature and naturally to be designed for rated armature current. Obviously there will be practically no voltage or very small voltage due to residual field under no load condition ($I_a = 0$). However, field gets strengthened as load will develop rated voltage across the armature with reverse polarity, is connected and terminal voltage increases. Variation in load resistance causes the terminal voltage to vary. Terminal voltage will start falling, when saturation sets in and armature reaction effect becomes pronounced at large load current. Hence, series generators are not used for delivering power at constant voltage. Series generator found application in boosting up voltage in d.c transmission system.

A compound generator has two separate field coils wound over the field poles. The coil having large number of turns and thinner cross sectional area is called the *shunt field coil* and the other coil having few numbers of turns and large cross sectional area is called the *series field coil*. Series coil is generally connected in series with the armature while the shunt field coil is connected in parallel with the armature. If series coil is left alone without any connection, then it becomes a shunt machine with the other coil connected in parallel. Placement of field coils for shunt, series and compound generators are shown in figure 38.1. Will develop rated voltage across the armature with reverse polarity.

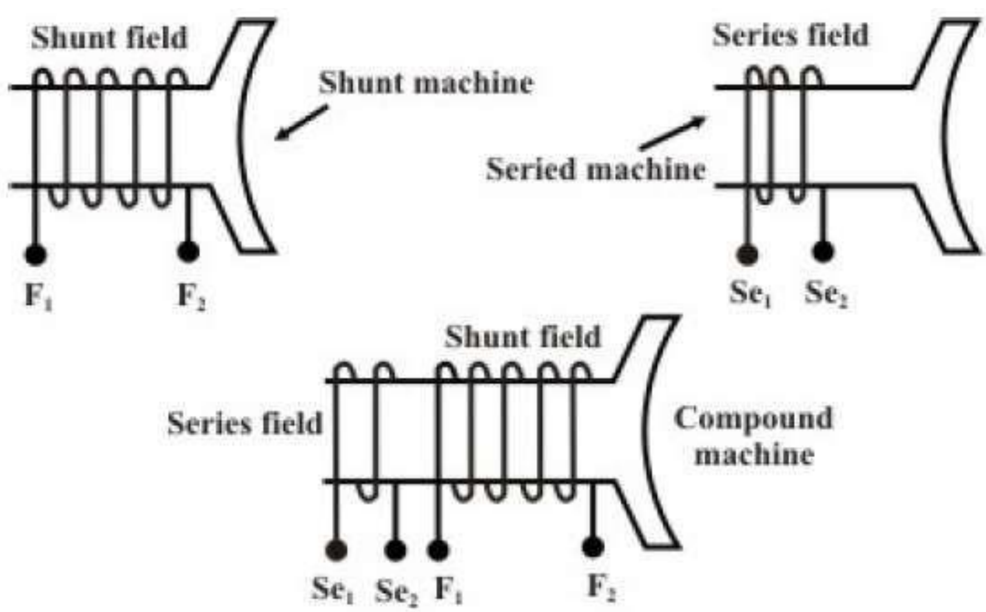


Fig2.11: Field coils for different DC machines

Characteristics of a separately excited generator

No load or Open circuit characteristic

In this type of generator field winding is excited from a separate source, hence field current is independent of armature terminal voltage as shown on figure (38.2). The generator is driven by a prime mover at rated speed, say *n* rps. With switch *S* in opened condition, field is excited via a *potential divider* connection from a separate d.c source and field current is gradually increased. The field current will establish the flux per pole φ. The voltmeter V connected across the armature terminals of the machine will record the generated $E_G = \frac{PZ}{A}\varphi n$ $=kn\varphi$). Remember $\frac{pz}{a}$is a constant (*k*) of the machine. As field current is increased, E_G will increase. E_G versus I_f plot at constant speed *n* is shown in figure.

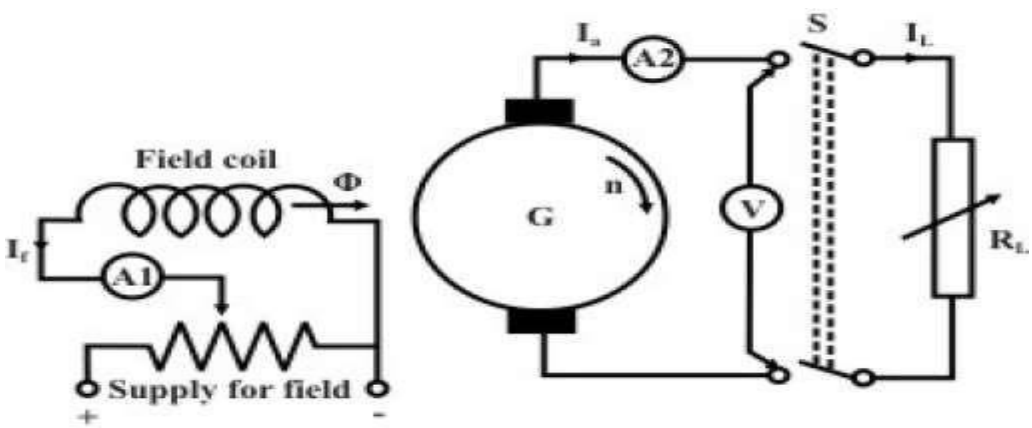


Fig2.12: Connection of separately excited generator.

It may be noted that even when there is no field current, a small voltage (OD) is generated due to residual flux. If field current is increased, φ increases linearly initially and O.C.C follows a straight line. However, when *saturation* sets in, φ practically becomes constant and hence E_g too becomes constant. In other words, O.C.C follows the *B-H* characteristic, hence this characteristic is sometimes also called the *magnetisation* characteristic of the machine.

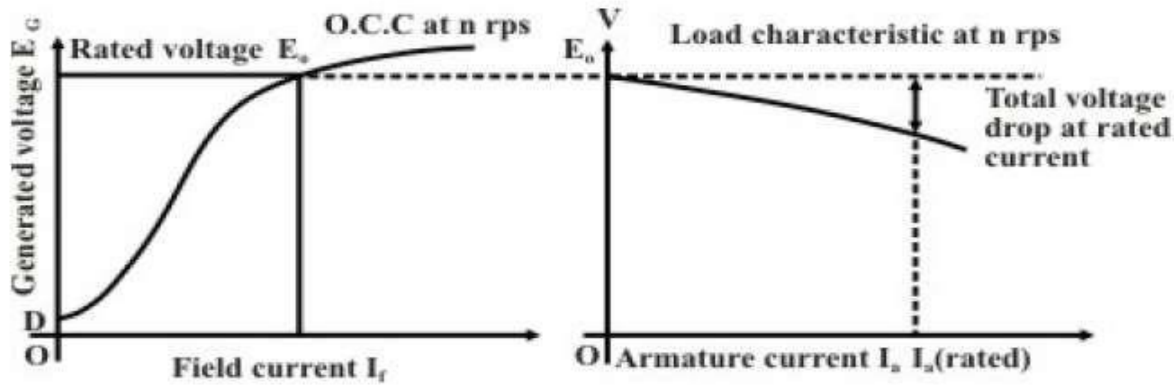


Fig: No load and Load characteristics of separately exited DC Generator

It is important to note that if O.C.C is known at a certain speed n_1, O.C.C at another speed n_2 can easily be predicted. It is because for a constant field current, ratio of the generated voltages becomes the ratio of the speeds as shown below.

$$\frac{E_{G2}}{E_{G1}} = \frac{\text{Gen. voltage at } n_2}{\text{Gen. voltage at } n_1}$$

$$= \frac{k\phi n_2}{k\phi n_1} \quad \because \text{voltage is calculated at same field current}$$

$$\therefore \frac{E_{G2}}{E_{G1}} = \frac{n_2}{n_1}\bigg|\, i_f = \text{constant}$$

$$\text{or, } E_{G2} = \frac{n_2}{n_1} E_{G1}$$

Therefore points on O.C.C at n_2 can be obtained by multiplying ordinates of O.C.C at n_1 with the ratio $\frac{n2}{n1}$ O.C.C at two different speeds are shown in the following figure

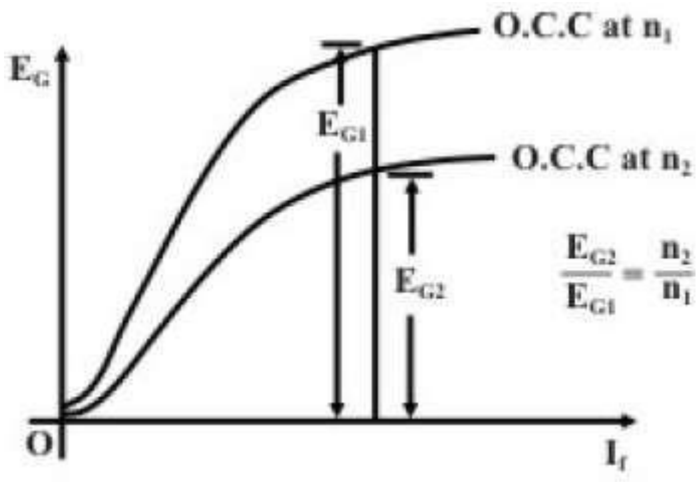


Fig: O C C at different Speeds

Load characteristic of separately excited generator

Load characteristic essentially describes how the terminal voltage of the armature of a generator changes for varying armature current I_a. First at rated speed, rated voltage is generated across the armature terminals with no load resistance connected across it (i.e., with S opened) by adjusting the field current. So for $I_a = 0$, $V = E_o$ should be the first point on the load characteristic. Now with S is closed and by decreasing R_L from infinitely large value, we can increase I_a gradually and note the voltmeter reading. Voltmeter reads the terminal voltage and is expected to decrease due to various drops such as armature resistance drop and brush voltage drop. In an uncompensated generator, armature reaction effect causes additional voltage drop. While noting down the readings of the ammeter A2 and the voltmeter V, one must see that the speed remains constant at rated value. Hence the load characteristic will be *drooping* in nature as shown in figure .

Characteristics of a shunt generator

We have seen in the previous section that one needs a separate d.c supply to generate d.c voltage. Is it possible to generate d.c voltage without using another d.c source? The answer is yes and for obvious reason such a generator is called *self excited* generator. Field coil (F1, F2) along with a series external resistance is connected in parallel with the armature terminals (A1, A2) of the machine as shown in figure. Let us first qualitatively explain how such connection can produce sufficient voltage. Suppose there exists some residual field. Therefore, if the generator is driven at rated speed, we should expect a small voltage $kn\varphi$ to be induced across the armature. But this small voltage will be directly applied across the field circuit since it is connected in parallel with the armature. Hence a small field current flows producing additional flux. If it so happens that this additional flux aids the already existing residual flux, total flux now becomes more generating more voltage. This more voltage will drive more field current generating more voltage. Both field current and armature generated voltage grow *cumulatively*.

This growth of voltage and the final value to which it will settle down can be understood by referring to where two plots have been shown. One corresponds to the O.C.C at rated speed and obtained by connecting the generator in separately excited fashion as detailed in the preceding section. The other one is the V-I characteristic of the field circuit which is a straight line passing through origin and its slope represents the total field circuit resistance.

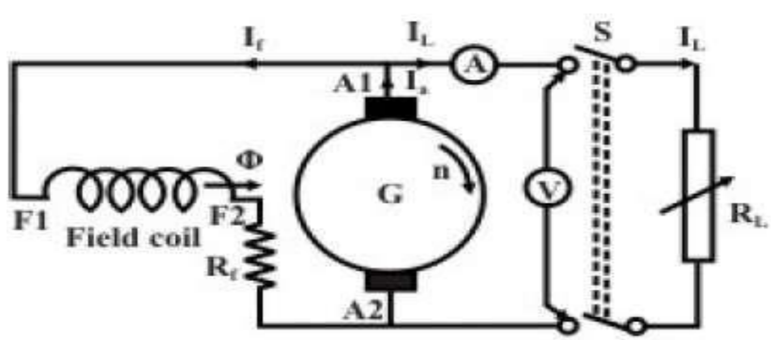


Fig2.13: DC Shunt Generator.

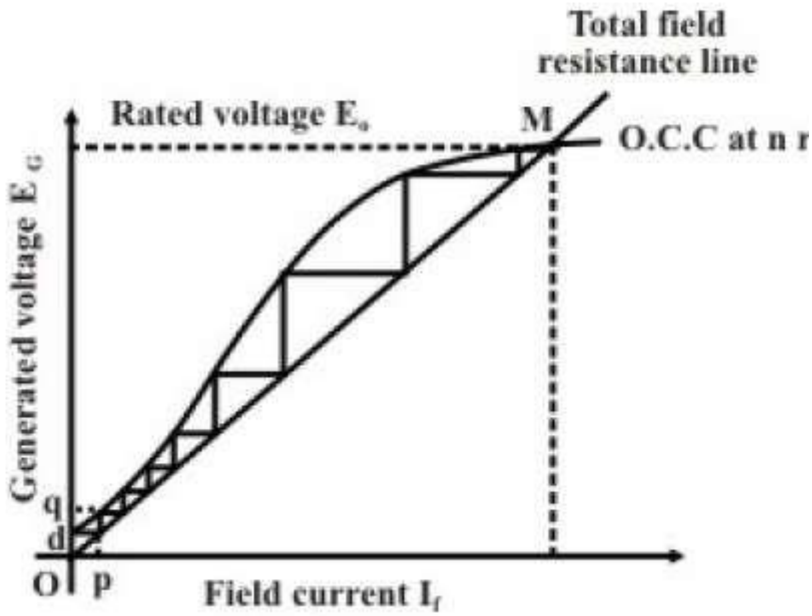
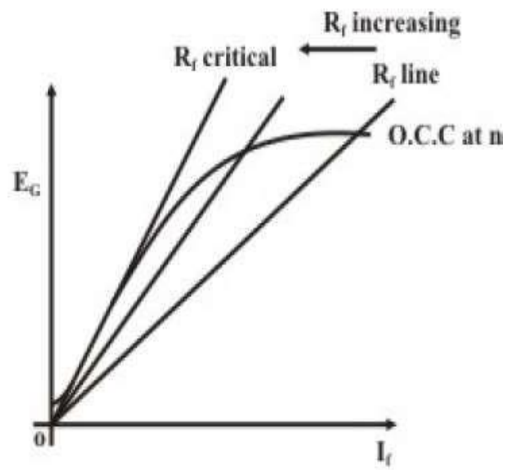


Fig 2.14: Voltage Build up in Shunt generator.

Initially voltage induced due to residual flux is obtained from O.C.C and given by Od. The field current thus produced can be obtained from field circuit resistance line and given by Op. In this way voltage build up process continues along the stair case. The final stable operating point (M) will be the point of intersection between the O.C.C and the field resistance line. If field circuit resistance is increased, final voltage decreases as point of intersection shifts toward left. The field circuit resistance line which is tangential to the O.C.C is called the *critical* field resistance. If the field circuit resistance is more than the critical value, the machine will fail to excite and no voltage will be induced. The reason being no point of intersection is possible in this case.

Suppose a shunt generator has built up voltage at a certain speed. Now if the speed of the prime mover is reduced without changing R_f, the developed voltage will be less as because the O.C.C at lower speed will come down. If speed is further reduced to a certain critical speed (n_{cr}), the present field resistance line will become tangential to the O.C.C at n_{cr}. For any speed below n_{cr}, no voltage built up is possible in a shunt generator.



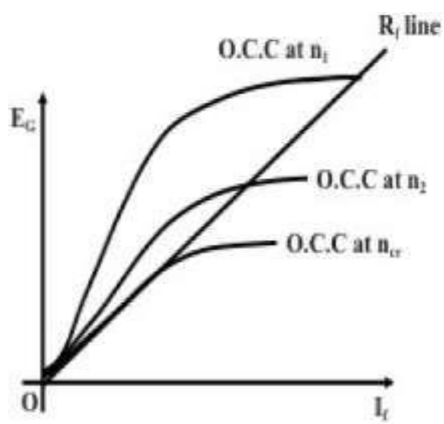


Fig 2.15a: Critical Field Resistance Fig 2.15b: Critical Speed

A shunt generator driven by a prime mover, can not built up voltage if it fails to comply any of the conditions listed below.

1. The machine must have some *residual* field. To ensure this one can at the beginning excite the field separately with some constant current. Now removal of this current will leave some amount of residual field.

2. Field winding connection should be such that the residual flux is strengthened by the field current in the coil. If due to this, no voltage is being built up, reverse the field terminal connection.

3. Total field circuit resistance must be less than the critical field resistance.

Load characteristic of shunt generator

With switch S in open condition, the generator is practically under no load condition as field current is pretty small. The voltmeter reading will be E_o as shown in figures and In other words, E_o and $I_a = 0$ is the first point in the load characteristic. To load the machine S is closed and the load resistances decreased so that it delivers load current I_L. Unlike separately as well. The drop in the terminal voltage will be caused by the usual *Ir*drop, brush voltage drop and armature reaction effect. Apart from these, in shunt generator, as terminal voltage decreases, field current hence excited motor, here $I_L \neq I_a$. In fact, for shunt generator, $I_a = I_L - I_f$. So increase of I_L will mean increase of $I_{a\ aa}$ φ also decreases causing additional drop in terminal voltage. Remember in shunt generator, field current is decided by the terminal voltage by virtue of its parallel connection with the armature. Figure (38.9) shows the plot of terminal voltage versus armature current which is called the *load characteristic*. One can of course translate the V versus I_a characteristic into V versus I_L characteristic by subtracting the correct value of the field current from the armature current. For example, suppose the machine is loaded such that terminal voltage becomes V_1 and the armature current is I_{a1}. The field current at this load can be read from the field resistance line corresponding to the existing voltage V_1 across the field as shown in figure (38.9). Suppose I_{f1} is the noted field current. Therefore, $I_{L1} = I_{a1} - I_{f1}$. Thus the point $[I_{a1}, V_1]$ is translated into $[I_{L1}, V_1]$ point. Repeating these step for all the points we can get the V versus I_L characteristic as well. It is interesting to note that the generated voltage at this loading is E_{G1} (obtained from OCC corresponding to I_{f1}). Therefore the length PQ must represents sum of all the voltage drops that has taken place in the armature when it delivers I_a.

$$E_{G1} - V_1 = length PQ$$
$$= I_{a1}r_a + \text{brush drop} + \text{drop due to armature reaction}$$
$$E_{G1} - V_1 \approx I_{a1}r_a \text{ neglecting brush drop \& armature reaction drop.}$$

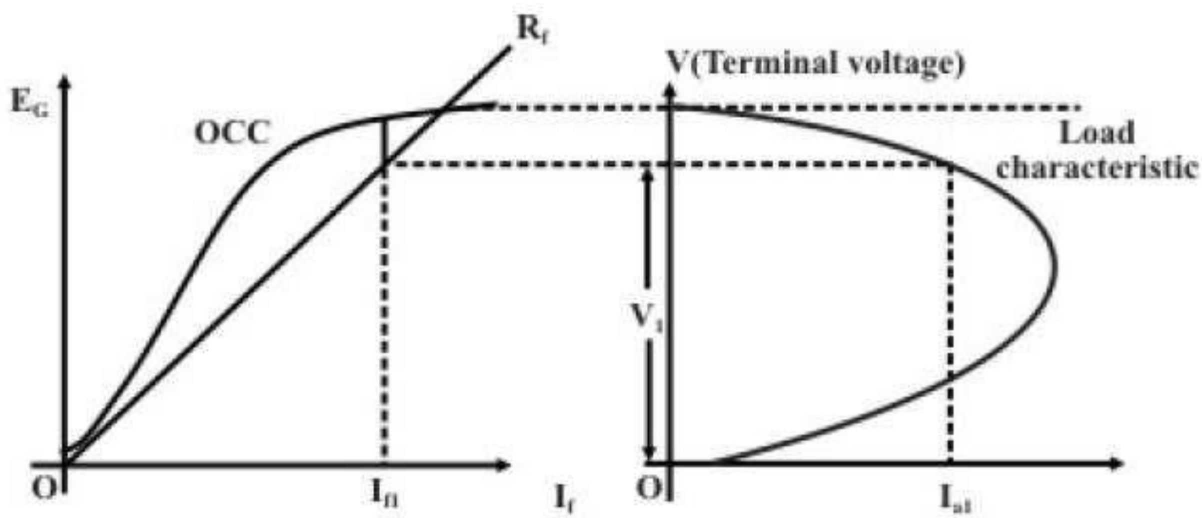


Fig 2.16: Load Characteristics of shunt generator

A compound machines have both series and shunt field coils. On each pole these two coils are placed as shown in figure 38.1. Series field coil has low resistance, fewer numbers of turns with large cross sectional area and connected either in series with the armature or in series with the line. On the other hand shunt field coil has large number of turns, higher resistance, small cross sectional area and either connected in parallel across the armature or connected in parallel across the series combination of the armature and the series field. Depending on how the field coils are connected, compound motors are classified as *short shunt* and *long shunt* types as shown in figures

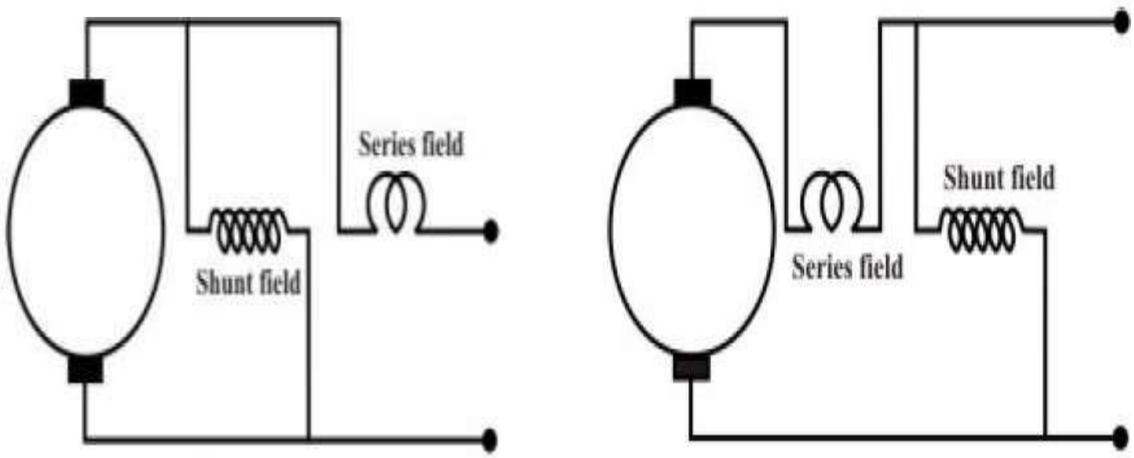


Fig2.17 a: Short Shunt connection. Fig2.17 b: Long Shunt Connection.

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

In a compound generator, series field coil current is load dependent. Therefore, for a cumulatively compound generator, with the increase of load, flux per pole increases. This in turn increases the generated emf and terminal voltage. Unlike a shunt motor, depending on the strength of the series field mmf, terminal voltage at full load current may be same or more than the no load voltage. When the terminal voltage at rated current is same that at no load condition, then it is called a level compound generator. If however, terminal voltage at rated current is more than the voltage at no load, it is called a over compound generator. The load characteristic of a cumulative compound generator will naturally be above the load characteristic of a shunt generator as depicted in figure 38.14. At load current higher than the rated current, terminal voltage starts decreasing due to saturation, armature reaction effect and more drop in armature and series field resistances.

To understand the usefulness of the series coil in a compound machine let us undertake the following simple calculations. Suppose as a shunt generator (series coil not connected) 300 AT/pole is necessary to get no load terminal voltage of 220 V. Let the terminal voltage becomes 210 V at rated armature current of 20 A. To restore the terminal voltage to 220 V, shunt excitation needs to be raised such that AT/pole required is 380 at 20 A of rated current. As a level compound generator, the extra AT (380-300 = 80) will be provided by series field. Therefore, number of series turns per pole will be 80/20 = 4. Thus in a compound generator series field will automatically provide the extra AT to arrest the drop in terminal voltage which otherwise is inevitable for a shunt generator.

For the differentially compounded generator where series field mmf opposes the shunt field mmf the terminal voltage decreases fast with the increase in the load current.

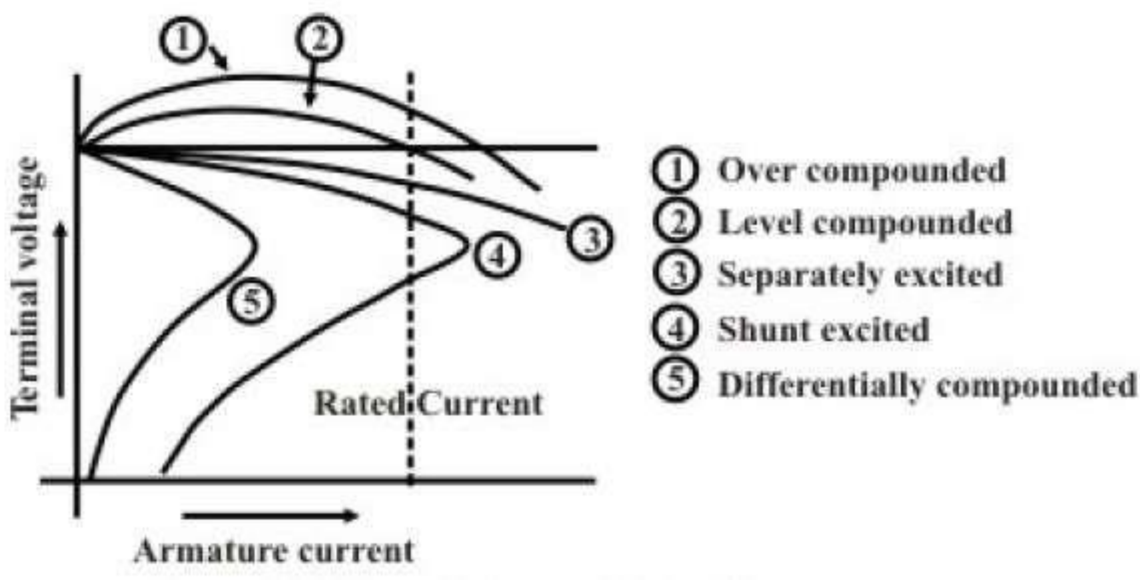


Fig 2.18: Load Characteristics of DC generator.

Synchronous Generators:

Introduction:-

An alternator is an alternating current voltage generator. It is also called a **"Synchronous generator"**. In the case of an alternator, the field system is rotating and the armature is stationary. This is because, in the case of an alternator, having a stationary armature has several advantages, which are listed below:

1. The generated voltage can be directly connected to the load, so that, the load current need not pass through brush contacts.
2. It is easy to insulate the stationary armature for high ac generated voltages, which may be as high as 11kv to 33kv.
3. The sliding contacts i.e. the slip rings are transferred to the low voltage,low power dc field circuit which can be easily insulated. The excitation voltage is only of the order 110volts to 220volts.
4. The armature windings can be easily braced to prevent any deformation produced by large mechanical stresses set up due to short circuit and large centrifugal forces that might set up.

Construction:

Basically an alternator consists of two parts.

a) Stator
b) Rotor

Stator

The stator of an alternator consists of a stator frame made of mild steel plates, welded together to form a cylindrical drum. Inside the cylindrical drum, cylindrical statorlaminations made of special steel alloy are fixed. The stator core laminations are insulated from one another and pressed together to form a core. On the inner periphery of stator core, uniform slots are cut to house the stator conductors. These are holes cast in the stator frame and radial ventilating spaces in the lamination which circulate free air and help in cooling of the alternator. For small alternators the laminations are in one section and for large alternators each lamination is made up of small segments

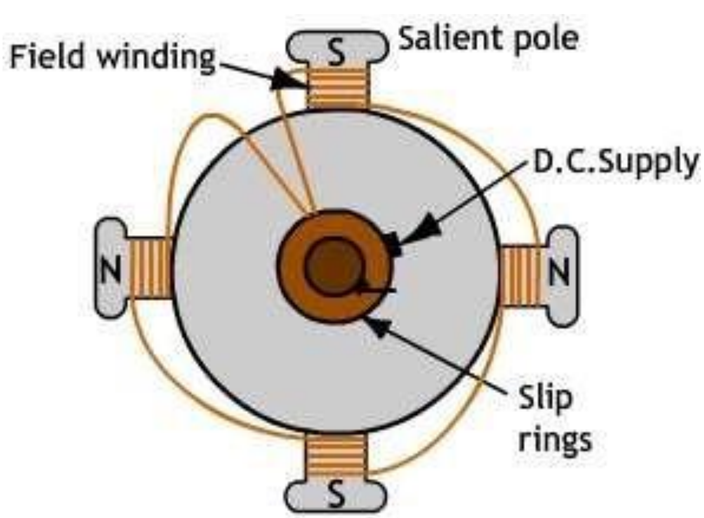
Rotor

There are two types of rotor.

1) Salient Pole Type
2) SmoothCylindrical Type

The alternator with salient pole type rotor is called salient pole alternator and the alternator with smooth cylindrical type rotor is called non-salient pole alternator or turbo alternator.

Salient Pole Type Alternator-

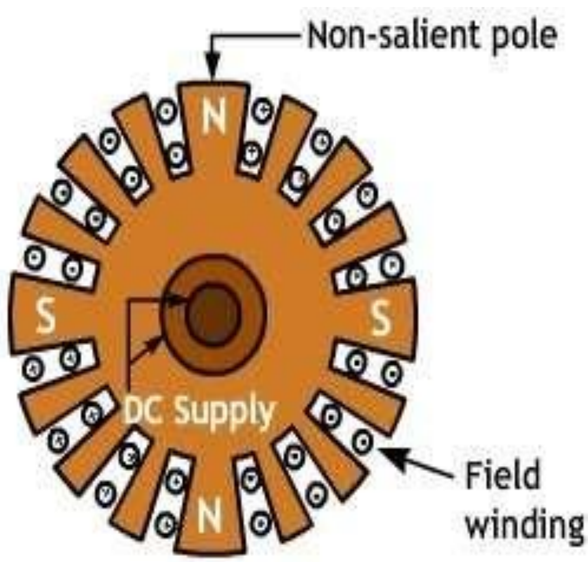


This is also called project pole type as all the poles are projected out from the surface of the rotor.

The poles are built up of thick steel laminations. The poles are bolted to the rotor as shown in figure above. The field winding is provided on the pole shoe. These rotors have large diameters and small axial lengths. The limiting factor for the size of the rotor is the centrifugal force acting on the rotating member of the machine. As mechanical strength of salient pole type is less, this is preferred for low speed alternators ranging from 125rpm to 500rpm. The prime movers used to drive such rotors are generally water turbines and IC engines.

<u>Smooth Cylindrical Type Rotor. (Non Salientor Non Projected Pole Type)</u>

The rotor consists of smooth solid steel cylinder having a number of slots to accommodate the field coils. These slots are covered at the top with the help of steel or manganese wedges. Theunslotted portions of the cylinder itself act as the poles.



The poles are not projecting out and the surface of the rotor is smooth which maintains uniform air gap between stator and rotor. These rotors have small diameters and large axial lengths. This is to keep peripheral speed into limits. The main advantage of this type is that these are mechanically very strong and thus preferred for high speed alternators ranging 1500rpm to 3000rpm. Such high speed alternators are called ‘turbo alternators’. The prime movers used to drive such type of rotors are steam turbines, electric motors.

Working principle

The field winding of the rotor is supplied with a dc voltage of 110v or 220 volts generated by the pilot exciter through the two brushes which are set to slide on two slip rings fixed to the shafts of the alternator. The rotor is rotated by a prime mover and the flux produced by the rotor poles sweeps across the stator conductors and hence the EMF is induced in the

Relation between Poles, Speed and the Frequency:

Let P= number of poles

N= speed of rotor in rpm.

f= frequency of generated emf in Hz.

Since one cycle of emf is induced when a conductor passes through a pair of poles, the number of cycles of emf induced in one revolution of rotor is equal to the number of pair of poles.

No. of cycles/revolution = P/2

No. of revolution/sec = N/60

Frequency = no. of cycles/sec

Frequency (f) =no. of cycles/revolution x No. of revolutions/sec

$$f = \frac{P}{2} \times \frac{N}{60}$$

$$f = \frac{PN}{120}\ Hz \ldots\ldots\ldots\ldots\ldots\ldots(1)$$

EMF Equation of an Alternator:

Let N= speed of rotor in rpm

Φ= flux per pole in wb.

P= no. of poles

f= frequency

Z=number of armature conductors in series per phase.

Z=2T, T→No. of turns per phase.

Time taken for one revolution → 60/N se

During this time a conductor crosses P poles and cuts a flux of PΦ wb.

Therefore according to faraday's law,

Average induced emf / conductor= flux cut/ time taken = PΦ/ (60/N)

= NPΦ/60 volts

But f= PN/120 Hz. Therefore,

$$avg\ induced\ emf/conductor = 120f\Phi/60 = 2f\Phi \quad volts.$$

Z conductors are connected in series per phase,

$$E(avg)/phase = 2fZ\Phi\ volts.$$

But Z=2T

$$E(avg)/phase = Zf\Phi 2T$$

$$= 4fT\Phi \quad volts.$$

Wkt,

$$Form\ factor = rms\ value/average\ value = 1.11\ for\ sine\ wave.$$

Therefore $E(rms/phase) = 4.44\ fT\Phi\ volts \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots (2)$

The above emf is derived assuming that the stator winding is full pitched and the emf's induced in the various conductors are equal in magnitude and does not have any phase difference. It is also assumed that all the conductors per pole per phase are connected in a single slot. But, in practice the coils are short pitched. The conductors are uniformly distributed in all the slots of the stator. Due to these two facts, the emf induced in the alternator gets reduced by a small quantity. The equation for induced emf is modified as,

$$E_{ph} = 2.22K_pK_d\ fZ\Phi \quad volts$$

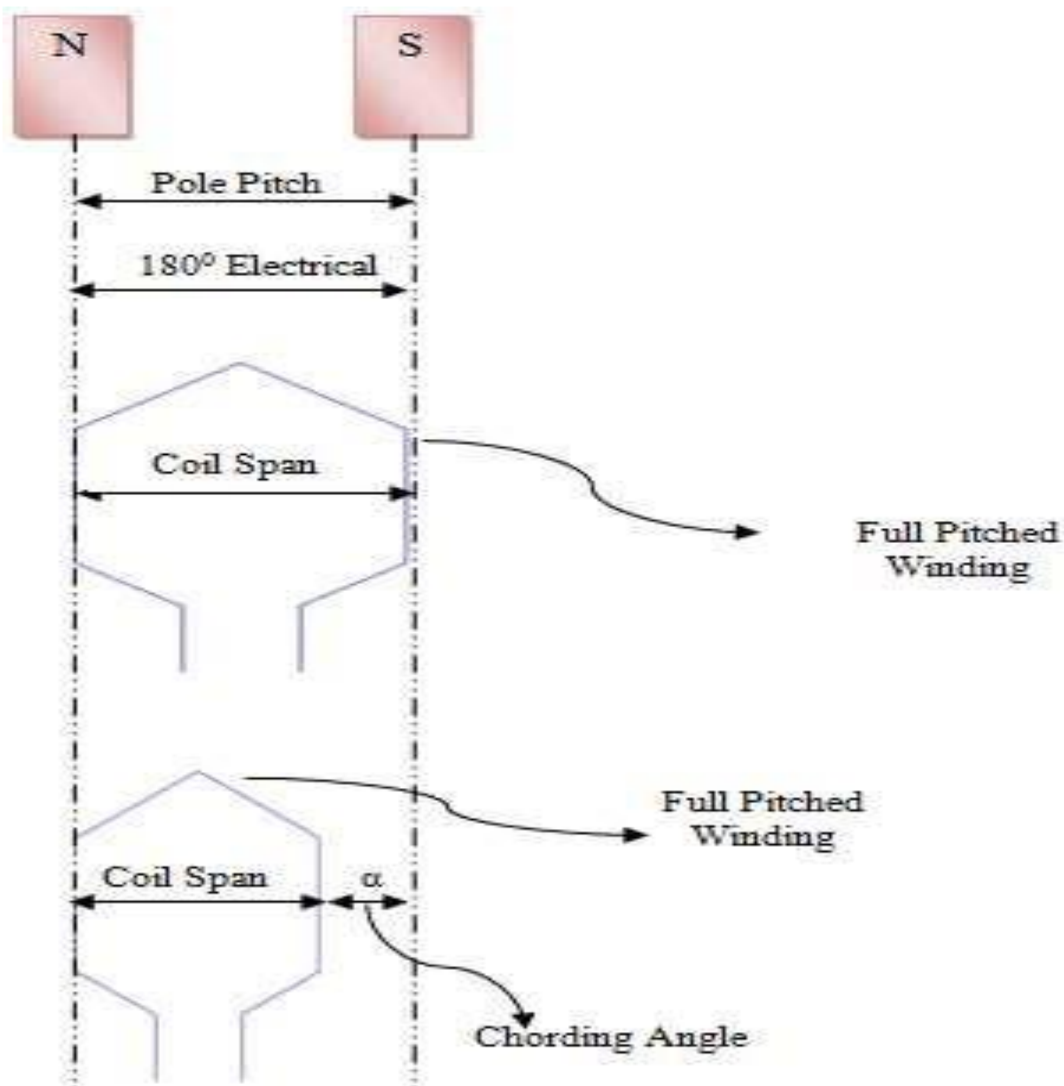
Where K_P=pitch factor

K_d= distribution factor

Pitch factor

It is **also** known as coil span factor or chording factor. Pole pitch is the distance between two similar points on adjacent poles and it is defined to be 180° electrical. Coil pitch or coil span is the distance between two adjacent sides of a coil.

If the armature winding is so wound that the coil pitch equals the pole pitch then it is called a full pitched winding. But for practical reasons, we make the coil span less than the pole pitch by angle α where α is called the chording angle(then the winding is said to be short pitched).



Due to this, the induced emf reduces by a pitch factor K_p, the pitch factor and $Kp = cos(\alpha/2)$

Distribution factor K_d

This is also known as breadth factor orwinding factor. Under the influence of each pole, Z/P conductors belong to one phase. All these conductors can be accommodated in one armature slot and we have to distribute them over two or more slots. This again reduces the induced emf by a factor K_d.

$$K_d = \frac{\sin\left({}^{m\beta}/_{2}\right)}{m\sin\left({}^{\beta}/_{2}\right)}$$

$$Where\ m = \ number\ of\ slots/pole/phase.$$

$$= total\ no.of\ armature\ slots/\ (no.of\ poles\ x\ no.of\ phases)$$

$$And\ \beta = \frac{180°}{(no.of\ slots \times\ pole)}$$

Taking these two factors into account,

$$E_{rms/ph} = \ 4.44\ K_p K_d\ fT\Phi\ volts$$

$$Or\ E_{rms/ph} \ = \ 4.44K_w fT\ \Phi\ volts\ \ldots\ldots\ldots\ldots\ldots K_w = \ K_p K_d$$

Voltage Regulation of an Alternator:

The total change in terminal voltage of the alternator from no load to full load, at constant speed and field excitation, is termed as *voltage regulation*.

[OR]

The voltage regulation of an alternator is the change in its terminal voltage when full load is removed keeping the field excitation and speed constant, divided by the rated terminal voltage.

$$Regulation = \frac{E_0 - V}{V}$$

Where E_0= no load terminal

voltage. V= full load

terminal voltage.

The regulation is usually expressed as a % of the voltage drop from no load to full load w.r.t full load terminal voltage.

$$\%Regulation = \frac{E_0 - V}{V} \times 100$$

MODULE – 4

Synchronous generators (continuation): Generator load characteristic. Voltage regulation, excitation control for constant terminal voltage. Generator input and output. Parallel operation of generators and load sharing. Synchronous generator on infinite busbars – General load diagram, Electrical load diagram, mechanical load diagram, O – curves and V – curves. Power angle characteristic and synchronizing power.Effects of saliency, two-reaction theory, Direct and Quadrature reactance, power angle diagram, reluctance power, slip test.

10 Hours

Synchronizing

The operation of paralleling two alternators is known as synchronizing, and certain conditions must be fulfilled before this can be effected. The incoming machine must have its voltage and frequency equal to that of the bus bars and, should be in same phase with bus bar voltage. The instruments or apparatus for determining when these conditions are fulfilled are called synchroscopes. Synchronizing can be done with the help of

(i) dark lamp method or (ii) by using synchroscope.

Synchronizing by Three Dark Lamp Method

The simplest method of synchronizing is by means of three lamps connected across the ends of paralleling switch, as shown in Figure 6.16(a). If the conditions for synchronizing are fulfilled there is no voltage across the lamps and the switch may be closed. The speed of the incoming machine must be adjusted as closely as possible so that the lamps light up and die down at a very low frequency. The alternator may then be switched in at the middle of the period of darkness, which must be judged by the speed at which the light is varying. By arranging three lamps across the poles of the main switch as in the case of machine *B* it is possible to synchronize with lamps dark. A better arrangement is to cross connect two of the lamps as given in machine *C*. Suppose that the voltage sequence *ABC* refers to the bus bars and *A¢ B¢ C¢* to the incoming machine *C*. Then the instantaneous voltage across the three lamps in the case of machine *C* are given by the vectors *AB¢*, *A¢ B*, and *CC¢*. Now both vector diagrams are rotating in space, but they will only have the same angular velocities if the incoming machine is too slow. Then diagram *A¢ B¢ C¢* will rotate more slowly than *ABC*. So that at the instant represented *AB¢* is increasing, *A¢ B¢* is decreasing, and *CC¢* is increasing. If the incoming machine is too fast, the *AB'* is decreasing *A'B* is increasing, and *CC¢* is decreasing. Hence, if the three lamps are placed in a ring a wave of light will travel in a clockwise or counter-clockwise direction round the ring according as the incoming machine is fast or slow. This arrangement therefore indicates whether the speed must be decreased or increased. The switch is closed when the changes in light are very slow and at the instant the lamp connected directly across one phase is dark. Lamp synchronizers are only suitable for small low voltage machines.

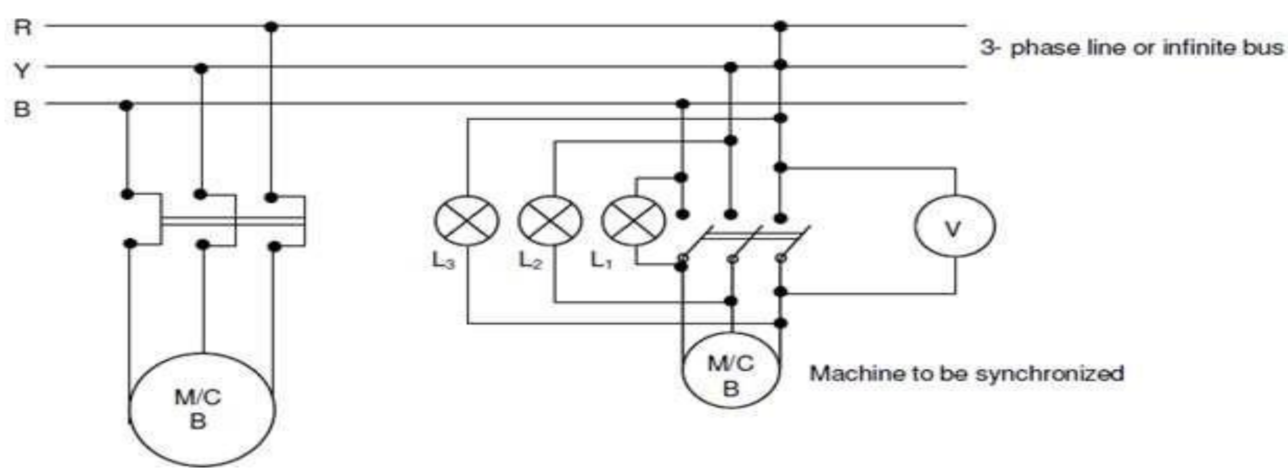


Figure 6.1: Illustration of Method of Synchronizing

Synchroscopes

Synchronizing by means of lamps is not very exact, as a considerable amount of judgement is called for in the operator, and in large machines even a small phase difference causes a certain amount of jerk to the machines. For large machines a rotary synchroscope is almost invariably used. This synchroscope which is based on the rotating field principle consists of a small motor with both field and rotor wound two-phase. The stator is supplied by a pressure transformer connected to two of the main bus bars, while the rotor is supplied through a pressure transformer connected to a corresponding pair of terminals on the incoming machine. Two phase current is obtained from the phase across which the instrument is connected by a split phase device.

One rotor, phase *A* is in series with a non-inductive resistance *R*, and the other. *B* is in series with an inductive coil *C*. The two then being connected in parallel. The phase difference so produced in the currents through the two rotor coils causes the rotor to set up a rotating magnetic field. Now if the incoming machine has the same frequency as the bus-bars, the two field will travel at the same speed, and therefore, the rotor will exhibit no tendency to move. If the incoming machine is not running at the correct speed, then the rotor will tend to rotate at a speed equal to the difference in the speeds of the rotating fields set up by its rotor and stator. Thus it will tend to

rotate in one direction if the incoming machine is too slow, and in the opposite direction if too fast. In practice, it is usual to perform the synchronizing on a pair of auxiliary bars, called synchronizing bars. The rotor of the synchroscope is connected permanently to these bars, and the incoming machine switched to these bars during synchronizing. In this way, one synchroscope can be used for a group of alternators. The arrangement of synchronizing bars and switch gear.

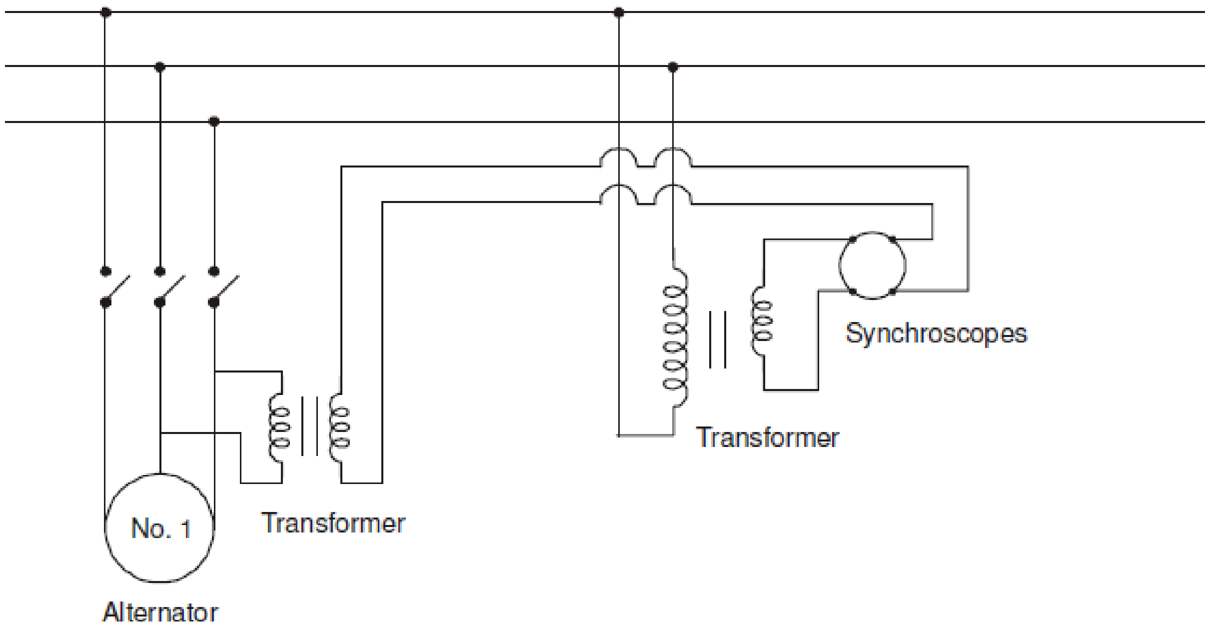


Figure 6.1(b) : Method of Synchronizing by Synchronoscope

Synchronizing Current

If two alternators generating exactly the same emf are perfectly synchronized, there is no resultant emf acting on the local circuit consisting of their two armatures connected in parallel. No current circulates between the two and no power is transferred from one to the other. Under this condition emf of alternator 1i.e. *E*1 is equal to and in phase opposition to emf of alternator 2.

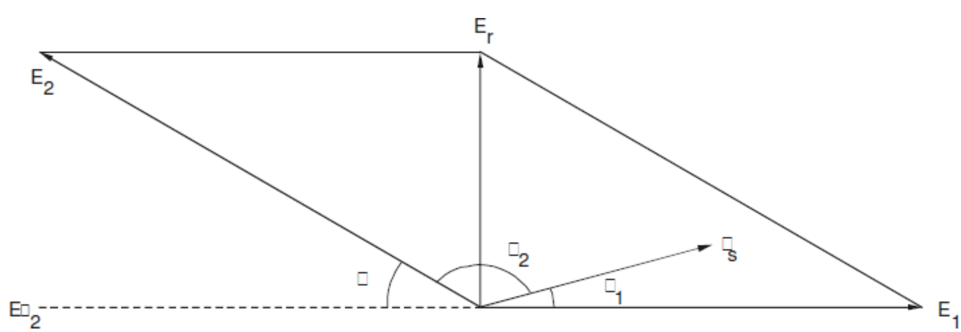


Fig6.2: *E*2 Falling Back

There is, apparently, no force tending to keep them in synchronism, but as soon as the conditions are disturbed a synchronizing force is developed, tending to keep the whole system stable. Suppose one alternator falls behind a little in phase by and angle q. The two alternator emfs now produce a resultant voltage and this acts on the local circuit consisting of the two armature windings and the joining connections. In alternators, the synchronous reactance is large compared with the resistance, so that the resultant circulating current *Is* is very nearly in quadrature with the resultant emf *Er* acting on the circuit. Figure 6.2 represents a single phase case, where *E*1 and *E*2 represent the two induced emfs, the latter having fallen back slightly in phase. The resultant emf, *Er*, is almost in quadrature with both the emfs, and gives rise to a current, *Is*, lagging behind *Er* by an angle approximating to a right angle. It is, thus, seen that *E*1 and *Is* are almost in phase. The first alternator is generating a power *E*1 *Is* cos f1, which is positive, while the second one is generating a power *E*2 *Is* cos f2, which is negative, since cos f2 is negative. In other words, the first alternator is supplying the second with power, the difference between the two amounts of power represents the copper losses occasioned by the current *Is* flowing through the circuit which possesses resistance. This power output of the first alternator tends to retard it, while the power input to the second one tends to accelerate it fill such a time that *E*1 and *E*2 are again in phase opposition and the machines once again work in perfect synchronism. So, the action helps to keep both machines in stable synchronism. The current, *Is*, is called the synchronizing current.

Synchronizing Power

Suppose that one alternator has fallen behind its ideal position by an electrical angle q, measured in radians. This corresponds to an actual geometrical angle of ,

$$\frac{2\theta}{p} = \psi$$

where p is the number of poles. Since $E1$ and $E2$ are assumed equal and

□□is very small Er is very nearly equal to □$E1$.

Moreover, since Er is practically in quadrature with $E1$ and Is may be assumed to be in phase with $E1$ as a first approximation. The synchronizing power may, therefore, be taken as ,

$$E_1 I_s = \frac{\theta E_1^2}{X}$$

Since

$$I_s = \frac{E_r}{X} = \frac{\theta E_1}{X}$$

Where X is the sum of synchronous reactance of both armatures, the resistance being neglected. When one alternator is considered as running on a set of bus bars the power capacity of which is very large compared with its own, the combined reactance of the others sets connected to the bus bars is negligible, so that in this case X is the synchronous reactance of the one alternator under consideration.

If

$I_x = \frac{E}{X}$ is the steady short-circuit current of this alternator,

then the synchronizing power may be written as

$$\frac{\theta E^2}{X} = E\, I_x \theta$$

although the current *Ix* does not actually flow.

In an *m*-phase case the synchronizing power becomes *Ps* = *m E Ix* q watts, *E* and *Ix* now being the phase values. Alternators with a large ratio of reactance to resistance are superior from a synchronizing point of view to those which have a smaller ratio, as then the synchronizing current *Is* cannot be considered as being in phase with *E*1. Thus, while reactance is bad from a regulation point of view, it is good for synchronizing purposes. It is also good from the point of view of self-protection in the even of a fault.

Effect of Voltage

Inequality of Voltage

Suppose the alternators are running exactly in phase, but their induced e.m.f.s are not quite equal. Considering the local circuit, their e.m.f.s are now in exact phase opposition, as shown in Figure 6.18, but they set up a resultant voltage *Er*, now inphase with *E*1, assumed to be the greater of the two. The synchronizing current, *Is*,

now lags by almost 90° behind *E*1, so that the synchronizing power, *E*1 *Is* cos f1 is relatively small, and the synchronizing torque per ampere is also very small. This lagging current, however, exerts a demagnetizing effect upon the alternator generating *E*1, so that the effect is to reduce its induced e.m.f. Again, the othernmachine is, so far as this action is concerned, operating as a synchronous motor, taking a current leading by approximately 90°. The effect of this is to strengthen its field and so raise its voltage. The two effects combine to lesson the inequality in the two voltages, and thus tend towards stability. Inequality of voltage is, however, objectionable, since it given rise to synchronizing currents that have a very large reactive component.

Effect of Change of Excitation

A change in the excitation of an alternator running in parallel with other affects only its KVA output; it does not affect the KW output. A change in the excitation, thus, affects only the power factor of its output.

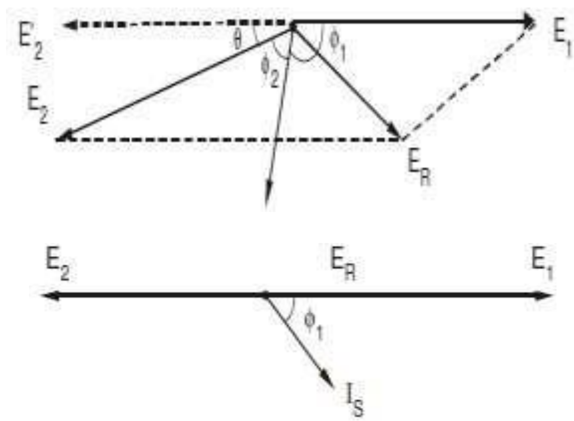


Fig 2a and Fig 2b

Let two similar alternators of the same rating be operating in parallel, receivingequal power inputs from their prime movers. Neglecting losses, their kW outputs are therefore equal. If their excitations are the same, they induce the same emf, and since they are in parallel their terminal voltages are also the same. When delivering a total load of *I* amperes at a power-factor of cos f, each alternator delivers half the total current and

$I1 = I2 = 0.5\ I$

Since their induced emfs are the same, there is no resultant emf acting around the local circuit formed by their two armature windings, so that the synchronizing current, *Is*, is zero. Since the armature resistance is neglected, the vector difference between *E*1 = *E*2 and *V* is equal to

$$I_1 X_{S_1} = I_2 X_{S_2}$$

this vector leading the current *I* by 90°, where X_{S1} and X_{S2} are the synchronous reactances of the two alternators respectively. Now examine the effect of reducing the excitation of the second alternator. $E2$ is therefore reduced as shown in Figure 6.19. This reduces the terminal voltage slightly, so let the excitation of the first alternator be increased so as to bring the terminal voltage back to its original value. Since the two alternator inputs are unchanged and losses are neglected, the two kW outputs are the same as before. The current $I2$ is changed due to the change in $E2$, but the active components of both $I1$ and $I2$ remain unaltered. It will be observed that there is a small change in the load angles of the two alternators, this angle being slightly increased in the case of the weakly excited alternator and slightly decreased in the case of the strongly excited alternator. It will also be observed that $I1 + I2 = I$, the total load current.

Load Sharing

When several alternators are required to run in parallel, it probably happens that their rated outputs differ. In such cases it is usual to divide the total load between them in such a way that each alternator takes the load in the same proportion of its rated load in total rated outputs. The total load is not divided equally. Alternatively,Bit may be desired to run one large alternator permanently on full load, the fluctuations in load being borne by one or more of the others.

Effect of Change of Input Torque

The amount of power output delivered by an alternator running in parallel with others is governed solely by the power input received from its prime mover. If two alternators only are operating in parallel the increase in power input may be accompanied by a minute increase in their speeds, causing a proportional rise in frequency. This can be corrected by reducing the power input to the other alternator, until the frequency is brought back to its original value. In practice, when load is transferred from one alternator to another, the power input to the alternator required to take additional load is increased, the power input to the other alternator being simultaneously decreased. In this way, the change in power output can be effected

without measurable change in the frequency. The effect of increasing the input to one prime mover is, thus, seen to make its alternator take an increased share of the load, the other being relieved to a corresponding extent. The final power-factors are also altered, since the ratio of the reactive components of the load has also been changed. The power-factors of the two alternators can be brought back to their original values, if desired, by adjusting the excitations of alternators.

V-Curves

If the excitation is varied, the armature current will vary for constant load. When armature curve is plotted against exciting current, the resulting curve takes the shape of word *V*, as shown in Figure 7.8, and is known as a *V*-curve. With one particular excitation the armature current is a minimum for unity power-factor. For smaller exciting currents, the armature mmf, *Fa* is made to lag, since the flux, f, and the resultant m.m.f., *Fr* are the same as before. A lagging armature mmf, *Fa*, is only brought about by a lagging armature current, *I* and motor operates as lagging *PF* load. For larger exciting currents, the armature mmf, *Fa*, is made to lead, in order

that *Fr* shall again remain unaltered and motor operates as leading *PF* load. This effect can be seen more clearly from the approximate vector diagram given in Figure 7.5. A low excitation here corresponds to a reduced back emf, giving rise to a resultant voltage that leads the applied voltage by a relatively small angle, thus causing the current to lag by a considerable angle. Since the power-factor is low, the current is relatively large. As the exciting current is increased, the back e.m.f. is also increased, thus swinging the resultant voltage vector round and advancing it in phase. The current is also advanced in phase, its magnitude decreasing since the power-factor is increasing. When the current becomes in phase with the applied voltage it reaches a minimum value, the power-factor being unity. A further increase in exciting current causes an increase in the armature current, which is now a leading one.

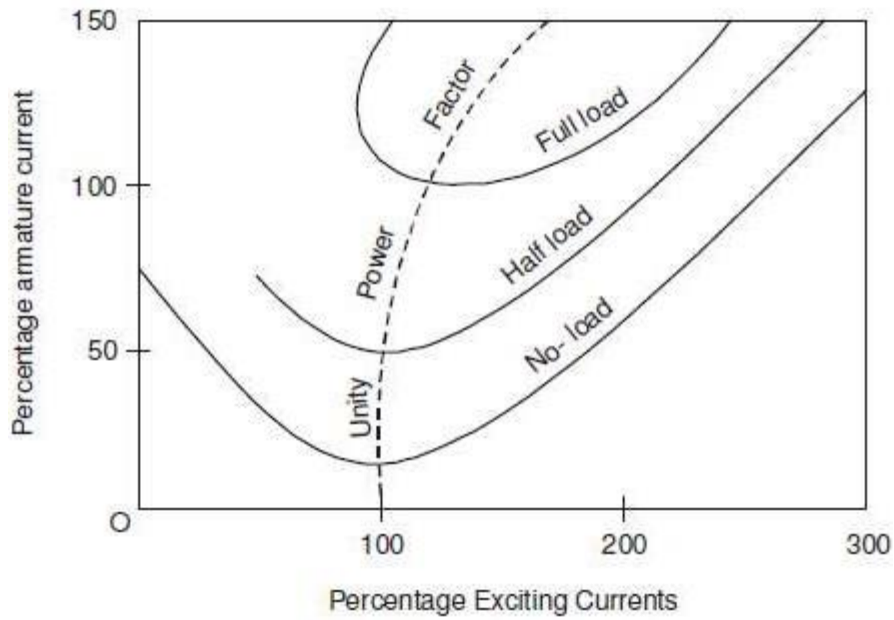


Figure 7.8 : *V*-Curves

The excitation corresponding to unity power-factor and minimum current is called the normal exciting current for that particular load. A smaller exciting current (under- excitation) results in a lagging armature current and a larger exciting current (over- excitation) in a leading armature current, due to the reduction and increase in the induced back e.m.f. respectively.

The excitation necessary for unit power-factor goes up as the load increases. On noload the point on the *V*-curve is sharply accentuated, but if the machine is loaded the tendency is to round off the point, this effect being more marked at the higher loads.

MODULE – 5

Synchronous generators (continuation): Open circuit and short circuit characteristics, Assessment of reactance- short circuit ratio, synchronous reactance, and adjusted synchronous reactance and Potier reactance. Voltage regulation by EMF, MMF, ZPF and ASA methods.

Performance of synchronous generators: Capability curve for large turbo generators and salient pole generators. Starting, synchronizing and control. Hunting and dampers.

10 Hours

Modern power systems operate at some standard voltages. The equipments working on these systems are therefore given input voltages at these standard values, within certain agreed tolerance limits. In many applications this voltage itself may not be good enough for obtaining the best operating condition for the loads. A transformer is interposed in between the load and the supply terminals in such cases. There are additional drops inside the transformer due to the load currents. While input voltage is the responsibility of the supply provider, the voltage at the load is the one which the user has to worry about. If undue voltage drop is permitted to occur inside the transformer the load voltage becomes too low and affects its performance. It is therefore necessary to quantify the drop that takes place inside a transformer when certain load current, at any power factor, is drawn from its output leads. This drop is termed as the voltage regulation and is expressed as a ratio of the terminal voltage (the absolute value per se is not too important).

Voltage regulation of an alternator is defined as the rise in terminal voltage of the machine expressed as a fraction of percentage of the initial voltage when specified load at a particular power factor is reduced to zero, the speed and excitation remaining unchanged.

Methods Of Predetermination Of Regulation

- Synchronous impedance method (EMF method)
- Magneto Motive Force method (MMF method)

• Zero Power Factor method (ZPF method)

• American Standards Association method (ASA method)

• Synchronous impedance method (EMF method) :

The experiment involves the determination of the following characteristics and parameters:

1. The open -circuit characteristic(the O.C.C)

2. The short-circuit characteristic(the S.C.C)

3. The effective resistance of he armature winding.

The O.C.C is a plot of the armature terminal voltage as a function of field current with a symmetrical three phase short-circuit applied across the armature terminals with the machine running at rated speed. At any value of field current, if E is the open circuit voltage and Isc is the short circuit current then for this value of excitation

$$Zs = E/Sic$$

At higher values of field current, saturation increases and the synchronous impedance decreases. The value of Zs calculated for the unsaturated region of the O.C.C is called the unsaturated value of the synchronous impedance.

If Ra is the effective resistance of the armature per phase, the synchronous reactance

Xs is given by

$$Xs = sqrt\ (Za^2 - Ra^2)$$

If V is the magnitude of the rated voltage of he machine and the regulation is to be calculated for a load current I at a power factor angle f, then the corresponding magnitude of the open circuit voltage E is

$$\mathbf{E = V + IZs}$$

Here bold letters indicate complex numbers.

$$Regulation = (E-V)/V$$

Procedure:

1. Open circuit characteristic

Connect the alternator as shown in FIG.1. The prime move in this experiment is a D.C. shunt motor, connected with resistances in its armature and field circuits so as to enable the speed of the set to be controlled. Run the set at the rated speed of the alternator, and for each setting of the field current, record the alternator terminal voltage and the field current. Note that there is no load on the alternator. Record readings till then open circuit voltage reaches 120% of the rated voltage of the machine.

2.Short circuit characteristic

(FIG.2) Connect as in FIG.1, but short-circuit the armature terminals through an ammeter. The current range of the instrument should be about 25-50 % more than the full load current of the alternator. Starting with zero field current, increase the field current gradually and cautiously till rated current flows in the armature. The speed of the set in this test also is tom be maintained at the rated speed of the alternator.

3. Measure the D.C. resistance of he armature circuit of the alternator. The effective a.c resistance may be taken to be 1.2 times the D.C. resistance.

Report:

1. Plot on the same graph sheet, the O.C.C (open circuit terminal voltage per phase

versus the field current), and the short-circuit characteristic (short-circuit

armature current versus the field current).

2. Calculate the unsaturated value of the synchronous impedance, and the value

corresponding to rated current at short circuit. Also calculate the corresponding

values of the synchronous reactance.

3. Calculate regulation of the alternator under the following conditions:

· Full load current at unity power factor

· Full load current at 0.8 power factor lagging.

· Full -load current at 0.8 power factor leading.

FIG.1 Alternator connection for open circuit test

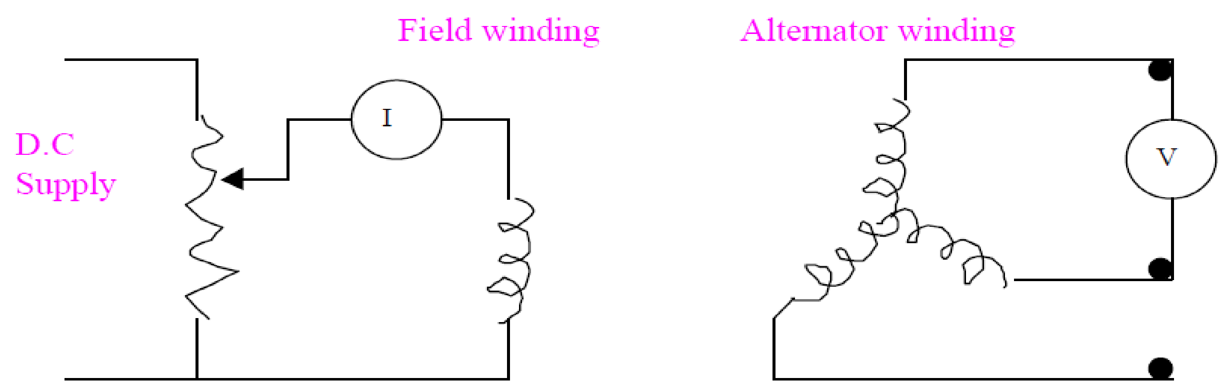
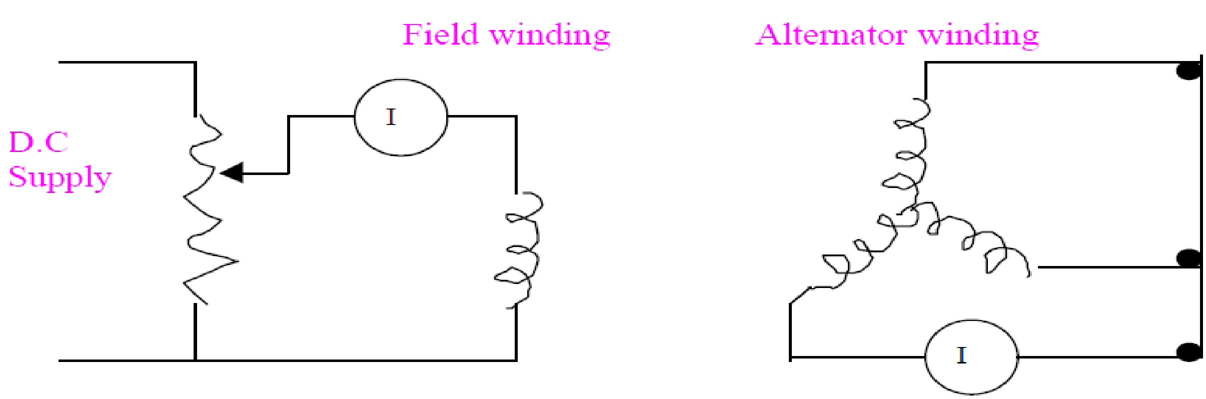
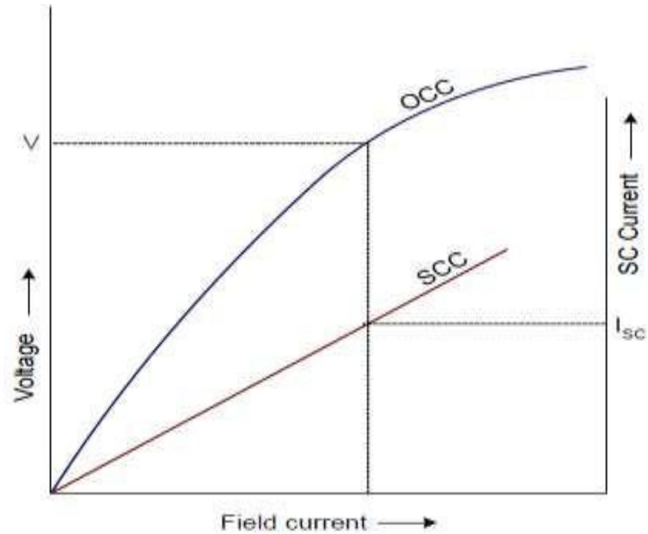


FIG.2 Alternator connection for short circuit test





Where

V = rated phase voltage

Isc = short circuit current corresponding to the field current producing the rated voltage

Synchronous impedance per phase,

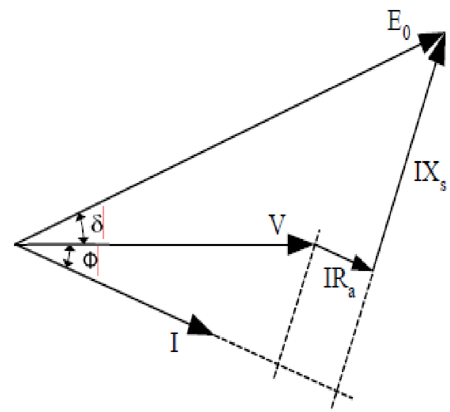
$$Z_s = V/I_{sc}$$

$$X_s = \sqrt{Z_s^2 - R_a^2}$$

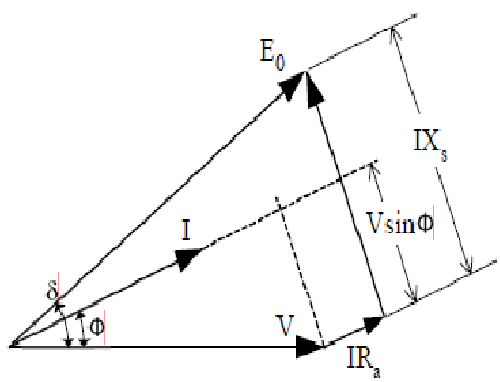
For any load current *I* and phase angle Φ,

find E0 as the vector sum of *V*, *IRa* and *IXs*

For lagging power factor

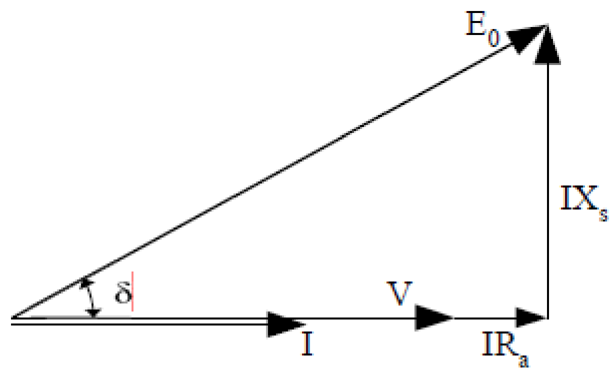


$$E_0 = \sqrt{(V\cos\Phi + IR_a)^2 + (V\sin\Phi + IX_s)^2}$$



$$E_0 = \sqrt{(V\cos\Phi + IR_a)^2 + (V\sin\Phi - IX_s)^2}$$

For Unity Power factor



$$E_0 = \sqrt{(V + IR_a)^2 + (IX_s)^2}$$

MMF method:

(Ampere turns method)

This method is based on the MMF calculation or no. of ampere turns required to produced flux which gives Rated Voltage at Open Circuit and Rated Current at Short Circuit. From open circuit characteristic field current *If*1 gives rated voltage *V* and *If*2 to cause the short circuit current which is equal to Full Load Current.

Steps to find regulation by using MMf method

1. By suitable tests plot OCC and SCC

2. From the OCC find the field current *If1* to produce rated voltage, *V*.

3. From SCC find the magnitude of fieldcurrent *If2* to produce the required armature current.

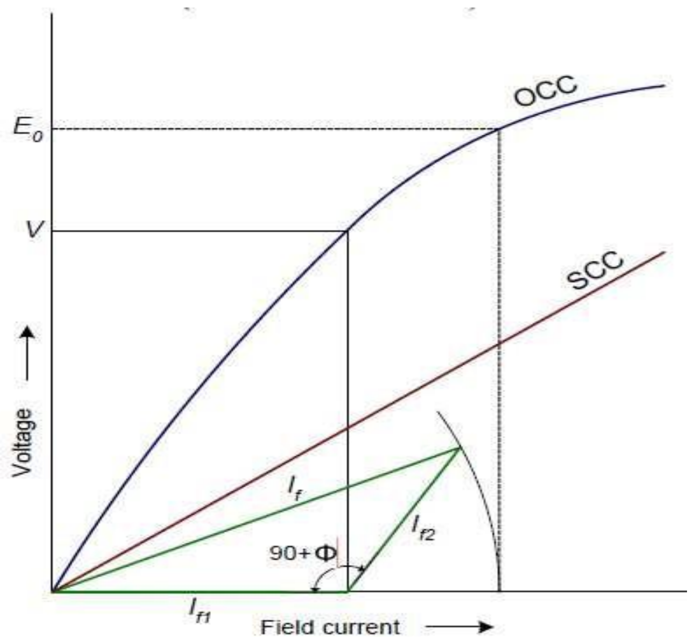
4. Draw *If2* at angle (90+Φ) from *If1*,

where Φ is the phase angle of current from voltage.

If current is leading, take the angle of *If2* as (90-Φ).

5. Find the resultant field current, *If* and mark its magnitude on the field current axis.

6. From OCC. find the voltage corresponding to *If*, which will be *E0*.



Potier method of predetermining the voltage regulation of an alternator.

ZERO POWER FACTOR METHOD (OR) POTIER METHOD:

- This method is based on the separation of armature leakage reactance drop and the armature reaction effect.This is more accurate than the emf and mmf methods. The experimental data required is

  No load curve (or) O.C.C

  S.C.C

  Armature resistance

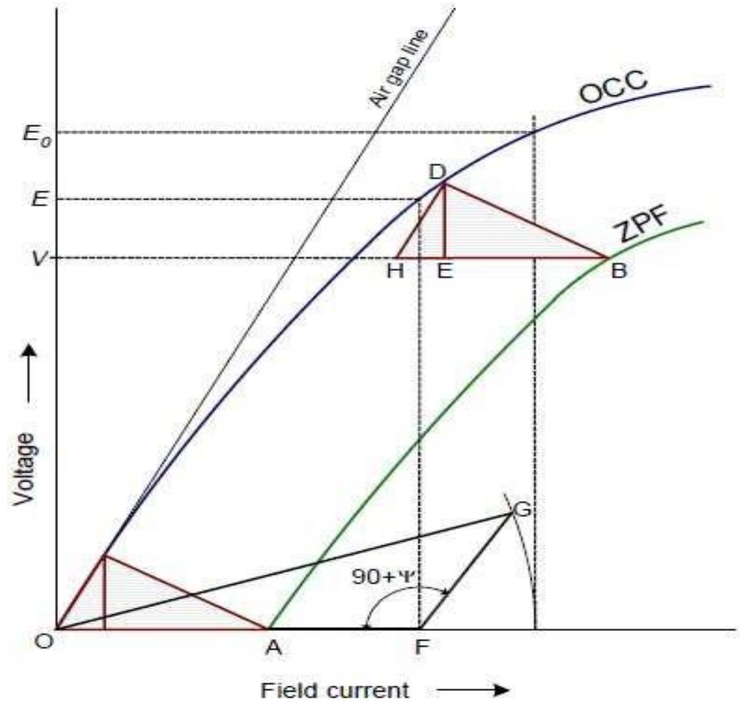
- Full load zero power factor curve (or) wattles load characteristics.
- The ZPF lagging characteristics is a reaction between terminal voltage and excitation when armature is delivering F.L. current at zero power factor.

- The reduction in voltage due to armature reaction is found from above and (ii) voltage drop due to armature leakage reactance XL (also called potier reactance) is found from both. By combining these two, EO can be calculated.
- It should be noted that if we vectorially add to V the drop due to resistance and leakage reactance XL, we get E. If E is further added the drop due to armature reaction (assuming lagging power factor), then we get Eo.
- The zero power factor lagging curve can be obtained If a similar machine is available which may driven at no-load as a synchronous motor at practically zero power factor (or) By loading the alternator with pure reactors.
- By connecting the alternator to a 3Φ line with ammeter and wattmeters connected for measuring current and power and by so adjusting the field current that we get full-load armature current with zero wattmeter reading.
- Point B was obtained in this manner when wattmeter was zero.
- Point A is obtained from a short circuit test with full load armature current. Hence OA represents field current which is equal and opposite to the demagnetizing armature reaction and for balancing leakage drop at full load.
- Knowing these two points, full load zero power factor curve can be drawn as under.
- From B, BH is drawn equal to and parallel to OA.
- From H, HD is drawn parallel to initial straight part of N-L curve i.e., parallel to OC which is tangential to N-L curve.
- Hence, we get point D on no-load curve, which corresponds to point B on full- load zero power factor curve.
- The triangle BHD is known as potier triangle.
- This triangle is constant for a given armature current and hence can be transferred to give use other points like M,L etc.
- Draw DE perpendicular to BH.
- The length DE represents the drop in voltage due to armature leakage reactance XL.

- BE gives the field current necessary to overcome demagnetizing effect of armature reaction at full load and EH for balancing the armature drop DE.
- Let V be the terminal voltage on full load, then if we add to it vertically the voltage drop due to armature leakage reactance alone (neglecting Ra), then we get voltage E= DF (and not Eo). Field excitation corresponding to E is given by OF.
- The voltage corresponding to this excitation is JK = Eo
  % regulation=Eo-V/V

Assuming a lagging power factor with angle Φ, vector for I is drawn at an angle of Φ to V.

- IaRa is drawn parallel to current vector and IXL is drawn perpendicular to it.
- OD represents voltage E.
- The excitation corresponding to it i.e., OF is drawn at 90° ahead of it FG (=Na=BE) representing field current equivalent of full load armature reaction is drawn parallel to current vector OI.
- The closing side OG gives field excitation for Eo.
- Vector for Eo is 90° lagging behind OG.
- DC represents voltage drop due to armature reaction



Steps:

1. By suitable tests plot OCC and SCC

2. Draw tangent to OCC (air gap line)

3. Conduct ZPF test at full load for rated voltage and fix the point B.

4. Draw the line BH with length equal to field current required to produce full load current at short circuit.

5. Draw HD parallel to the air gap line so as to touch the OCC.

6. Draw DE parallel to voltage axis. Now, DE represents voltage drop IXL and BE represents the field current required to overcome the effect of armature reaction.

Triangle BDE is called Potier triangle and XL is the Potier reactance

7. Find E from V, IXL and Φ. Consider Ra also if required. The expression to use is

$$E = \sqrt{(V\cos\Phi + IR_a)^2 + (V\sin\Phi + IX_L)^2}$$

8. Find field current corresponding to *E*.

9. Draw FG with magnitude equal to BE at angle (90+Ψ) from field current axis,

where Ψ is the phase angle of current from voltage vector *E* (internal phase angle).

10. The resultant field current is given by OG. Mark this length on field current axis.

11. From OCC find the corresponding *E0*

American Standards Association Method (ASA Method)

• The field currents If1 (field current required to produce the rated voltage of Vph from theair gap line).

• If2 (field current required to produce the given armature current on short circuit) added at an angle of (90± Φ).

• Load induced EMF calculated as was done in the ZPF method - Corresponding to this EMF, the additional field current (If3) due to saturation obtained from OCC and air gap line - If3 added to the resultant of If1 and If2 -For this total field current, Eph found from OCC and regulation calculated.

Steps:

1. Follow steps 1 to 7 as in ZPF method.

2. Find *If1* corresponding to terminal voltage *V* using air gap line (OF1 in figure).

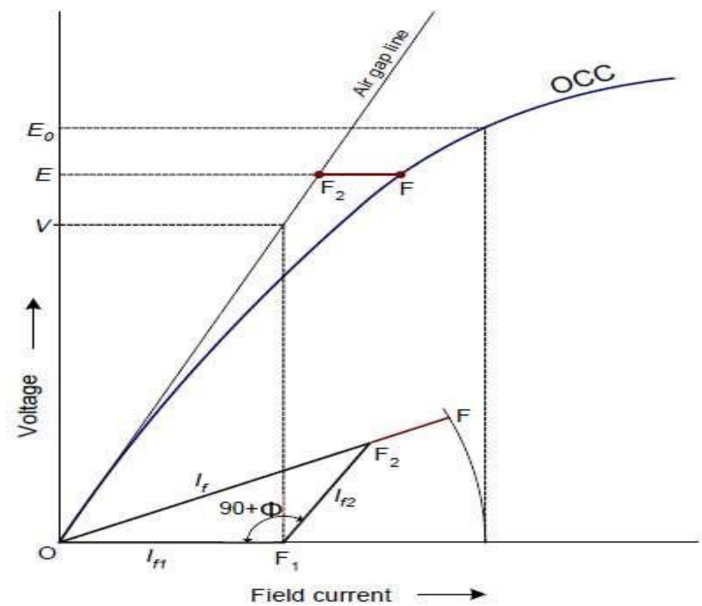
3. xDraw *If2* with length equal to field current required to circulate rated current

during short circuit condition at an angle (90+Φ) from *If1*. The resultant of *If1* and *If2* gives *If* (OF2 in figure).

4. Extend OF2 upto F so that F2F accounts for the additional field current accounting

for the effect of saturation. F2F is found for voltage E as shown.

5. Project total field current OF to the field current axis and find corresponding voltage E0 using OCC.



HUNTING AND DAMPER WINDING

Sudden changes of load on synchronous motors sometimes set up oscillations that are superimposed upon the normal rotation, giving rise to periodic variations of a very low frequency in speed. This effect is known as hunting or phase-swinging. Occasionally, the trouble is aggravated by the motor having a natural period of oscillation approximating to the hunting period, when it is possible for the motor to phase-swing into the unstable region, thus causing it to fall out of synchronism.

Damper Winding

The tendency to hunt can be minimized by the addition of a mechanical flywheel, but this practice is rarely adopted, the use of a damper winding being preferred. Assuming that the speed of rotation of the magnetic flux is constant, there is relative movement between the flux and the damper bars if the rotation of the field system is also absolutely uniform. No emfs are induced in the damper bars and no current flows in the damper winding, which is not operative. Whenever any irregularity takes place in the speed of rotation, however, the polar flux moves from side to side of the pole, this movement causing the flux to move backwards and forwards across the damper bars. Emfs are induced in the damper bars forwards across the damper winding. These tend to damp out the superimposed oscillatory motion by absorbing its energy. The damper winding, thus, has no effect upon the normal average speed, it merely tends to damp out the irregularities in the speed, thus, acting as a kind of electrical flywheel. In the case of a three-phase synchronous motor the stator currents set up a rotating mmf rotating at uniform speed (except for certain minor harmonic effects), and if the rotor is rotating at uniform speed, no emfs are induced in the damper bars.

SYNCHRONOUS CONDENSER

We know that over excited synchronous motor operates at unity or leading power factor. Generally, in large industrial plants the load power factor is lagging. The specially designed synchronous motor which runs at zero load takes leading current approximately near to 90° leading. When it is connected in parallel with inductive loads to improve power factor, it is known as synchronous condenser. Compared to static capacitor the power factor can improve easily by variation of field excitation of motor. Phasor diagram of a synchronous condenser connected in parallel withan inductive load is given below.

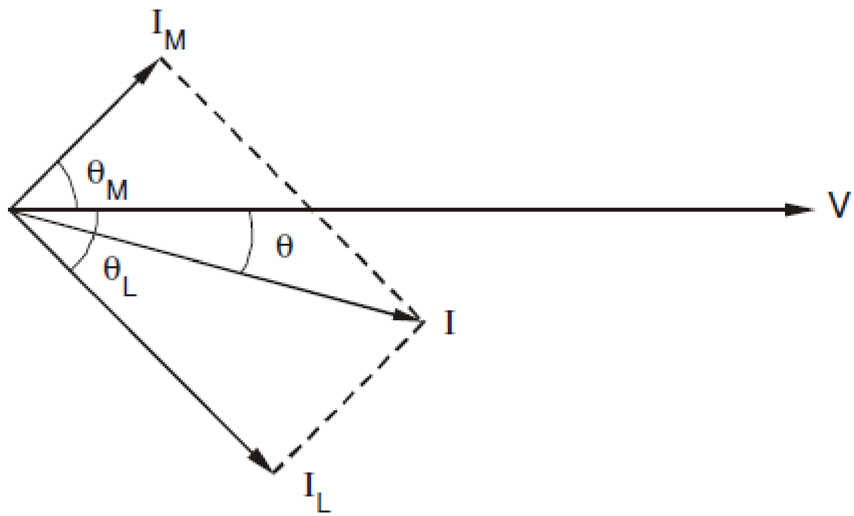


Figure 7.9 : Phasor Diagram

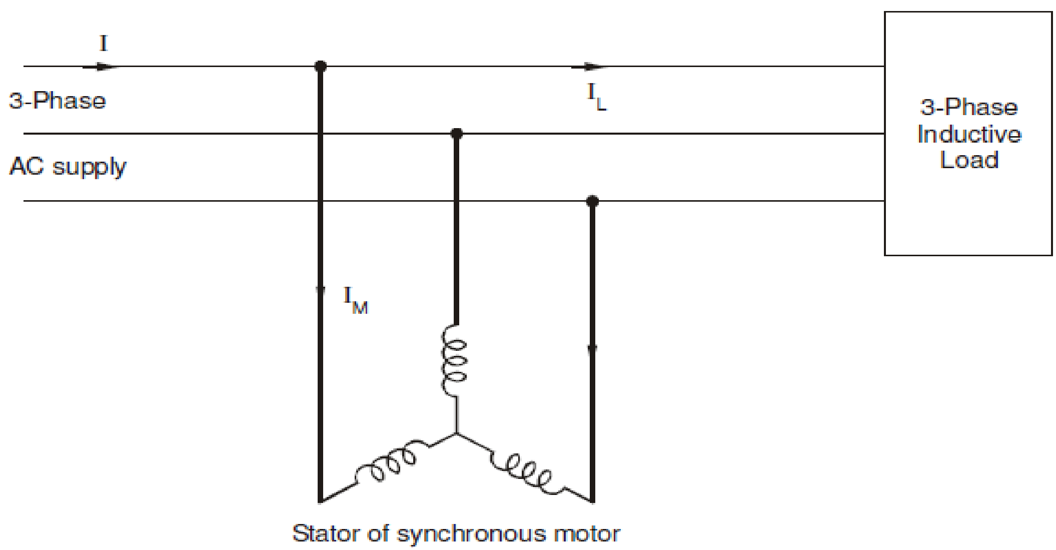


Figure 7.10 : Connection of Synchronous Motor with Connected Load